UNIVERSITETET I AGDER

3D printed concrete bridges

Opportunities, Challenges, and Conditions.

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Preface

The master's thesis has been made at the University of Agder, Norway, as part of the Master's Programme in Civil and Constructional Engineering. The academic responsibility lies with the Department of Engineering Sciences. The master thesis was prepared in the fourth and final semester, spring semester in 2020, and equals 30 credits.

It assumes that anyone who chooses to read this report has a basic understanding of engineering and concrete technology. The purpose of this master's thesis is to identify the limiting factors and challenges associated with 3D concrete printed bridges, consider opportunities and important conditions for the concrete and the equipment.

I would like to thank my supervisors Rein Terje Thorstensen and Lars Toverud for professional insight, good advice, and excellent support throughout the whole process.

I have interviewed several people from the construction industry, universities, and research institutes during the project. I would like to thank everyone who participated in interviews and shared their time, useful information, and interesting thoughts. I found great passion and interest in the subject and the study. Their participation has been necessary due to the focus on the industry's experiences, attitudes, and opinions on opportunities and limitations with 3D printing technology.

Finally, but not less importantly, I would like to thank my family and friends for their support, interest in my studies and believing in me.

Karoline Friis

Fredrikstad, 22th June 2020

Abstract

The purpose of this master's thesis is to identify the limiting factors and challenges associated with 3D concrete printed bridges, and to consider opportunities and important conditions for the concrete and the equipment. Through the work on the thesis, it is endeavoured to review the 3D printing market with current practices for 3D concrete printing, with original research covering an overview of the technologies relevant for 3D concrete printing for large scale structures.

A literature review and semi-structured interviews were selected as primary methods for collecting information to a qualitative study. The thesis is based on an extensive literature review, looking at what has been done before in other countries and where the industry is headed. Semi-structured interviews were conducted with professionals from diverse fields to get a broader picture of the construction industry.

There are many challenges that 3D printing has to deal with, and several requirements are given for 3D printing to succeed. A complicating factor for the application of 3D printing in the construction area is that the requirements for this sector are tough when considering durability, safety, and strength. The study results show there are several advantages of 3D printing in the construction industry that can lead to great opportunities. 3D printing can most definitely be used for elements, in particular where there is flexibility with design. It opens up how we look at tools, equipment, materials, and design.

Table of content

Figure list

Table list

Abbreviations and Acronyms

°C	Degrees Celsius
3D	Three dimensional
3DCP	3D concrete printed
AI	Artificial intelligence
AM	Additive manufacturing
AMT	Additive manufacturing technologies
BIM	Building information modelling
CAD	Computer-aided design
CO_2	Carbon dioxide
CNC	Computer numerical control
EPD	Environmental Product Declaration
GDP	Gross domestic product
GHG	Greenhouse gas emission
HINDCON	Hybrid Industrial Construction
HSE	Health, safety and environment
IoT	Internet of Things
IPR	Intellectual property rights
LCA	Life cycle assessment
N3XTCON	the next generation of concrete structures
R&D	Research and development
RP	Rapid prototyping
RE	Rare earth
SDC	Smart dynamic casting
SDG	Sustainable development goals
SM	Subtractive manufacturing
SMEs	Small and medium enterprise
SMT	Subtractive manufacturing technologies
UHPC	Ultra-high-performance concrete
VMA	Viscosity modifying agent
w/c	Water to cement

1 Introduction

The building and construction industry is one of the largest industrial sectors in Norway, measured by both turnover and employment [1]. It is accepted internationally that productivity is too low and that the industry has not kept up with re-industrialization – i.e. automation and use of digital technology. The construction industry is a small margin industry, and the cost level for Norwegian labour is high. It is often claimed that the accumulated R&D activity in this industry is insufficient, when considering the size and importance of the construction industry.

Norway has not yet developed and built a 3D printed concrete bridge. The international competition is high as other countries already have projected and implemented 3D printed constructions like bridges, smaller buildings, and elements.

Several years have passed since the first bridge was 3D printed in 2016, and one can wonder why there are no more than five 3D printed bridges in the world, four of which are concrete bridges. Today, most bridges are constructed with concrete cast in-situ, and these are tailor-made for each location. The use of prefabricated elements is continuously increasing, as it contributes to shorter construction time, simplified construction process, and possible cost savings.

This project aims to investigate the situation with 3D printing with concrete in the construction industry in 2020. Through the work on the master's thesis it is examined to look into existing bridges that have been 3D printed in other countries, what the 3D printing market looks like, the possibilities that 3D printed concrete bridges provide, the challenges involved with the 3D printer, and the properties of concrete as a material.

The thesis is structured according to the report template for the Civil and Constructional Engineering Master program at the University of Agder.

2 Significance of the work

Sustainability has become a highly debated topic within the construction sector during the past decade. As worldwide population steadily increases, the need for better and improved constructions and infrastructure increases as a natural response. As such, material resources will eventually become scarcer and, thus more expensive [2]. Global issues such as climate change, biodiversity loss, desertification, and ecosystem degradation have caused an accelerated need for natural resources globally as a serious threat to well-functioning economies and societies [3]. The construction sector is a crucial sector to evaluate the processes of reaching the United Nations (UN) Sustainable Development Goals (SDGs). These goals were established to achieve smart, sustainable, and inclusive growth. The UN has developed 17 SDGs for 2030, addressing all the global challenges the world is facing [4]. Goubran (2019) looked into the role of construction in achieving the SDGs and concluded that the industry contributes largely to 11, 6, and 7 [5]. Crump (2017) considers goal number 9 in addition to 6 and 11 as the critical goals for building environmental professionals [6].

These four goals represent the following:

6. Clean water and sanitation
7. Affordable and clean energy
9. Industry, innovation and infrastructure
11. Sustainable cities and communities

In 2016, the Paris Agreement came into force, and several countries signed it. Today, all countries have an obligation to cut greenhouse gas emissions and work together so that the average global temperature does not rise more than a maximum of two degrees Celsius (°C), and one of the goals is to be climate neutral by the second half of the century (2050-2100). According to scientists, the planet is currently heading towards a 3°C or more increase, which would have catastrophic consequences [7]. To stop this, significant measures and innovative thinking are required, including within the construction industry.

Today's construction industry accounts for major emissions. According to the 2019 Global Status Report for Building and Construction, the world's building and construction generates around 39 percent of the total CO_2 emissions [8]. 3D printing with concrete generally needs less concrete due to optimizing the design of the structure. If elements or smaller structures are individually produced, it is possible to produce the structure under controlled conditions. If items are printed indoors under controlled conditions, the HSE associated with the process will also be significantly higher.

Concrete has a reputation for being a less environmentally friendly material. As mentioned above, 3D printing generally uses less concrete. On the other hand, concrete consists of high cement content. The concrete bridges that have been printed so far have a higher cement content than bridges cast in-situ. The cement manufacturers have developed and are still working on the development of environmentally friendly cement, which could make the printing process more environmentally friendly as well if it printed with a concrete that is less "ordinary". The reason behind the high cement content in concrete is to get a more manageable concrete, which is technically called mortar, which is one of the most disputed elements of 3D printing with concrete, if it is mortar or concrete.

Statistics show that reported work accidents in 2018 for the construction industry were 5.2 per 1,000 employees, where it is assumed that an accident results in a long-term absence of over three days [9]. A fall is the type of work accident that constitutes the most substantial proportion accidents, followed by a thrust/hit of the object [10]. Bridge construction often occurs at height, with high activity in small geographical areas and extreme time constraints. 3D printing can be a part of the improvement of the HSE situation by reducing the number of workers exposed to accidents, or by creating safer working environments.

Professor Klaus Schwab, Founder and Executive Chairman of the World Economic Forum, explored the beginning of what he believes to be the fourth industrial revolution. The fourth industrial revolution is characterised by a range of new technologies integrating the digital, biological, and physical worlds, influencing all industries, economies, and disciplines [11]. Through digital networks, it is possible to connect all people, productively enhance the performance of organizations, and even handle assets to help reinvigorate the natural environment. This could possibly undo the damage of previous industrial revolutions, which has emancipated the human race from animal power and made mass production possible [11]. Schwab also elucidates concerns about organizations' abilities to adapt if governments fail to employ and regulate new technology; security concerns with the shifting power; and the increasing inequality in a fragmented society. The concerns about the fourth industrial revolution will become major problems only if communication and collaboration across disciplines, sectors, and geographies does not enable the possibilities it presents from being fully realised [11]. All stakeholders, from both public and private sectors, should be involved for it to be comprehensively integrated [12].

> "(…) together shape a future that works for all by putting people first, empowering them and constantly reminding ourselves that all of these new technologies are first and foremost tools made by people for people."
>
> -Schwab

The fourth industrial revolution provides excellent opportunities. It has the potential for income levels to grow globally and improve life quality on the earth [12]. So far, those that have benefited from it are those who have access and can afford it. Schwab predicts a future where technological innovations will lead to a supply-side revelation with long-term gains in efficiency and productivity [12]. Transportation costs will decrease, global supply chains and logistics will become more efficient, and trade costs will diminish. It will open up new markets and drive economic growth. Schwab [12] also refers to Erik Brynjolfsson and Andre McAfee. They have pointed out that the revolution can do the opposite and yield greater inequality, especially due to the potential to disrupt labour markets.

3 Theory

3.1 Technology in the construction industry

The terms used in this master's thesis can have several meanings, due to different perceptions of them, and it can be difficult to separate the different terms, in particularly those concerning technological concepts. These terms are clarified and defined in Table 1.

Table 1 Definition of terms

Terms	Definitions
Construction industry	The construction industry is a branch of commercial enterprise concerned with construction of building, bridges, etc. [13], and is used to cover the entire value chain. The construction industry is also referred to as the industry.
Technology	Methods, systems, and devices which are the result of scientific knowledge being used for practical purposes [14].
Digitalization	Digital information, turn into a form that can easily be read by a computer [15].
Automation	The use of methods for controlling industrial processes automatically, especially by electronically controlled systems [16].
Robotization	The introduction of robots to carry out industrial tasks [17].
Industrialization	To develop industry or to undergo development of industry to an extensive scale [18]. It is used to describe the transition from craftsmanship and one-of-a-kind solutions, towards standardized and automated production [19].

There is a plethora of articles, reports, or other forms of written expression, filled with arguments on how the construction industry needs to transform [20]. People around and outside the industry expect change, plus pressure from external organisations shows that the construction industry wants a change.

The construction industry is a small digitalized industry as of today. The rising digitalization trend will help drive the industry forward - and that could trigger a substantial gain if the industry manages the new technology in the right way [21]. The industry has a way to go, but the potential benefits that digitalization can bring are significant. One of the success criteria for the future is more collaboration and sharing of knowledge. Success is not just about technology, but about humans using and developing technology and having the right leadership driving change in the organization. Digital aids and tools can contribute to skills' enhancement and a safer, more comfortable working day [21]. In the competition between advisors, the competitiveness lies in not simply following, but driving digitalization with the client. With regards to digitalization, technology is only a small part of the process, as it is people's ability to use technology that is crucial [22].

Digital developments increasingly influence today's business models. So far, digitalization has just enabled more efficient production, but this is changing. In recent years, the consulting engineers have seen rapid developments in paperless projects, and the use of virtual reality and augmented reality. The awareness of machine learning and artificial intelligence (AI) is increasing among consultancy companies [22]. Especially in AI, robotics, and machine learning, other sectors are leading, leaving the construction industry behind. There will probably be an overhaul of digitalization to streamline old processes to completely new processes, based on new technology.

The use of BIM (Building Information Modelling) related tools is increasing in the construction industry [23]. BIM could be the foundation or springboard for further development and implementation of an ever-expanding range of new technological innovations. With its related tools and standards, BIM is a powerful platform for information flow across stages and actors. [24]. In an industrialized process, BIM will enable data flow between design tools and digital production equipment. Through BIM and the Internet of Things (IoT), building and construction generate vast amounts of data over its lifetime, which can be used for production, operation, and learning about future processing. The term for this is Big Data and, in simplified terms, the utilization of Big Data is based on volume (cloud computing), velocity, and variation (data structure) [23]. New technological opportunities can change many of the work processes and roles in the construction industry. Soon, construction projects will be managed through real-time digital twins, where the IoT generates Big Data processed by AI in cloud services [23].

An increasing number of construction's data services can now be provided as cloud services. In cloud services, the computers in the data centres partner with the cloud service providers to provide customers with access to the desired computing power and storage capacity [23]. It is a fundamental change in how the internet works and has provided many new companies with a foundation to offer valuable services. The cloud services are rapidly evolving and will only provide much more computing power and storage space over the next 5-6 years, and more significant opportunity for parallel processes [23]. Cloud solutions have great potential to provide value for the construction industry. With all the information available in the cloud, communication is made more accessible and more efficient. It applies to all participants in a project. Not least, it has great utility in terms of communication between those who sit in the office and those who work outside on the construction site [25].

To take advantage of Big Data (and IoT), high-speed 'data transport systems' are also needed for immediate access [23]. Big Data must be structured for it to be utilized. One way to do this is to structure the data in graph databases. It allows the machines to read the data themselves, thus utilizing AI. [23]

The use of Big Data technology can connect actors in several parts of the value chain through visualization [24]. Data collection and data analysis can help to create more efficient logistics systems, pattern recognition models, state controls and easier maintenance, etc [24]. Smart systems based on data collection and analysis can be developed to be self-optimizing for resource use, energy, etc.

AI utilises the extreme increases in computing power to analyse large, structured data sets to see new patterns and learn from them. Thus, robots cannot only handle complicated and complex tasks such as designing and producing but can also learn better practices by comparing solutions and how they work [23]. AI can be divided into software and hardware, where the hardware that drives the cloud services forward is the same that drives the AI going forward. The software consists of Big Data Analytics and machine learning algorithms, of which Deep Learning is a sub-category [23].

Within automation, the focus on flexible factory automation can help increase production capacity and make jobs easier. It involves automated production lines with flexible jiggers, lasers, and machine vision technologies for measurement, positioning and sorting, Computer Numerical Control (CNC) machines, and sensor-based robot systems [24]. A prerequisite is the digitalization of BIM data that can be interpreted by production machinery [24]. With automation, quality is continuously ensured throughout the value chain, and no final inspection is necessary [24]. The majority of processes can be automated, but the company's expertise needs to be updated so that new technology can be handled. It is essential to have the necessary competence to achieve process control: (1) materials, (2) processes, and (3) organization of work and communication [24]. For the process itself, automation means that all individual operations must be performed perfectly every time. The individual operations can be compiled differently each time meanign the overall process can vary, but on the specific detail level, variations will not occur. Another important aspect is that the input to an industrialized process must be under specific criteria [24]. The process should not make any unplanned adjustments. However, it is easy to think that an automated solution to all or part of the production line will solve all problems. It is much more important to look at the flow through the entire value chain and identify bottlenecks. When the process is designed so that the flow is more optimal, automated solutions can be considered. So, there is no point in speeding up a bad process.

In large value chains where actors in design and engineering, contractors and clients, and subcontractors work more efficiently and collaborate seamlessly, it becomes essential to adopt new enabling technologies [24].

3.2 3D printing in construction industry

3D printing in the construction industry has generated an increase in attention. 3D printing can be a way to make the construction process faster, cheaper, and better. The technology provides for a wide range of applications, and the versatility is due to the variety of materials, almost limitless freedom of design, and the ability to fabricate complex shapes offsite and on-site [26].

BCG defines 3D printing as [26]:
"The term 3D printing *refers to the production of physical objects layer-by-layer by an automated and usually computer-controlled machine. The machine, most often guided by digital 3D models, either melts metal or powdered solids or ejects liquid or semiliquid materials."*

Twente AM defined 3D printing as [27]:
"3D printing, also known as Additive Manufacturing, is a process in which material is joined together using computer numerically controlled machines to create a three-dimensional object. 3D printing allows for the complex shapes and objects to be manufactured precisely and quickly without the need for additional tooling."

Additive Manufacturing (AM) was previously called rapid prototyping (RP), and is often referred to today as 3D printing. AM is an umbrella term for 3D printing, rapid prototyping, and direct digital manufacturing [28]. The International Organization for Standardization (IOS) has defined the terms as [29]:

"3D printing is fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology."

"AM as a process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies."

In the construction industry, 3D printing is making progress and gaining ground [30]. The construction industry has used 3D printing for many years to create models and prototypes in the construction process. But the technology is developing further and will soon be just as relevant also at construction sites and facilities. There have already been examples of individual parts being printed in fields, which reduces the need for complete sets of tools and spare parts. Mainly-remote projects can significantly increase efficiency by printing on-site rather than transporting everything needed for the construction process [23].

The fundamental characteristics of 3D printing could naturally be linked to construction (Figure 3.1) [26]. Together with the features of automated and autonomous production, it is well suited, and BCG have expressed the natural fit with the construction industry:

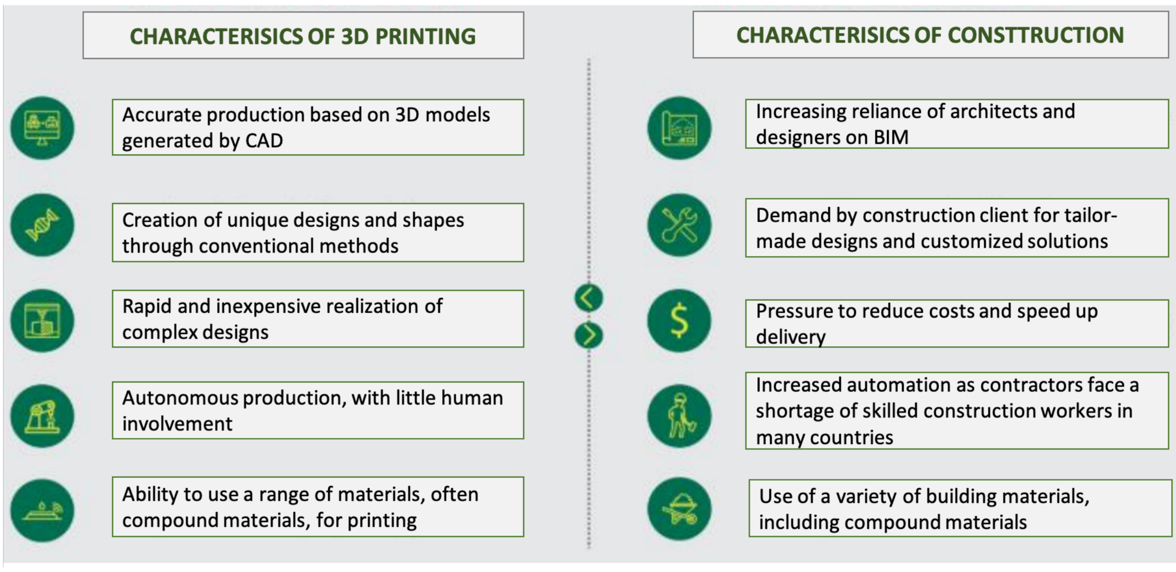

Figure 3.1 Linkages between 3D Printing and Construction [26].

3D printing has proven to provide cost savings, increased accuracy, and reduced environmental impact. Challenges have been scalability and the development of appropriate processes [23].

Robots can be used both at construction sites and in factories. They are primarily off-site, used in conjunction with the automation of production lines (by flexible jiggers, lasers, and machine vision technologies for measurement, positioning, and sorting, CNC machines, sensor-based robot systems, etc.) that are associated with the industrialization of the industry [23]. For the construction site (on-site), it is the beginning of robotization, as with autonomous cranes and construction machinery - and the digital construction work [23], as a part of industrialization.

Several actors already specialize in element- and/or module-based construction - but what is particularly interesting in the quantum leap context is when new actors outside the industry, with a completely different competence in production lines than the traditional ones, establish themselves [23].

The European Construction Sector Observatory (ECSO) in 2019 published a trend paper on how innovations in the construction sector are integrated [31]. ESCO looked at applications of 3D printed solutions in the construction sector and it proved to be applicable for several areas: building, bridges, printed moulds, building components, architectural models, and interior design [31].

One of the key lessons learned from the ESCO case study of the 3D printed cladding 'shrouds' of the 6 Bevis Mark office in London, was that the most significant issue around 3D printing concerns the 3D printing material (concrete) and the lack of standards, and not the 3D printer [31]. Another case study form ESCO was the Yhnova, housing project in France (Nantes). One of the key lessons from that case was that 3D printing could not be done alone, and still relies on the traditional way of building [31]. It is not a choice between 3D printing or traditional construction, and it is about how to combine them efficiently. 3D printing might be best suitable for specific purposes as particular building components or components with a unique design [31].

In Europe, several firms, not only construction, have started investing in 3D printing. ESCO have reported that the total number of businesses and associations engaged in 3D printing in construction has increased from 20 start-ups in 2013 to 65 in 2018 that offers prototyping solutions for engineers and architects, computer systems and programs, structural components or an entire building [31]. Academia also plays a vital role by participating in numerous 3D printing pilot projects, providing and supporting the knowledge development process.

3D printing has been in use in the construction industry for many years, mainly for building prototypes [32]. Soon, the technology will be seen more at the construction site as well. Additive technology makes it possible to build structures in inaccessible environments (e.g., on the moon), and architecturally distinctive buildings can be constructed with irregular shapes and complex connections [32]. But technology has, first and foremost, the fantastic potential for creating better housing for most people. Additive technology makes it possible to tailor buildings to local climate and users' wants and needs, at no extra cost [32].

When printing on a larger scale, the materials for the printer must also be developed. To exploit the possibilities of additive production, the entire construction process has to be reassessed - from planning and design to construction and use [32]. Processes, workflows, and new business models, value chains, and markets must be developed. Ground-breaking technologies such as 3D printing and robotization will require new expertise from the authorities and clients, in the design team, in the factory hall, and at the construction site.

The materials and equipment for 3D printing are improving as well as a reduction in cost. Research institutes such as MIT, ETH Zurich, TU Delf, and Loughborogh University, are continually developing 3D printing [26].

In some contexts, it is argued that 3D printing could trigger an archetypal shift in terms of production - from prosthesis in the health sector to consumer goods in the commodity-producing industry. Figure 3.2 illustrates the industry's maturity through mapping conducted by Labonnote et al. [33]. While there are already examples of constructive joints in 3D printing, there is a long way to go before 3D printing of entire structures or building segments is used in practice [24]. How fast this will go depends, among other things, on the development of suitable materials and printers (for example, robot arms at the construction site).

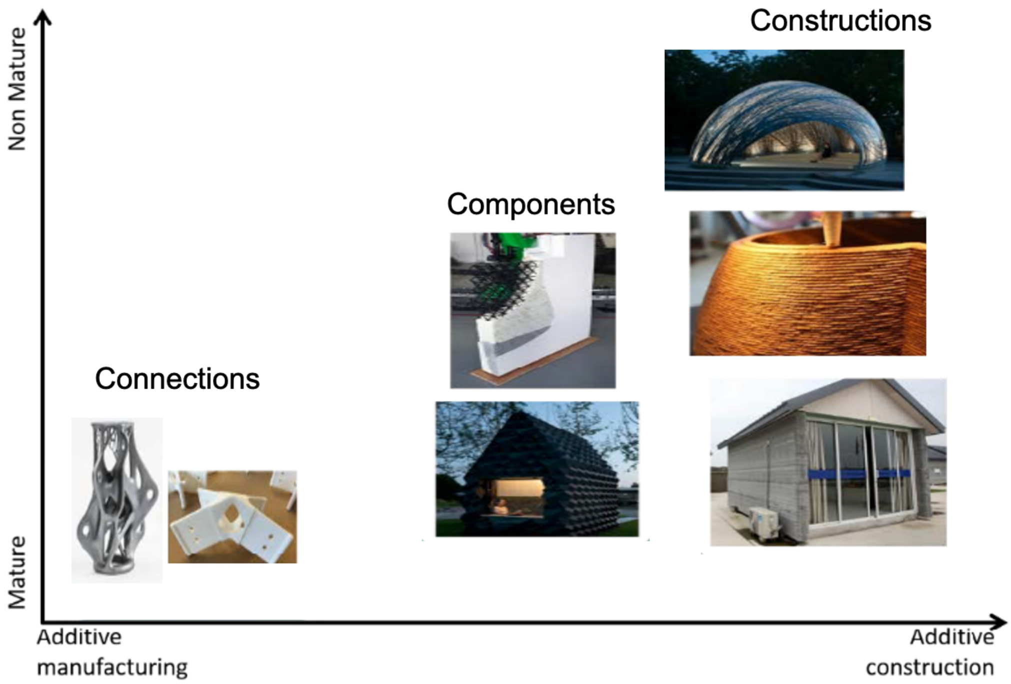

Figure 3.2 Maturity for 3D printing and AM in the Construction Industry [16].

3.3 Experience with 3D printed concrete in construction

3.3.1 3D printed structures

3.3.1.1 Skanska

In 2016, Skanska UK was a key contributor in a 3D print project with collaboration between Skanska UK, engineers at Loughborough University and the company Foster [34]. It was about industrializing the construction process, which also is an overall goal for Skanska. The robotization of the casting process is an element of this industrialization. Loughborough University has developed patented 3D concrete printing (3DCP) technology for full-scale construction and components [35].

By combining material technology with digital technology, obvious benefits are achieved, such as increasing productivity and competitiveness [34]. But the industry is in an early stage of development in the commercial sense. The technology must be significantly more developed to be economically profitable.

The well-known 3D technology is used today in a number of areas, but by using robotics and material technology for concrete, the technology is used in a new way. The machine is lined with a 3D model of the element to be built - then the machine controls design and production. One of the great advantages of this technology is that the machine can work unmanned around the clock. As a result of such robotization, there will be fewer hours per unit produced [35].

The project aimed to demonstrate that 3D concrete printing could be applied to produce objects in forms unfeasible with traditional casting methods [36].

Skanska was one of the first to exploit 3D printing in a commercial real-estate project [26]. Skanska found an economical and innovative solution by printing complicated nylon sleeves at the office building in the City of London. Their next project was with Loughborough University and in collaboration with ABB and Foster + Partners, among others, on a 3D printing concrete project. The project involved a type of façade (high-spec concrete), which is usually extremely costly and therefore had great potential to be cost-effective with the use of a 3D printer [26].

3.3.1.2 Winsun

In 2013, Winsun 3D printed a residential house that escalated into a batch of ten houses using a mixture of cement, sand, fibre, and additives, where the company printed it in a factory before assembling on-site [36]. Since then, several prototypes have been developed by the company.

Winsun has a factory near Shanghai with a printer that is more than 100 meters (330 feet) long and uses a mix of cement, sand, and fibres where 50 percent comes from recycled demolition waste. The oriented hollow walls are transported to the construction site, easily assembled and filled with reinforcement and insulating materials. According to Winsun, the printing process reduces construction time by 50-70 percent, labour 50-80 percent, and materials by 30-60 percent due to minimization of waste and use of detritus. It gave Winsun a $1.45bn deal with Al Mobty Contracting to lease 100 3D printers to build 1,500,00 affordable homes [26].

3.3.1.3 Hybrid Industrial Construction

Hybrid Industrial Construction (HINDCON) is a project founded by the European Commission under the Horizon 2020 Program. It is about the adaption of manufacturing technologies to the construction sector, introducing Additive and Subtractive manufacturing (SM) in construction. HINDCON has four primary areas of development, (1) Additive Material Development, (2) AM, SM and Robotics Technologies, (3) Software Development, and (4) Manufacturing and Construction Processes. The overall aim is to adapt manufacturing technologies to the construction sector to enhance industrialization and overcome limitations for introducing additive and subtractive manufacturing, developing an "all-in-one" hybrid machine for 3D printing technologies with concrete material for large-scale advanced manufacturing and building process [37]. The project duration was from 2016-2019, with a consortium of 12 members from around Europe, all of whom are leading companies within their respective fields [38]. Figure 3.3 shows how the project is organized into nine Work Packages (WP) and how the WP relate to each other. The technical core is WP2-5; (WP2) Additive material development, (WP3) Printing and robotic technologies, (WP4) Control software development, and (WP5) Manufacturing and Construction Processes [39].

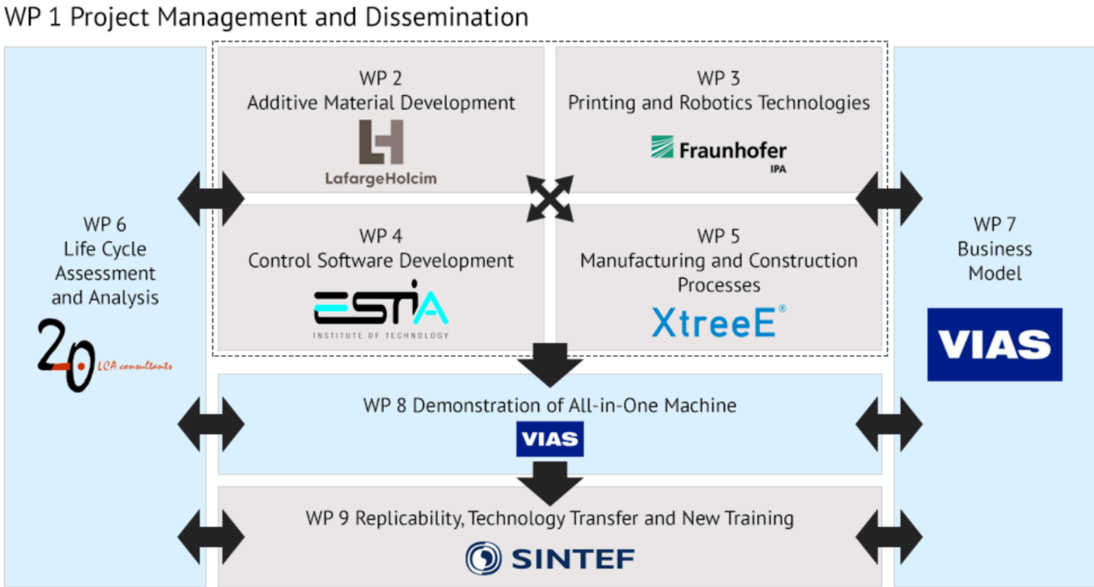

Figure 3.3 Diagram Illustrating how HINDCON is organized in Work Packages [40].

The value proposition of HINDCON is divided into three stages [41]:

1. All-in-one machine with extruder system and subtractive tools: The first is to have in the same machine additive and subtractive technology. It is new, and there is no other proposition on the market. The double technology allows the end-user to benefit from intricate pieces with laying treatment.
2. Special concrete with high performance: The second is the performance of the material. Lafarge Holcim (LH) has developed a variety of materials from low cost to ultra-efficient concrete.
3. Cable technology: Lastly, discover robotics and adapt it to the concrete 3D printing, which is new and can print large scale precast pieces with a robot-driven positioning system.

3.3.1.4 N3XTCON

In the project N3XTCON, construction experts, together with the industry and supported by the Danish Innovation Fund, will among other things develop a computer simulation tool and new concrete printers with associated control, so that 3D concrete printers can be incorporated as a reliable and resource-saving construction method, which creates entirely new opportunities for future buildings [42]. The new technology 3D printing with concrete in the construction industry must go from being experimental to a real and reliable construction method in line with other building technologies.

The goal of N3XTCON is to develop 3D printing technologies that enable 3D printing of concrete structures (CON) in the future (next generation (N3XT) [42]. The key, and where the project differs from other projects is, in particular the simulation tool and reinforcement strategies. In this way, the 3D printing process can be predicted under given conditions and for a given task, and thus can be adapted without expensive and often blindly performed trial and error experiments.

Also, the project differs from the vast majority of projects and experiments with 3D printed concrete in the construction by considering reinforcement in the printing process [42]. The concrete must be reinforced to achieve several of the significant advantages and application areas of concrete in usable constructions. Today, there is no industrialized, workable solution for reinforcing the 3D printed concrete structures [42].

3.3.1.5 Dubai

In Dubai, the world's first 3D printed laboratory was contracted [43]. The Emirate is investing heavily in futuristic construction technology. 3D printing of buildings has so far been a curious exception in the international construction arena. In the United Arab Emirate Dubai, technology has been discussed more frequently than anywhere else, and in 2015 Dubai had the world's first printed office.

In October 2016, the contract to build the world's first 3D printed laboratory was signed in Dubai, and the laboratory was to research 3D printing and drone technology [43]. It was the first building in Dubai to be printed on the site, and not at the factory and then mounted.

The project was part of a broader strategy for the United Arab Emirates. The construction of the 3D printed lab, by Mohammed bin Rashid Al Maktoum Solar Park, was intended to reflect their ongoing work on showing government directives [43]. Dubai's 3D printing strategy is a unique global initiative to use technology in the service of humanity, as well as raise the United Arab Emirates' status and Dubai as a leading name in 3D printing technology by 2025. The goal is for 25 percent of all new buildings to be 3D printed in Dubai by 2025.

Acconia's newly opened centre in Dubai has the world's largest 3D printer, as of November 2019, with Powder Bed technology in operational use. The technology is particularly well suited for making resilient parts. Also, concrete is used as the base material, which makes it an ideal solution in, for example, architectural and construction solutions [44].

The 6x3x2 meter printer streamlines and automates the construction process [44]. Acconia's new production facility is the result of an innovation project that started in 2016, which has fine-tuned the technology and made it ready for commercial use.

During this process, Acciona has had several milestones: the world's first 3D printed walkway in Madrid, and the first 3D printed, full-scale memory in concrete; a Romanesque arch of San Pedro de las Dueñas (León, Spain), in collaboration with the Spanish National Archaeological Museum [44].

3.3.2 3D Printed concrete bridges

Four concrete bridges have been 3D printed so far in the world. One concrete pedestrian bridge is located in Spain. Netherland has printed two bridges, where one is a bicycle bridge, and the other is made of steel. China has 3D printed a 26.3-meter-long pedestrian bridge, and Japan is the last one to have 3D printed a bridge. This chapter will give a brief overview of the 3D printed bridges.

3D printing can increase the options for bridge construction [45]. BCG states researchers believe the next step is to investigate printed bridges that are strong enough to carry motor traffic [26].

3.3.2.1 Spain

The first large-scale 3D printed concrete pedestrian bridge was built in Madrid and opened in 2016. The project, which took a year and a half, was led by the Institute of Advanced Architecture of Catalonia (IAAC) and was collaborating with D-shape. Accionia led the execution of the project with a multidisciplinary team consisting of architects, structural and mechanical engineers, as well as representatives from the municipal administration [46]. The bridge is 12 meters long and 1.75 meters wide and was printed with micro-reinforced concrete. Segments of the bridge were printed and assembled before it got transported and lifted into place. Because it was installed in public space, it fulfilled the legislation.

The shape and size of the construction influenced the strategy and the design due to the size of the printer, which has a maximum dimension for the pieces that it can print [46]. It is a specific challenge regarding 3D printing concrete bridges.

The footpath bridge in Madrid used a D-shape printer [47]. It was developed through parametric design, making it possible to optimize the distribution of materials and minimize the amount of waste by recycling raw materials during manufacture. The development of the design is illustrated in Figure 3.4. Structural performance is maximized with a computer-generated design where the material is only used where it is needed, allowing for total freedom of shapes thanks to the use of generative algorithms [46].

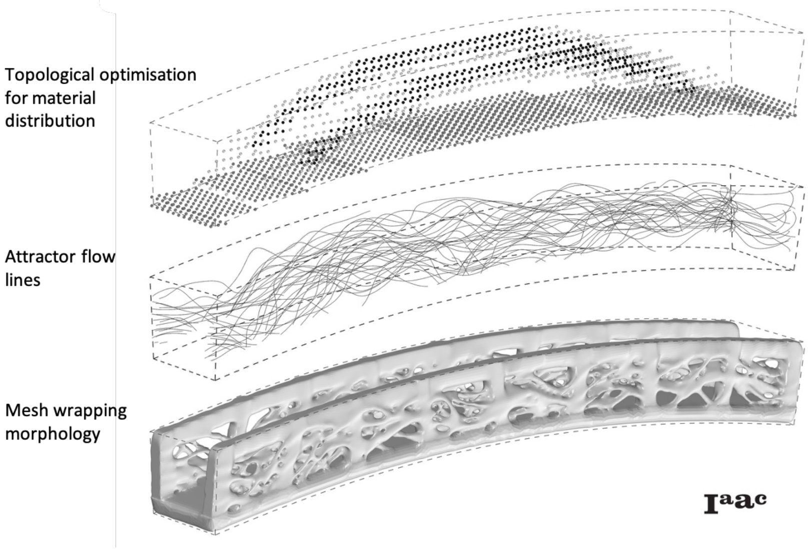

Figure 3.4 Design Development Progress Diagram [46].

3.3.2.2 Netherland

In the town of Gemert stands an eight-meter-long bicycle bridge in concrete, 8m long, 3.5m wide and 0.9m thick (Figure 3.5) [48]. The bridge was made in a collaboration between the company BAM Infra and Eindhoven University of Technology (TU/e), and was built to last 30 years or more [48]. It is designed for cyclists only, and the uniformly distributed design load is 5.0 kN/m^2 [49].

The used 3D printer prints the mortar layer-by-layer, where steel wire is simultaneously inserted into in each layer, which reinforces in the construction [48]. It took three months to print the bridge, which consists of a total of 800 layers of shotcrete. Six items were printed out, which were then put together into a continuous concrete bridge.

Big steel cables connect all the blocks together. The bridge was created in one facility and then transported to the site where it is put into different blocks. After that, it was assembled before it was lifted and put into place [50].

Figure 3.5 Bicycle bridge in Gemert made by BAM Infra and TU/e [51].

The concept of 'Design by Testing' was used to allow a 3D concrete printed (3DCP) structure to be certified as safe for the public [49]. The 3D printing technology is being explored using 'trial and error' method, and this method has been used in the development of the bridge [49].

The bridge was designed after the capabilities of the 3D concrete printer at TU/e. The entire bridge could fit into the print box, but it was decided to print multiple elements instead of one piece from bottom to the top of the deck to optimize the cross-section.

Six elements composed the bridge, and the height of each element was 1.08m, consisting of 89-90 layers of 12mm each. The size of the elements was limited due to the lifting capacity of the crane in the laboratory. In total, the bridge has 535 layers, each layer with a length of 25m that worked out to a total of 13.4km print path length [49].

It took 48 hours to complete the printing of all the elements using two full wet systems, including two mixing devices and pumps [49]. To avoid try joint, each system was used for approximately two hours, based on the open time window. Then, within minutes, a switch was made to the other system to continue printing. This solution avoided the inside of the hose and parts of the pump from hardening due to the open time window of approximately three hours. That resulted in an amplified temperature and print pressure, which influenced the character of the printed filaments and can lead to pump failure [49].

The reinforcement consists of high-strength steel cable wire embedded in the concrete filament during printing. For this TU/e has developed a Reinforcement Embedding Device. The cable pre-stresses the element in compression transverse to the load because of the restrained lateral deformation [49]. Finite element analysis was used to determine the final design structurally with more detail [49].

The people doing the study recognize the potential improvement of architectural design in the future. With regards to the focus of safety in this project, architectural design was not central. For the same reason, parapets were chosen not to be integrated with 3D printing [49].

3.3.2.2.1 Steel bridge

The Dutch company MX3D designed a steel bridge made with robotic 3D printing (Figure 3.6). The 12-meter-long bridge is different from most previous bridges. While steel structures often require straight lines and angles, there are not many limitations to 3D production. The bridge was manufactured using a six-axis welding robot, which offered new possibilities both in terms of design and how the supporting elements are designed. MX3D built a “plug and print” robotic AM software that was easy to utilize and moveable to change standard industrial robots into a bigger scale. For MX3D, the idea was to apply robotic 3D metal printing to the construction process [52].

Figure 3.6 MX3D Steel Bridge [53].

In 2019, the final load test of a 3D printed steel bridge was conducted. After several years of development, they succeeded, the first in the world, in 3D printing an entire steel bridge. The bridge was thoroughly tested. A 20-tonne test was carried out in order to get the necessary permit in place before it could be used in Amsterdam [53].

The project has enabled creative collaboration with over 25 stakeholders such as ArcelorMittal, ABB, Arup, Autodesk, Heijmans, Air Liquide, Delft University of Technology, Imperial College London, and the Amsterdam City Government [53].

MX3D started with 3D printing ten years ago. But none of the people behind the innovative company's backgrounds are from the construction industry. MX3D consists of a group of artists and designers who are continually looking for new ways to use digital aids - both on the software and production sides [54]. The construction industry was brand new to the founders, and they felt that it is a very conservative industry in the sense that it is not particularly innovative [54]. Innovators often come from different industries. It is no coincidence that it is designers and artists behind the bridge project [54]. There were a whole host of partners in this work, but few of them were from the construction industry. One of the reasons that the construction industry does not take the step itself is low margins. One needs to show that innovation is profitable quickly; preferably, it should have paid off within two years [54].

They tested the printing of objects and art in various forms and materials fairly early. They quickly realized that one of the things that were missing was the opportunity to conduct large-scale 3D printing of, for example, large art projects, larger building structures, and large pavilions. The company first started using a robot to build with the material resin. The tests were very positive, but the material did respond as wanted, thus, the idea of 3D printing in steel emerged. It started quickly with 3D printing new and exciting geometric shapes. First, they started using the robot in various art projects, where it gradually built up to have the capacity to print a steel bridge [54].

The developed robotic and print technology can cut both costs and time in construction projects, but the steel bridge MX3D built was costly [54]. It was both expensive and time-consuming to build. It was expensive to figure out what to do with certification requirements. It was necessary to use resources to research what forms that can print, and robots were broken down along the way. In the next projects, the work and results from the project can be utilised, thus costs can be cut significantly. MX3D envisions that further projects can be optimized, and if the technology is further developed it may be possible to print a bridge without humans being part of the process at all. Even in the design phase, you can deduct part of the cost you have from using human labour, and then the construction phase can be fully automated [54].

3.3.2.3 China

The world's longest 3D printed concrete bridge opened in China in 2019 (Figure 3.7). Chinese scientists believe they are now at the forefront of 3D printing, after setting a new world record in Shanghai. A 26.3-meter-long and 3.6-meter-wide pedestrian bridge in 3D printed concrete opened in mid-January 2019 at Wisdom Bay Industrial Park in China. The bridge was developed by a team led by Professor Xu Weiguo at the Architecture Line at Tsinghua University in Beijing [55].

Figure 3.7 3D printed concrete bridge in Wisdom Bay Industrial Park in China [55].

A single arch structure was deployed to bear the load. The structure failure test was conducted on a physical model on a scale of 1:4, illustrating the load of pedestrians crowding over the whole bridge [55]. The test provided a positive result as the bridge's strength met the load requirements.

The 3D printed system had been developed independently by the team at Tsinghua University and were self-appointed taking the leading position in the field globally, based on three main innovation point of the system [55]:

1) The printer with a robot arm that avoided plugging in the extrusion process and failure when layering materials.
2) The print path generation and the operating system integrated form design, movement of the printing tool and robot arm, material pumping, and systems working together.
3) A special printing material composite with stable rheology properties and sensible performance.

The method was assimilated with technologies like digital architectural design, operation control system, printing path generation, printing tool, concrete material. It has high printing efficiency, moulding precision, and constancy in prolonged work [55].

The concrete components were printed in 450 hours, using two robotic arm 3D printed system. In comparison with a conventional bridge of similar size, Tsinghua University alleged that the 3D printed bridge cost two-thirds of that - primarily because the main part of the bridge did not use any templates or reinforcing bars during printing and construction, saving costs significantly [55].

The pedestrian bridge design adopted three-dimensional modelling and attempted an elegant attitude [55]. It consisted of three parts: the arch structure consisting of 44 hollow-out 3D printed concrete components in the size of 0.9x0.9x1.6 meters. The handrails were divided into 68 printed units, and the pavements were divided into 64 units for printing [55].

Composite materials composed of polyethylene fibre concrete with various admixtures were used in the printed components [55]. Repeated ratio tests were conducted, as well as printing experiments, resulting in controllable rheology to meet printing requirements. Pressure resistance strength and flexural strength reached 65 MPa and 15 MPa, respectively [55].

To collect data of force and deformation of the bridge in real-time, they set up a real-time monitoring system, including a vibrating wire stress detector and a high-precision strain monitoring system. The monitoring system tracked the concrete material performance, as well as the mechanical properties of the units [55].

The Tsinghua University expressed how 3D printing, as an essential part of intelligent construction, can be an important factor in the intelligent development of engineering construction by solving the problem of demand for labour in construction projects, especially in China with their current situation of disappearance of demographic dividend [55].

Although many bottlenecks need to be dealt with in 3D printing of concrete structures, competition in this field is becoming increasingly fierce as it increases. The Tsinghua University marks a step for the 3D printing technology from R&D to practical application, as well as the entry of China's3D concrete printing and construction into the world's advanced level [55].

3.3.2.4 Japan

In February 2020, a Japanese contractor Taisei Corporation revealed Japan's first 3D printed pre-stressed concrete bridge (Figure 3.8). The bridge is 6.0m long, 1.2m wide, and 1.0m high and was made with 44 3D printed elements with pre-stressed steel [56]. The company prepared holes for inserting steel in advance. When members were in place, the steel was inserted and integrated. [57]. The printer that was used is named T-3DP (Taisei-3D Printing).

Figure 3.8 3D printed pre-stressed concrete bridge by Taisei Corporation [57].

3.4 Current standards and regulations

As of today, there are no standards or regulations for 3D printing. Because of the lack of 3D printing standards, 3D printing must follow the same standards as any other concrete construction. The constructions that are 3D printed must follow the standards regarding requirements for material properties, but also production and process. Eurocode is a series of standards that apply to European countries. In total, there are 10 Eurocodes. These are used in the design, as well as documentation of constructions. Parameters and regulations that are peculiar to the country are discussed in national annex included with the Eurocodes.

WIth regards of 3D printed concrete bridges, several Eurocodes are relevant:

- Eurocode 0: Basis of structural (EN 1990)
- Eurocode 1: Actions of structures (EN 1991)
- Eurocode 2: Design of concrete structures (EN 1992)
- Eurocode 8: Design of structures for earthquake resistance (EN 1998)

With regards to concrete, the standard that must be followed is *EN 206:2013+A1:2016 Concrete: Specification, performance, production and conformity* for concrete production, and it contains special requirements for work management and staff competence. These competence requirements apply to all work covered by this standard. In EN 206, conditions are set for the competence of the production manager, mixer operator, labourer and concrete conveyors, including band truck drivers and pump operators [58].

To support the viability of the technology, regulations and standards are important components as they provide information about the use and increase of HSE image associated with the application. The study of the ECSO's report reveals that few governments have yet developed a regulatory framework as setting performance-based standards and widening building codes to incorporate 3D printing technology, materials, and testing [31]. Regulations and standards would help with information and can be powerful for potential clients, stakeholders, and the construction industry regarding the durability and safety of 3D printing.

Looking at BIM, which is required in several EU member countries (e.g., Denmark, UK) as part of their public procurement policy, regulations can involve public sector procurement as an incentive for companies to invest in 3D printing [31].

Construction companies, e.g., Winsun, is working with construction departments and regulators on different levels to adapt and enhance building codes. Also, companies can develop prototypes that are adaptable and can be tested and proved compliable with existing building codes. It can help educate the market on the reliability of 3D printing as well as the potential 3D printing has [31].

4 Research question

The aim of this thesis is to see if there is a future for 3D printed concrete bridges in the construction industry. Therefore, the research question is:

How do we see the future with 3D printed concrete bridges?

To answer this question the specific operational questions have been created:

- **I.** How is the market for 3D printing?
- **II.** Which conditions must be met to 3D print concrete bridges?
  - i. What does the construction industry know about the equipment that can be used?
  - ii. What kind of requirements must be given to the concrete for it to be printable?
- **III.** What challenges do we see with 3D printing of concrete bridges and how can they be handled?
- **IV.** What opportunities does 3D printing of concrete bridges give?

4.1 Limitation

To be able to answer the above researcher question, several limitations have been made. 3D printing of concrete bridges involves several areas of interest. The equipment and concrete technology will be considered in this thesis. For 3D concrete printing to be used in the construction industry, several requirements are necessary. The research will focus on printable concrete, and the specifications given in the Eurocodes will not be repeated or summarized in this thesis, including concrete properties, the design of bridges, the load on bridges in all conditions. Design is an essential prerequisite for the proper use of 3D printing but will not be evaluated. Economics is part of the basis for the market analysis, RQ1, the results of which are taken from the literature study. Otherwise, no economic calculations are made on the profitability of individual projects.

5 Case

The work on the thesis investigates whether there is a future and a market for 3D printed concrete bridges and will considering the opportunities 3D printed concrete bridges give, as well as conditions, and the challenges they face.

To answer the research question, the thesis is divided into several parts:

- Overview of existing 3D printed bridges globally
- Qualitative interviews of representatives from the construction industry
- Technology in the construction industry and 3D printing market
- Study of requirements for equipment and the concrete for it to printable
- Study of challenges and opportunities with 3D printed concrete bridges

The mapping of existing 3D printed bridges is carried out globally to illustrate what has been done in terms of design, span, and total lengths.

Furthermore, a survey will be conducted among representatives from the building and construction industry. This is done to highlight the challenges and opportunities of 3D printed concrete bridges that the industry itself can identify. The study is executed with qualitative interviews.

The study will look at the properties necessary for the concrete to be printable and the type of equipment available. Opportunities and challenges with 3D printed concrete bridges will also be explored.

Finally, the results of the studies mentioned above will be summarized and discussion about what should and must be the basis for using a 3D printed concrete bridge will be carried out.

6 Methods

6.1 Methodology

It is necessary to obtain information on the topics to answer the research question. In this thesis, a literature review and semi-structured interviews were selected as primary methods for conducting information. The literature study was used to find information to develop a theoretical foundation, which formed the basis the qualitative survey in the form of interviews. In total, the overarching purpose of the paper is to investigate the 3D printed concrete bridge's position in the construction industry. Finally, the findings were analysed and discussed in light of the literature. This resulted in a conclusion and further recommendations.

Semi-structured interviews were selected as the method for extracting relevant data from representatives of the construction industry. The reason for choosing a semi-structured interview is to allow interviewees to respond openly, have a dialogue and allow new ideas to come forward. This was selected as an empowerment tool to highlight tacit and latent practices towards technology. The goal was for the correspondent's responses to represent the construction industry. Therefore, a total of 25 interviews was carried out with representatives from within the entire value chain including universities and research organisations.

6.2 Data collection - interview

The book "How to conduct surveys: Introduction to the social science method" by Dag Ingvar Jacobsen [59] is the basis for the method on how the survey was conducted.

6.2.1 Approach to the problem

The purpose of surveys can mainly be divided into two main types: (1) Describe the current situation, and (2) measuring the impact or effect a measure has. Jacobsen also distinguishes between types of issues [59]:

1. Exploratory: The purpose is to elaborate about what we know little about
2. Testing: The purpose is to see the range or extent of a phenomenon

The work on this thesis intends to clarify the challenges, opportunities, and requirements of 3D printing, through this descriptive and exploratory study. In an exploratory study, it is often appropriate to use a qualitative approach. The qualitative approach concentrating on a few units is better suited to capturing nuances and penetrating in-depth data than quantitative ones [59]. Therefore, it was decided to conduct interviews with respondents who could throw light on the topic of the thesis.

An issue was developed since a topic alone cannot be empirically researched. A review of the following areas was needed to determine the issue [59]:

- Variables of the survey - what needs to be considered?
- The entity - who will be interviewed?
- Where will the investigation take place?
- When will the investigation take place?

There is a question about the prevalence of the use of 3D printing, but also what level of knowledge and attitude the industry has towards this technology as a production method. The survey is to take place in this context. It was defined, not by a geographical area or a single organization, but rather the construction industry, mainly based in Norway, but also in other European countries. It was decided to interview people who, through their current position or experience, knew about concrete or 3D printing, or both to get a representative picture of the industry's view on the topic. The study's location in time follows the industry's current view (carried out continuously in the spring of 2020).

When the problem was set, there was a clear desire for what should be investigated, but delimitation set what should not be investigated [59]. It may be conscious or unconscious. For example, the chosen issue does not focus very much on whether there is a financial potential for 3D printed concrete bridges. It was a deliberate choice, as it was not possible to compare cast in-situ with 3D printed bridges due to lack of access to cases with direct numbers. An unconscious or implicit exclusion was that the survey did not cover or consider people's perceptions of what is aesthetically pleasing. It could be interesting to investigate this further, but it would require a different method of investigation.

A question should phrased in a way that the result is unknown from the beginning, it is possible to answer and possible to investigate empirically, and add new knowledge [59]. The question is exciting because the result is not necessarily known before. It was possible to investigate empirically by asking the industry and also likely to be answered by summarizing the challenges and where the possibilities lie with 3D printed concrete bridges. The knowledge gained is not necessarily new as it existed before, but this study gathers the knowledge in one place and attempts to identify the most significant challenges or the best opportunities.

In this study, an unclear issue was chosen, based on a desire to elucidate a topic on which there is relatively little overall knowledge [59].

The last point that was important in shaping the study and the issue was a generalization: whether it was desirable to be able to conclude the study to represent more than the entities studied [59]. The study aimed to discover what the construction industry knows and think about 3D printing and, therefore, need to be generalizable.

6.2.2 Survey set-up

In general, the survey set-up was chosen because it best suited that particular problem. A distinction was made between designs that can be called descriptive or correlational, and those called causal [59]. To describe a situation and what conditions were occurring at the same time, a survey was carried out that take a cross section at a specific time. For cause and effect, the selected design should contain information from multiple times, so-called time series data [59]. In this paper, a descriptive survey was chosen. Variation over time was not interesting in this context.

There was also a distinction between intensive and extensive survey set-ups. Intensive survey set-ups go into the depth of a phenomenon and aim to gain a detailed understanding [59]. Many nuances are studied but relatively few units, making them well suited for theoretical generalizations. Based on a smaller number of observations, one forms a more general theory of how phenomena are related. Extensive research schemes go wide and study many units with usually a few variables [59].

The survey set-up used here was a sample survey, more specifically, a small-N-study [59], in which nineteen respondents participated. It was expected to have ten respondents, with twenty-five participants, although only nineteen of the interviews were transcribed due to time limitations. The main focus was 3D printing of concrete bridges as a phenomenon where the respondents were different actors from the construction industry. The purpose was to reveal different understandings and, to learn about different views from various actors in the industry. Typically, small-N studies have few respondents, usually between five and ten, where you focus on a specific phenomenon that is elucidated from different points of view. In this study, there were more than ten participants as the positive response for participation was higher than expected. The strength of this method of investigation was that it gives a relatively abundant description of the phenomenon that was investigated and a sound basis for understanding the phenomenon better [59]. Small-N-studies can have challenges in the generalization of results due to relatively few units investigated. In this case, more unites than for normal small-N-studies were investigated and, but it still remains a challenge.

6.2.3 Option of information types

A testing issue is often intended to determine the extent, frequency or extent of a phenomenon. The issue wants to go wide and to examine many. This will be an extensive scheme or method that examines few nuances but extends across many units. With such issues, a quantitative or closed approach is chosen [59].

An exploratory problem will often require a method that produces nuanced data, is in depth and is sensitive to unexpected conditions and thus open to contextual relationships. This often entails few research units that will produce many nuances. Such methods are suitable for the collection of qualitative data [59].

In this thesis, it was desirable to obtain 'real-life' information, which provided a better understanding of the phenomenon, but with few investigative entities. Therefore, it was decided to use a qualitative approach. This approach did not require the information collection to be categorized and structured based on prior knowledge, and thus, it opened many different types of information and topics. It is in contrast to the quantitative method in which, as a researcher, one must lay clear guidelines for what kind of information one can expect, and risk ending up with a more distant understanding [59]. Furthermore, it is a prerequisite for quantitative studies to quantify the phenomenon that is investigated to some extent. That was not the case in this thesis.

When choosing a survey method, it is essential to understand the strengths and weaknesses of the method. Regarding qualitative data, it can be pointed out that by collecting words rather than numbers, you will be able to achieve a greater worth of information. One gets close to the respondent, and the respondent controls the type of data to a greater extent. Thus, one can argue that the qualitative approach will have high relevance, or, the 'correct' understanding of a phenomenon. It is often said that a qualitative study should have internal validity [59]. Also, it makes it possible to capture the nuances of the phenomenon. This provides a deeper understanding. The last advantage is the potential that the researcher himself can actively use, namely flexibility. As a qualitative study progresses, your understanding of the problem will increase as you collect data on it. It is possible to adapt your research to the problem or survey scheme to the new information [59].

As mentioned, it is also important to understand the limitations of the method. Qualitative data is resource-intensive to process, so it is often necessary to investigate few units. The fact that only a few units are handled also presents challenges in generalizing the results, as the sample may not be representative, which causes problems with what is called 'external validity' [59], that is, how well the results describe the reality outside the investigated group investigated. The closeness that was mentioned as an advantage in the section above can also compromise the researcher's objectivity, but this effect is greatest where the researcher spends a lot of time with the respondents. Also, the said closeness can cause the investigated person not to behave naturally or respond honestly; this is called the "investigator effect". Flexibility can also be a pitfall to be aware of. If you continuously change the program, you will risk never completing or researching something completely different from the area you started with [59]. Also, in interviews, unbiased data is crucial to rely on. It requires minimization of the Hawthorne effect [60], which is when participants have increased awareness of issues when observed.

6.2.4 Collection of information

A qualitative data collection begins with the collection of primary data, where observation, the open individual interview, and the group interview are essential aspects. Furthermore, it is possible to supplement with secondary data and source investigation [59].

Open interviews were used in this study. An interview was best suited as there were few units to be investigated, and it engaged with individual views and interpretations of a phenomenon. There are four different forms of interviews: face-to-face, telephone, chat, and e-mail. By conducting a face-to-face interview, another type of closeness will be present compared to the other three forms. Trust, openness, and good flow are established in the conversation due to minor distractions. But there are also some weaknesses to this type of interview, including being present during the interview itself, which can incur high costs. The interviews were conducted face-to-face where possible. Due to geographical obstacles, but first and foremost, Covid-19, several of the interviews were done using video telephony, Microsoft Teams, or Skype. This method will be weaker in establishing trust and openness but still allows good flow in the conversation. Since these were completed over Microsoft Teams or Skype, significant control over the interview situation was maintained. In total, two interviews were accomplished face-to-face before lock-down.

As mentioned earlier, the qualitative approach is good at producing nuances by being open to many inputs. However, it is important to not leave the interview utterly open about a topic to avoid extra work. Therefore, an interview guide was used to ensure that all the sub-topics were reviewed (see Appendix *12.1. Interview Guide).* The interview guide consisted of different themes and allowed for open answers. On the scale unstructured/structured, the interview was semi-structured, as illustrated in Figure 6.1.

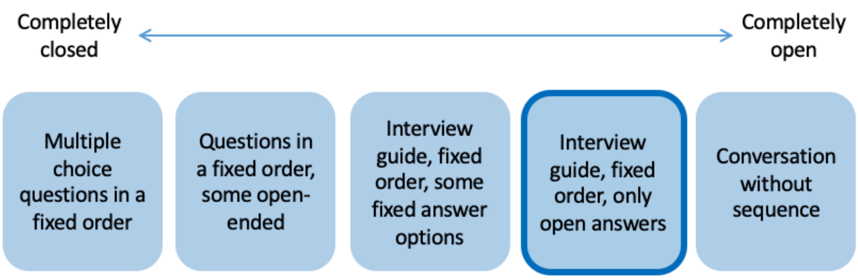

Figure 6.1 Degree of structuring an interview. The study's degree of structuring marked with a blue frame. Based on [59, p. 145].

The interviews were to take place somewhere that would feel natural to the respondent. Thus, one of the interviews was conducted at their workplace, one interview at a meeting room organized by the supervisor in Oslo. One of the interviews was completed over the phone. The remaining 16 interviews were conducted over Microsoft Teams or Skype, where they sat in their office or at home. The surroundings were, therefore, known to all respondents precisely to create as natural conversation as possible. The purpose of the interview was also made clear in advance and again at the beginning of the interview so that the respondent was aware of what the results would be used for. All conversations were recorded using a smartphone, so no thorough notes were necessary. As a result, all respondents' statements were included, quite literally, to be transcribed later. Audio recording can provoke a negative reaction; therefore, it was always stated before the interview started so that the respondent could rescind if desirable. Also, it was stated that all interviews would be anonymized.

The respondents were selected based on their job position and experience so that the topic of the interview should be elucidated from several points of view. All respondents were contacted via mail, where the author introduced herself, the background for the thesis was presented as well as the reason for contacting the respondents. After the respondent expressed willingness to be interviewed, the time of the interview was agreed, and where the interview would take place.

One-off interviews were done. The duration was set to one hour based on the scope and number of questions to be asked. In most cases, this period was more than enough, but for some, it exceeded. Open questions were asked so that what the respondent thought was important came out in his/her own words. The respondent needed to be allowed to speak freely; neither interrupted or asked too many questions [59]. The questions asked in the interview are enclosed (Appendix *12.2 Interview questions)*.

It ended with a general question where the respondent was given the opportunity to add any additional information he or she felt had not come up during the interview and was important. In this way, it was rounded off in a natural way and without the respondent leaving without revealing important information [59]. It was natural to round off the interview as it neared the end at the agreed time. There was more time, on our part, if the respondent wanted to complete something or provide more information.

6.2.5 Selection of interviewees

The selection criterion was based on information to suit the problem [59]. The selected respondents were employed in various companies, representing one of the actors in the value chain, from the universities or research institutes. They had experience in one or more of the following areas:

- Concrete Technology
- Additive Manufacturing
- Design/Construction of bridge structures
- Building with prefabricated elements
- Manufacturer of prefabricated elements
- Clients role in road project

An overview of the 19 respondents' background and current function is given in Table 2.

Table 2 Respondents' Background and Current Function.

Respondent	Current function	Experience
1	Supplier of prefabricated concrete elements	40 years in concrete element industry. Experience as an engineer of buildings and elements as well as various infrastructure groups, sales and business developer.
2	Contractor	35 years with concrete technology and structures, working as a supplier and as a concrete technologist.
3	Contractor	30 years of experience with concrete. Working for a contractor with concrete technology, prefabricated concrete and construction, as well as R&D
4	Consultancy	30 years of experience with bridges as a client and consultant.
5	Chief engineer and technical expert	25 years of experience. Worked as a consulting engineer with bridges, and a chief engineer and technical expert with design, regulations and maintenance as Client.
6	Consultancy	40 years of experience in consultancy as an engineer in construction, doing civil structural engineering advice, nearly all on bridges.
7	Concrete Organisation.	35 years of experience with concrete, fibre reinforced concrete, additives. International experience.
8	Industry Organisation	25 years of experience with precast concrete and construction, as an engineer and client.
9	Consultancy	35 years of experience mostly as a client working on bridges, tunnels, and roads. Experience as concrete producer and consultant.
10	Supplier of cement	30 years of experience with cement, concrete, R&D.
11	Consultancy	55 years of experience in consultancy as an engineer in construction, most of the time with bridges. International experience and now as an international expert consultant, and strategic development consulting where needed.
12	Research organisation. University	Background from Aerospace. Worked in the construction industry as a researcher in the field for 12 years. Knowledge in AM.

13	Client	10 years of experience as a client, working with control and approval of bridges and other supporting structures.
14	University	25 years of experience with additive manufacturing, materials and design. International experience as lecturer. Works with R&D 3D printing and pedagogy. Wrote a book about additive manufacturing.
15	Consultancy	35 years of experience with cement and concrete technology, and construction. Combined experience through contractors, university, R&D, and consultancy. Work on Eurocodes and standardisation.
16	University	40 years of experience, mostly as a professor and R&D with focus on bridges for over 25 years and consultancy.
17	Technological institute	12 years of experience with materials, constructions, aesthetics and energy.
18	Research organisation	40 years of experience of construction and materials in research organization.
19	Consultancy	45 years of experience with consultancy

6.2.6 Processing and analysis of collected data

The information gathered in connection with the interviews had to be processed. First, all interview recordings were transcribed. With transcribed interviews, it allowed use of the analysis program NVivo (version 12.6.9). NVivo is software for qualitative data. It is designed to help with organizing, analysing, and structuring qualitative or unstructured data. It also contains tools that can help streamline the analysis of the data [61].

As the interview was transcribed verbatim, there were some incomplete sentences where the respondent interrupts themselves, and some silences in the interview recordings. The transcription was started before all interviews were completed. Some knowledge was developed along the way, but the questions remained the same throughout the research period.

After the transcription was done for 19 respondents, they were reviewed. They were read and heard at the same time. The transcript was then loaded into the NVivo program. Open coding, also called first-cycle coding, was performed, simplifying complex and detailed data [59]. Here, words, sentences, and paragraphs were divided into categories. It began with Construction Industry, Opportunities, Approaches, Requirements Concrete, Challenges, and Future with 3D printed Concrete as the first six categories. The responses from each respondent were thoroughly reviewed, and the data from the interviews were sorted into these six categories. The six categories were divided into subcategories to make the data analysable. In this way, it became an overview of the various topics and respondents' opinions.

Using the NVivo program, it was possible to see how many people had said something within the different categories. It was also possible to go back to the context from which words, sentences, or paragraphs were taken.

Following this categorization and systematization, there were several statements within several different categories. Within social sciences at this point, the researcher is beginning to look for causal relationships. That is why a phenomenon occurs and often also has a connection with the respondents' background and experience of a phenomenon [59]. Although it might have been interesting in this study to examine whether there is a difference between what challenges and potential respondents are facing and their position in the industry, it has been chosen not to go into this. Instead, the focus has been on gathering information from multiple sources that can easily complement each other. Thus, the analysis of the data was completed after all relevant and interesting statements had been categorized. The information is presented collectively in Chapter 7.1 *Main findings from interviews.*

6.3 Literature review

Research papers concerning 3D printed concrete bridges were investigated. That was to get a broader knowledge of the subject. The purpose of the literature study is to shed light on the knowledge level of 3D printing with concrete focusing on bridges and concrete properties and find any knowledge gaps. In the thesis, a literature study was conducted based on various written sources. Most literature searches were done on Oria as well as Scopus, Google Scholar, and other databases. The advanced search criteria limited the search to English or Norwegian written articles between the timespan 2015-2020. As this is a quite recent focus for most construction companies, and is a subject under continuous research, newly written research papers were preferred. Despite this, older articles and papers were read when investigating the already chosen articles. Keywords were used to narrow down the search for articles suitable for the literature review.

7 Results

In this chapter, findings from the interviews are presented in *7.1 Main findings from interviews*. Then follows *7.2 Technology in the Construction Industry* where the use of technology in the construction industry and an overview of 3D printing market are presented. Chapter *7.3 Opportunities with 3D printed concrete bridges* explores just that. This is further elaborated in *7.4 Conditions for 3D concrete printing* about what equipment can be used and what requirements must be given to the concrete for it to be printable. Finally, Chapter *7.5 Challenge*s *with 3D printed construction*, explains what is challenging for 3D printing technology and concrete. Chapter 7.1 is based on the interviews alone as it presents the findings from the interviews. The chapters 7.2-7.5 are based on a literature review and are also set in the selected order based on the research questions.

7.1 Main findings from the interviews

Findings from the interviews are divided into the same categories as the post-treatment: Construction Industry, Opportunities, Approaches, Requirements Concrete, Challenges, and Future with 3D printed Concrete. A word cloud was created to give an overall picture of the findings from the interviews. This is shown in Figure 7.1. All the text in this chapter are the participants' opinions and thoughts. For some of the chapters, quotations banks show essential opinions from the participants to summarise the opinions from the group and give a better illustration of their thoughts. Due to the participants' anonymization, it is not possible to know where the participants belong in the value chain or whether several people represent the same place in the value chain who share the same opinions. The number of participants and references for each subject and category are listed in a table in Appendix *12. 3 Categories form NVivo.* This table demonstrates how many people speak about each subject, as well as how many times the subject or category were mentioned. The strength of each statement is uncertain, but the table helps to emphasize each topic and each category.

Figure 7.1 Word Cloud from all interview. From NVivo.

7.1.1 Construction industry

7.1.1.1 Challenges within the construction industry

The construction industry is facing several challenges with technology among different actors and within the organization and at an organisational level.

Actors

"It is in collaboration with contractors, project consultants, and clients, a development that is done together."

It was a general agreement among the participants that what is said to be low production is probably accurate. There are more significant gaps between the public side and the craftsman today compared to 15 years ago. It is more difficult to achieve development in production technology now than it was 15 years ago. There are many more people sitting in the office on the computer than before, compared to supervisors back then. The supervisors knew much more about the subject and produced better work. We have a massive challenge in the industry.

One participant looked at the consultants as the bottleneck of today:

"So, when you design something, you have B35 and maybe even B45. The design standard NS-EN 1992 goes all the way to B95, and we can make B95 with ordinary materials. We have made concrete with compressive strength of 130 MPa, just by changing the W/C ratio number. And then we utilize the materials, but no one wants to design something like that. Same with fibre reinforced concrete, which is coming now, almost no one can design for it to be used in construction. Then we save 40 percent of the ribbed bars if we can run with fibre concrete. But there are very few, maybe two large consulting companies that have two men in each company who know this."

One of the participants excluded contractors as a driver for development in Norway. It is merely to do with the business model. If you are going to be a driver of change, you also take some risk. And those cases where the cost-sharing between the client and the contractor becomes a bit "Unfair", especially if the client expects development, innovation, and development in his project, like many people want, but are not willing to take the risk of l the insurance premium, i.e., the cost of running it.

Several participants had some thought about the clients. Clients tend to be the most risk averse. In the end, the system means that they are the ones who will not adopt new things because they are uncertain about them. They need to have the confidence that it is going to work. We do not seem to see as many clients who want to push the innovation and new technology as we need. And this is partly because of the risk factor that they feel, causing them to be inherently conservative, mainly because many of them are public authorities. They do not feel comfortable doing something which has not been done before.

A few participants stated that there must be a claim from the client or developer. The whole industry and all the links in the value chain are ready, more or less, but as long as requirements do not come and no one will pay for these solutions, then they will not be used, putting them on hold. It is a thought that if there is no demand for it, it will not develop either. So, ultimately, the changes must come from those who see the potential in it and say "*we need concrete that is like this or that*". And that must come before the material developers act.

One of the participants thought that the construction industry may not be as far ahead as when we started using information models. So, the construction industry on bridges may be five years behinds, but the technology is developing so fast that it may be smart to find out how we can do it.

R&D was a subject that was mentioned in several settings by numerous participants. One of the respondents thought that if we ask an actor in this industry about development, R&D, there will be very few who have it in their budgets, to some extent. Their impression was that the suppliers to the industry might have developed more than the industry itself. The biggest development of old and new technology in the construction industry, or the element industry, is hollow-core slab production. The industry is being forced to develop on the mix of concrete, different concrete quality, environmental classifications, EPD on all products, etc. So, there it has significantly improved over the last ten years but overall there are too few resources.

Technology

"The construction industry is less efficient because they do not use available technology."

One respondent did not believe technology has been the bottleneck in the development and used an example from the time the Troll Platform in the North Sea were developed. They decided to build a structure that no one at the time knew how to build when they made the decision to start building. They just knew that during the 2-3-year period, they had to get it flowing. They started and knew that technology would waste away during that period, which it did. So, it turned out that when you set clear goals, technology is not the bottleneck. But if you do not set clear goals where you want to, then technology development spreads so much in every possible direction that nothing seems to be happening. One does not get the physical proof as when a platform is delivered, for example.

Another participant mentioned a technology that has been developed in the last few years, floating bridge technology, which has evolved during the previous decade with some fascinating possibilities. Tet kind of technology that has been used in Bjørnefjord (floating bridge) is very innovative, and obviously enables something which otherwise could not happen. That is a situation where things are being held back due to technology as the technology has to be developed in sync with the project as its design evolves. Otherwise, it is mainly that things do not happen as fast, or maybe they do not happen as efficiently because the technology is not being adopted, which is much more common.

One of the participants recognized the lack of technology as an obstacle for innovation but also a lack of risk-taking and lack of the right budget and so on. There is an incredible number of examples of this, almost all projects seen start with big visions. Even when they become real, and money comes, they downgrade. And in the end, manufacturers, and especially contractors, think it is exciting if they can use new technology. Still, if they have not seen it been used many times before and in that way been convinced, then they will not use it. The challenge may not be so much that the lack of technology, but perhaps more the lack of understanding of what can be used. Many technologies are waiting to be used in practice, but because they are only spoken about for so many years, it is thought to be already in use when it is not. It does happen, but there are no robots at construction sites either in Denmark or Norway, or for that matter, any other places in the world.

Sustainability is a subject that was discussed by many participants. In the world generally, we cannot continue in the way we do now. We do not have enough resources to continue, or we have a massive unavoidable climate problem. So, something must be done even if it is more expensive to find the right sustainable solutions.

One of the participants had previously tried to start a project with 3D printing. The organizations were very interested, but no one had the resources. There was willing, but they did not have the resources or an organization that dares to invest in such an unknown and uncertain technology. It was abandoned and nowadays, there are quite a few who are aware that 3D printing is coming, but most say that they would choose to sit on the fence to see what happens because it takes quite a bit of effort hold and it seems like contractors today do not have the muscle to do it. It seems sensible to prioritize today's situation and make the most of today's position as they already need to make money tomorrow. Otherwise, one loses the competition, so it is understandable in a way. The construction industry is not particularly innovative.

A few participants thought that the technology is there, but it will not evolve without anyone using it either. So, this is a 'the chicken or the egg' case, we need to have a development for the technology to develop as well. Right now, we face a challenge with the use of open formats. And it is, after all, technology development for the software industry that we would preferably have a more significant and broader capability between the technologies in digital development.

It was stated that the construction industry is less efficient because they do not use available technology. One participant believed that to get started with technology without talking about finances, a cultural change is needed. Not everyone is ready for it, and many are not prepared for it. It is not only economics, but cultural change or the restructuring required that is challenging for organisations in the construction industry.

Organisation

"It's a very complex picture in the construction industry when it comes to technology."

One of the participants sees that the construction industry is a very fragmented, so there are many small organizations and few that are very large. Of course, the few who are big have bigger muscles to be able to invest in 3D printing, or drones, or something else. The others who represent about 90% of the construction industry have fewer than ten employees (typically a regular carpentry company), and they may not have enough money to invest in new technology. That does not mean that it is not appropriate for them. It just means that there is a very unbalanced picture of the construction industry that means that the biggest ones who are perhaps the most driven in the construction industry represent so little (as a percentage of the construction industry). Therefore, it is difficult to get the whole construction industry to move in an efficient manner.

Another one of the participants has learned that those who are innovative and want to move forward with technology in the construction industry do not come from the construction industry. Typically, start-ups come from outside the industry and have no background in construction are the ones who come up with new technology and will attack the construction industry market. A lot of start-ups think about sustainability by developing 'whatever' technology with a fancy app. However, they know nothing about building – they come from an app software developer. The second type are those from the financial sector, especially concerning the insurance sector and insurance companies. They also come with a fancy app to be able to e.g., install sensors throughout the building to get moisture, temp, weather data to avoid damage, for example. Both types work with sustainability and finance/insurance, and do not come from a construction background, and come with technology because they are used to using technology.

One participant believes that development has nothing to do with technology because it is an organizational challenge, but it has something to do with making technology evolve.

Creativity and ambition for change was mentioned as a challenge in the construction industry by one participant. Companies tend to treat creative people in different ways, and not everyone wants creativity. It may be about the lack of ambition to create big disruptive changes. So, one has not managed to get into a position if they have been very disruptive.

Conservatism

"There is not much to gain. People talk a lot about the fact that there is no productivity development in the concrete industry, you build similarity as you did 30-40-50 years ago, but that's partly because it's a very good way to build."

Many participants believed the construction industry to be the most conservative industry. It is not only because one is less smart, but because it has, unlike others, a completely different approach. For example, if the client would like to build something, he hires a consultant to design, and maybe an architect, and then it expands. There is an interface from client to consultant, consultant to contractor, contractor and subcontractors, suppliers, etc. So, the construction is cut into a lot of "slices" with interfaces between them. And that is the main problem because everyone has their finances, each has a contract, and each has to produce optimally, so there will be no innovation. It is a huge challenge with all the interfaces, and it is here where the construction industry is developmentally. It is not possible to divide the building into slices, where each part makes its own. It is contradictory because one part cannot change anything without the other changing and the third changing. It is a chain that is connected.

One participant mentioned that there are many requirements that must be met, and one cannot check that the requirements are met after it has been designed. The creation process is critical upfront because once you have designed the bridge and are awaiting approval from environmental authorities and others, then they can say that it is not enough. Something must be changed before it can be approved, which is a waste of time. That is the way you do it, but it is not rational.

Someone thought that the division into contracts, or the division into roles, stands in the way of development. It is not just about 3D printing. The construction industry is extremely conservative, and we can acknowledge that. it cannot cause offence because it is a well-known truth that is a challenge when it comes to development in general. It also applies to the development of 3D printing and many other developments.

“I often come across someone who says, “It has never been done before. We cannot do it. Forget it. It is complicated. You are disturbing my bureaucratic mind“, and so on.”

A few pointed out that it may be easy to say that the construction industry is conservative and that it is going too slowly, but they are also conservative for a good reason. It must comply with many requirements, standards, and legislation, so objects do not fall onto the heads of people. Perhaps it is more a matter of legislation and standardization being "relaxed" a bit. Not so that it is dangerous to build. The rules set by standards are quite conservative, and they have to be. Sometimes you can see that some of the bigger ones are very true to these standards and have a hard time getting involved with things that are beyond them. In practice, Americans are a little better at testing and building based on testing, regardless of what theorist says it is not.

“It is not only finance but a cultural change and restructuring that is required, which is challenging for the construction industry.”

One of the participants exemplified how prejudice and extreme conservatism as a professional approach is a huge obstacle to development. The Norwegian road construction, particularly the Norwegian bridge construction, has a kind of aversion to building with prefabricated elements. In the Norwegian Public Roads Administration, there was, and still is, a kind of aversion to prefabricated concrete, as it has had a bad reputation in the Public Roads Administration. A bachelor thesis studied the technical quality of prefabricated beam bridges, how much damage there were on the prefabricated bridges, and of the 1400 bridges they studied, they found four bridges where there were damages. So, prefabrication got an undeserved reputation. Thus, prejudice causes an extremely conservative professional approach is a huge obstacle to development, and it is hard to do anything about it. The Norwegian road construction environment has been extremely focused on costs until Nye Veier arrived. Nye Veier have been an incredibly useful occurrence in Norwegian road construction to expose the Norwegian Public Roads Administration. Other issues make things conservative. There is a monopoly, and it is a monopoly that decides what the bridges should look like, and what is not right, which is a barrier to 3D printing.

One of the participants specified that there has been virtually nothing in the rationalization of the construction process in the last 100 years. For example, the Golden Gate Bridge was built in three and a half years in San Francisco with rivets. The big bridges today are being built in 8 years. So where is the rationalization?

“I think it is really nice that some people work to bring this world a little further, but then it is a little shame that sometimes it is a bit too difficult to do it. And it does not have to be the developer's fault. It may simply be the environment that does not accept new things."

7.1.1.2 Driving force of technology

"We have different types of companies operating different technologies."

Figure 7.2 Quote bank: Driving force of technology.

The participants were asked who they thought was the driving force of technology in the construction industry, and they had many different opinions. It differed from one actor as the driver and to the entire industry doing it together.

When identifying a need, it can be because of a lack of technology, and it can be due to a lack of a regulatory framework. It is often the motive for launching research and development projects to develop technology and regulations.

It is evident when you start a project you should consider alternative solutions, and you often rely on known technology and previously completed projects, etc. One participant suggested that there is also a willingness in the industry in Norway to challenge known technology, such as these floating structures, floating bridges, for example, which it was previously thought were impossible to implement. But a structured and targeted approach then proves that those challenges are also possible to solve.

Several participants mentioned that the driving force for innovation must be the actors in the industry, i.e., all actors. These are clients, builders, architects, consultants, contractors, manufacturers, and suppliers. There must be interaction to make it.

One participant thought that the client with the architects who is the driving force for the solutions and what they want to achieve. This is where the requirements are set. Had it not been for them, there would have been little development. Another participant said that getting it done depends on the contractor and the manufacturer.

It is a general view among the participants that the client has a central role. It is not necessarily those responsible for technology development, but those who take the risk. Without a client who is willing to order, you get little risk from the other actors. Someone has to pay for the risk it takes to switch to new technology. Statsbygg was mentioned by a few of the participants as an example, as one of the largest state developers in Norway. As a client, they made it mandatory for digital information models to be used in their projects, and it has been a building block for the construction industry. With the development of technology as a kind of engine for disruptive change, Statsbygg is the foremost driver as a motivator. The reason for that is that Statsbygg has been a kind of incubator or driver to promote BIM and promote BIM digitally so that the data can be reused in the operational phase and the maintenance phase. Statsbygg is, in a way, the primus engine behind (and Entra - but it is part of the state), in driving development to reuse building parts i.e. the reuse of hollow-core slabs from concrete element structures.

One participant considered an organization, that when it comes to bridges in Norway, it is, a big actor traditionally, and that is the Public Road Administration. They have built the highest number of bridges and operate most bridges as well. Thus, they have also had a leading role in the development of material technology, for example. Within the concrete industry, they have been a leading actor in Norway and partly internationally as well. Also, things have changed a lot in many ways lately because the Public Roads Administration has been given a slightly different role than they have had in the past. However, the new position is still in the mould, so to speak, because regional reform as of 1 January this year, then the area of responsibility and tasks of the Public Road Administration is for many is still unclear. Nor have the Public Road Administration been first in digitalizing and introducing BIM etc. Nye Veier have, in a way, taken over and have been the leading point in the industry in many ways by setting requirements.

Someone thought that some very enlightened contractors recognize the inefficiency and slow productivity. They have been working to look at automated systems, modular construction, and so on, to create systems to give them a competitive edge in the marketplace e.g. Companies like Lang or Roark, who have done a lot of work, mainly in building design, construction, not building bridges specifically, but in finding better ways of building.

A few mentioned the consultants. It is a combination of the very large consultants who have big budgets to be able to throw out research and innovation, ideas, the likes of Arup or COWI, but also some of the very small consultants who like to think of themselves leading at the cutting-edge, technology.

One participant believed that there has been a shift from the fact that it has been the universities that have primarily worked with innovation in technology. After all, they are building laboratories for testing, and no private actors could afford it or justify it. They researched and developed, and it was the professors who stood for the most development in the so-called old days. It has changed now because consulting firms such as Multiconsult, COWI, Ramboll, and all the others have grown larger. And just to put it in proportion, now COWI has around 600 bridge engineers around the world, and the Technical University of Denmark (DTU), which has a pretty good reputation, has about one or two people working on bridges. The innovation power now lies with the private consultants and depends on the private consultants' ambition to be a technological leader, and if they are working on it. Some consultants live by the innovations of the past and produce as best as possible, as quickly as possible, as cheaply as possible. Other consultants have a little more interest to say *"Yes, but we also need to innovate for the future*".

Some thought that the consultants are a little ahead of the contractors, but the consultants only deliver what is ordered or bought.

One participant clearly stated that the contractors are the driver of technology as contractors who see the greatest benefit of automation. They have a challenge when it comes to future labour, among other things. And not least in terms of efficiency because they have made quite a big development in terms of manufacturing and building technology. They are solution-oriented and get things done almost regardless, so they are innovative in that way.

Another participant thought the opposite: no Norwegian contractors are a driver for development, but Norwegian contractors are very good at portraying that they are. It merely has to do with the business model. Because, if you are going to be a driver, it is about taking some risk. And the cost-sharing between the client and the contractor becomes a bit unfair – especially if the client then expects some innovation and development in their project but are not willing to take the cost of running it.

One of the participants suggested it was the suppliers that are the driver of technology. When it comes to technology, there are often machine and software suppliers, suppliers of chemicals, and auxiliaries. They are often the innovators, and it is then driven by contractors and clients buying the technology, who facilitate innovation in their projects. So, to a large extent, many of the suppliers push the producer link ahead. That is because of the industry we represent; there is a lot of focus on production. It often takes mere hours from ordering products to delivery. So, the whole focus of the factory concrete industry is on delivering only what is in demand. So, there is technology available to them, plus the demand that drives the industry meaning when the demand for e.g. environmental declarations, comes up, solutions are developed.

One participant mentioned interaction - it is the chicken or the egg, who has the risk, and where do you see the benefits. The benefits are different in the different production stages, so the driving force is a collaboration where you have a unified understanding of risk in the project.

Several of those who talked about interaction found it difficult to highlight some actors. After all, we have chosen the approach that states that we need to include the entire value chain so that it comes out of the ramp and becomes commercialized. The universities need to contribute in-depth knowledge of these areas so that we can create this robustness and flexibility. We also need the architects to give us some suggestions on how to use this technology so that it is not only needless 3D printing, but we are using it in a new, exciting and sustainable way. We need manufacturers to offer new technology and some new products. There is also a need for contractors to print them, either at a factory or at the construction site. And then we also need some clients who dare to throw themselves out in the first projects because until they do, it will also not fit into future construction.

One participant thought bit differently about how much big change is going on, but there have been small things happening all the time. After all, one of the great things we are experiencing now is moving from drawings to model-based design. And there is a lot to be gained when we get a little further. Perhaps the design environments and, of course, those who deliver computer programs and hardware that are in the driver's seat.

Some thought that Norway is good at R&D, but another felt that actors in this industry do not have R&D in their budgets to any great extent.

7.1.1.3 Who benefits from technology?

"Everyone benefits from it in some way. It depends on what's evolving all the time."

The participants were asked who they thought would benefit the most from technology in the construction industry and had many different opinions. The sections below are summarizing their sayings.

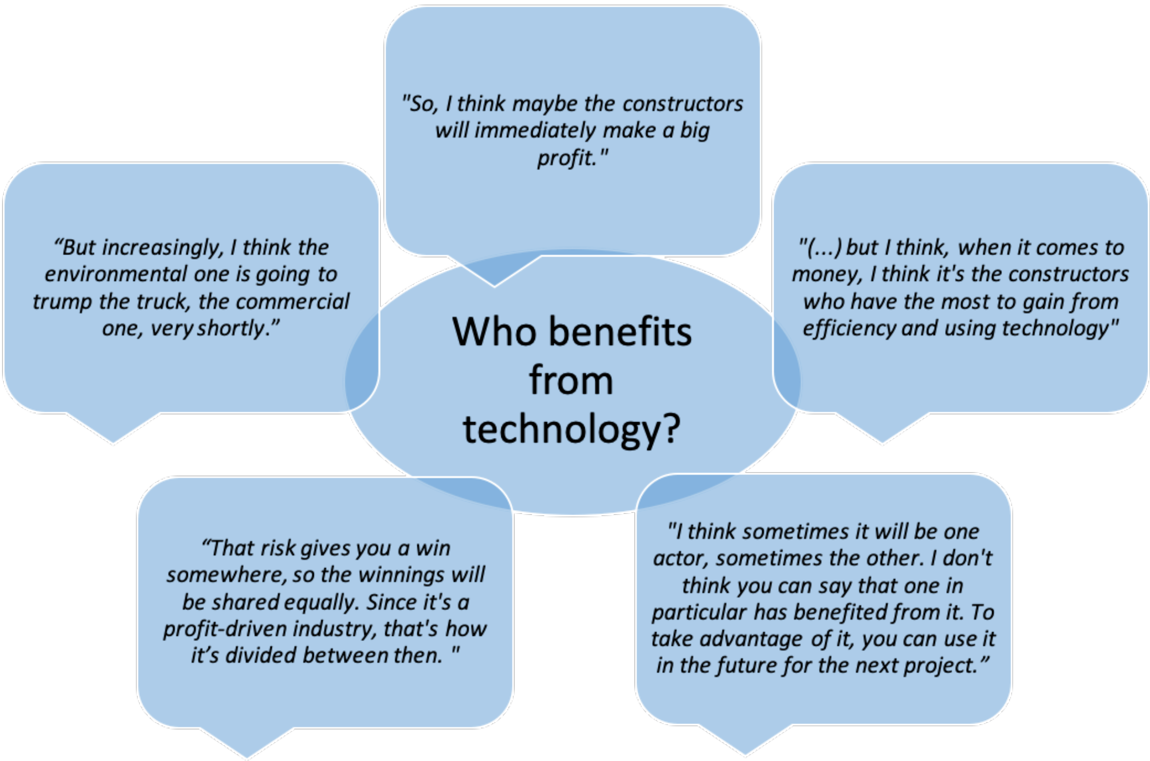

Figure 7.3 Quote Bank: Who benefits from technology?

Several of the participants felt that the contractors would benefit most from new technology. The contractors can get the most benefit because there is an incredible amount of manual work on construction sites. They could create higher productivity by using digital technologies such as 3D printing. If it gives a competitive advantage, then it will be exploited, so what you have to do is to develop technologies that provide an early competitive advantage. That is the big engine in change, and so all change regimes are governed by more significant potential for earnings. All contractors are flow-through companies so they are concerned about reducing costs, either in the form of material consumption or in the way of time, and especially working hours on construction projects. If a robotic technology gives them an efficient time saving or effective time reduction, then it is attractive. But the technology itself is worth nothing if it cannot offer an economic advantage. Skanska is at the forefront of the environment and offers all clients environmental measures. It is not because they are concerned about the environment, but their main argument is that it gives a competitive advantage. They become a little more attractive to a client because they can offer extras. Therefore, there are more chances that the client will chooses, giving them a financial advantage. The contractors then become more competitive and can give a better offer to the next customer and thus win the contract. So, in other words, they can provide a slightly higher price than a competitor because they are right on the environment. That is the main reason they stick with it. And the same will be right for automation, and no one will grasp it entirely because it is attractive in itself. They look at two things, one is finance, and the other is that something is difficult to recruit.

Several participants believe that it is the executors, i.e., the contractors and the client, who benefit most from it as they are the ones who use the solutions. The client can take efficiency, money, and the environment out of it. And the client also gets something out of it because they get a project that contains a greater innovation value and thus a higher PR value. For example, the Danish Road Directorate in Denmark has gained a vast benefit from owning the Little Belt Bridge, which is the demonstration project for them. Ultimately, it benefits the client and the customer, not only because it is about improved products, but they also reduce unit costs on the products or projects that are implemented.

The architects and consultants were not mentioned to the same extent. The architects are used to using new technologies, digital technologies, and trying to push them. They will be happy to get some new opportunities, but this will probably not increase their productivity. The same goes for the consultants, if you give a consultant challenges they think are great fun, they are then allowed to do things that they are ready to do but have not yet been commissioned. Both the architect and the consultant take advantage of it and will create a more innovative project next time for the next customer and thus be attractive to the next customer.

Many felt that it is not only the actors who benefit, but that it can be the whole community. For example, one contractor develops a competency to build faster and cheaper than another. Then that actor will benefit for a period, but not forever unless it can be patented.

As some pointed out, ideally, if we were to motivate everyone to join, then everyone must have a cut of such a development. But basically, it is the commercial, the link between production-construction and operation and the sales stage where there will be a gain as well as those who sell residential projects. It will also be left to the contractors if they have the sales lead. For example, when Contractor X that builds homes also has a real estate company that sells homes, the cut will be with them.

One participant believed that the competitive edge, being able to build something cheaper, faster, more efficiently must be something which not only contractors are interested in, but that everybody is interested in. One of the driving forces now is the climate issue, where we are now trying to find much better ways of using materials and processes to reduce the carbon footprint of what we are building. But it is nearly always driven by commercial targets.

One of the participants talked specifically about digitalization. With digitalization, there is an excellent development in how we plan and build bridges that we, to a greater extent go away from drawings in the planning phase, but also the execution phase, so everything is done in a model. That is an advantage for all actors, both for those who are planning, constructing, and those who will be running it. So, digitalization is underway throughout the value chain.

It was discussed by one participant that those who are part of the development or who sit in the driver's seat and who drive this forward have the highest gain, but it will drip down on everyone involved. It is about developing both methods and regulations to make concrete more environmentally friendly, which has been a real focus in recent years. And that is something that everyone enjoys and that everyone eventually uses. This, as well as regulations, publications, and preparation of publications under the Norwegian Concrete Association's direction, is very important for the technical development. Those who join these committees are often drivers for change, such as Norcem, like Skanska and the Public Road Administration, compile these publications, which are later used by all in the industry and in a way becomes such a standard that raises the level of the entire industry.

One participant mentioned that all the construction industry actors work based on regulations, which are governing, and it is challenging to implement innovation that is not included in the regulations. Therefore, at least in Norway, so much of the concrete construction research is done by regulations. And it is a tradition to create industry programs that encompass as much of the industry as possible and then extract the result, for example, in guidelines written by the Norwegian Concrete Association or influence the regulations and standards. Then everyone benefits from it. The research that is done will help society by making things cheaper and better. It is not so much a deception product as in many other industries - that you have to invent something smart. You have to work for better practices and better regulations. It is also challenging to get so much innovation from the industry.

One of the participants thought it was the size of the company that decided. If you are bigger, then you can invest more money in the beginning, and then it is easier to make money on it, especially when you think of 3D printing as it is a significant investment in the beginning, and you have to get something out of it. If you are only a carpenter with four employees, investing so much money, in the beginning, is not profitable. It is the largest companies that can make money out of it in the first place, but that does not mean that the others cannot take advantage of it eventually. It is just the level of investment or capacity.

A participant pointed out that everyone, more or less, has access to the same technology, so that competition conditions are relatively equal. If someone has come up with very advanced, innovative, and efficient technology, then they would have had a clear competitive advantage, but it is not so easy that the big contractors have already done so. There may be small or medium-sized businesses that might benefit from this. It is not enough to just be a contractor or producer, but they must have a great breadth of technology for automation in general, and programming and management, not least.

A story from one of the participants' experiences was shared in light of society's gain of technology. In the 1970-80s, much research was done in Norway on high-strength concrete and lightweight concrete. And the driving force behind it was the clients of the oil platforms, Condeep, which is a brilliant example of new profit. After all this research, they wanted to find out what it was worth, compared to what it cost. Following the Concrete Association's initiative, they ask a professor, who collected all the projects that were done and set up the costs. The costs were known to be paid research, SINTEF, for the most part. When they had all the costs, some people sat down and tried to value what the different results had. Then they found that the value of that research was 19 times as great as it had cost. That in itself was an excellent conclusion, and in the concrete environment, the number 19 was somehow hanging. Then they also considered who had the pleasure of that value increase. It was then found that it was not necessarily those who had worked on it that received the benefit; it was the society in general. For example, if you had developed self-pouring concrete, the construction process went faster, and the competition meant that the price would be lower so that it was the community that got most of the gain.

7.1.1.4 Impact of 3D

"It has an incredible potential to revolutionize the whole way we build because it not only means we get higher productivity, but it also has a huge impact on how things are going to be."

Several participants could see that 3D printing will affect the construction industry.

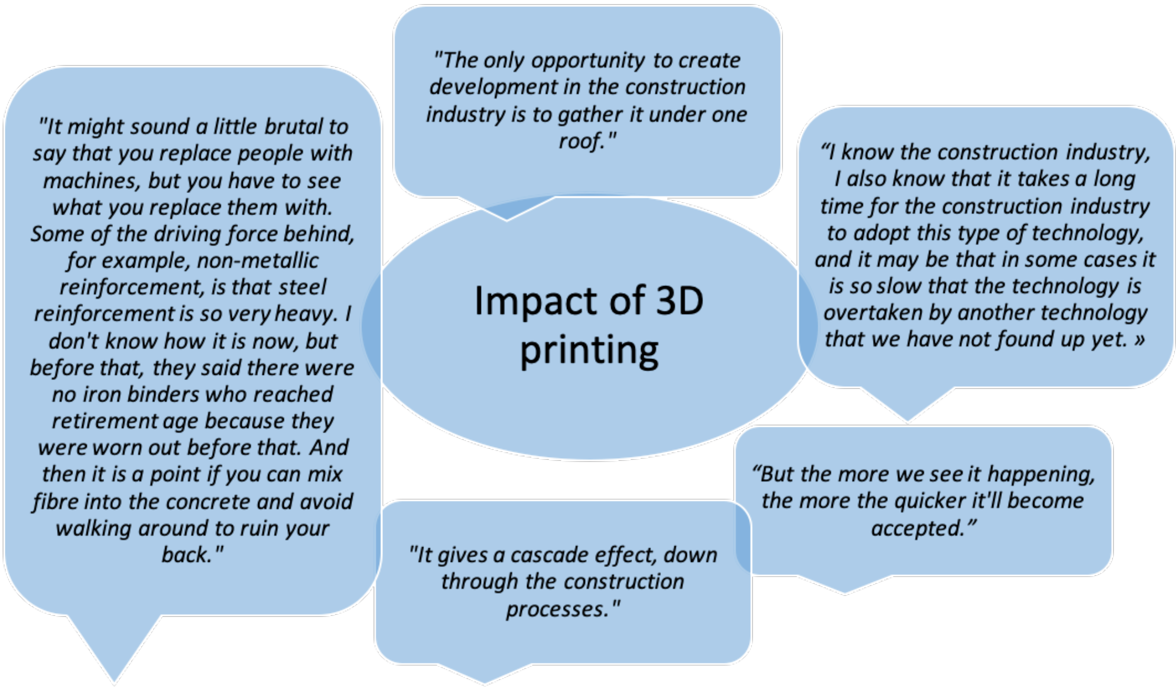

Figure 7.4 Quote Bank: Impact of 3D printing.

It was a general view that the construction industry is over-mature for innovation. But there is potential, especially in industrialization and innovation related to production in the construction industry in general.
Several participants when thinking in the direction of industrialization, thought that 3D printing can affect the construction industry, but must find the right applications to showcase the potential of rationalization. And there is something many actors are looking at now, i.e., industrialized construction, and it is a sense a buzz word discussed in many contexts.

Quite a few thought that 3D printing will affect the construction industry most quickly when contractors adopt the technology, and clients are prepared to accept it. But clients tend to be the most risk averse. In the end, the system, they are the ones who do not want to adopt new things because they are uncertain about them. They need to have the confidence if it is going to work. So, it will take time, but the more we see it happening, the more the quicker it will become accepted.

Some believed 3D printing can help the construction industry achieve a higher level of security. We get fewer people at the construction site and probably faster production, and then you will reduce the number of unwanted construction site events, thus better security. And then they can cut costs, because if labour costs go down, so will total costs.

Only a few participants mentioned that when it comes to the development of new technology, such as robotization, it is saving labour, and flows to local manufacturers. What exists in a country ever further east that can produce things cheaper, also applies to our industry. Items are retrieved from the Baltics, Hungary, and Romania, etc., which have travelled throughout Europe to come to Norway and be mounted, i.e., concrete elements. If development entails a more efficient, cost-effective function, fewer working hours, then it will strengthen Norwegian jobs and help ensure that we get local/regional, or at least national jobs. But some will see that livelihoods can disappear, those who work with plastic and concrete for example, it will be a completely different way of working. And it can inspire and increase focus on improving. It is certain that for the working environment it will affect concrete workers which have probably one of the most laborious occupations in existence. Both iron bonding and vibration of concrete are heavy work that causes health damage in the long term. 3D printing will provide a better working day for many, compared to digitalization where there is currently a tremendous development to use a parametric design philosophy in a computer to connect to the printer and get the design out directly without intermediaries, can be labour-saving.

Several participants agreed that there is no doubt that it can affect the construction industry in a positive direction, both when it comes to meeting challenges in terms of minimal labour in the future. Not many people want to work with grey concrete anymore and get dirty, wet, and cold. The construction industry in general, and concrete in particular is known to be a bit grey and sad. To get a robotization of that process, it will tell the community that now we have renewed ourselves similar to many other technologies.

To influence the construction industry, we must first evaluate how much better it will be. One of the participants points out that many say it improves, but no one can document it professionally or objectively. If we get to the stage where we can say that yes, it is 50 percent faster or safer to use a robot and not humans, etc., then it could affect the construction industry by making it change architecture or geometry. Then it will be more optimized concerning both materials, but also the end-user. Then we get something more suited to our needs. We can push “OK 3D print” and get something that is completely customized for end users. To be able to 3D print something like this or that, has the same process for you as a human being pressing print/OK. Mass customization is the greatest potential for getting started with 3D printing considering the needs of end-users. But first, we need to know if it will be better or not because we do not know yet.

Some envisioned opportunities with a higher degree of R&D. The only way to get ahead of this is some proper research programs, which have both size and weight, and combine those who practically do this and also consultants who stand for design and dimensioning to find and prepare regulations and prerequisites. That is the way most things have started. You have to go through it, and then you have to have some projects that test these prerequisites. You have to go the ranks to find out what will work in practice.

Numerous participants thought there were a lot of opportunities. Still, it requires that some experts who know a great deal about the technology of 3D printing throw themselves into collaboration with consulting companies and constructors and will find out where the arrow is pointing. Create a development team with all the experts gathered. Those who can use robotics know something about cement technology, those who know something about concrete technology, who know something about hardened technologies, and design because the construction must also have a different shape to get concrete that should be printable. It will be an extensive interdisciplinary development project where one must have a clear goal. For example, we should be able to create a construction that is viable with 3D printing, where we have designed in the execution of the materials, production and durability, and all the different things in a unified symbiosis. If we are going to proceed with construction, one must think in totality, integrated teams, and integrative processes.

One participant suggested that we must think in cycles, back and forth with feedback mechanisms. If you create 3D printed elements that look like this, which then can be changed to think about further in the process. Then those who work with the process will say, "but if we are to do it, we can just as well create something in a slightly different way ...?" then the feedback is "yes, we can," and so it continues.

It was quite a few participants thought that if 3D printing is to work, all representatives from the value chain must be gathered to create the innovation, targeted, and financing. It does not develop by a fire engineer sitting and doing a project alone. It is developed by a bridge engineer, together with traffic and economy, environment, resources, etc., sit together in a team and create an overall optimization of how the bridge should be for all purposes. A bridge is not just one thing that should carry some cars over something. It is a monument that stands for 200 years out in the wild. It is part of the community, it should hold, and it should be built to be environmentally friendly, etc.

A few of the participants saw opportunities for the concrete element manufacturers to own the 3D printers. Just as falsework companies today supply the mould to the construction sites, companies can also provide 3D printers to the contractors. It is natural that it is the element industry that has this as a development goal. It is because many participants felt that 3D printing had to happen in factories. Then it is natural and logical to see this as the next development step for element manufacturers. And it is unclear if an element manufacturer increases its automation within the product type they have today or switches to 3D printing is more important. But the most important thing is to increase productivity. And you can achieve that within the framework of existing technology or use something completely new.

Several thought there should be someone starting a pilot so that you can see the value in it—a research development project owned by a public state developer, where the technology can be spread. One of the participants talked about the importance of actually building some projects as a key to the development getting stronger. There is currently some development down in Dubai at the moment, but the reason they are printing is because the government has a goal that a certain proportion of all newbuilding within ten years should be 3D printed. Nevertheless, it can help create development and may inspire others to loosen the grip and to experiment a bit. There are many technologies that no longer reach an experimental stage and the laboratories. It is a technology that has come out and been tried in the right building contexts at a very early stage. It may be the key if it continues.

Some participants have mentioned that there are currently many start-up companies, especially science computer engineers who are throwing themselves at the 3D printing that do not know the construction industry and concrete. It may be helpful to get some new impulses.

7.1.2 Approaches

"I think many times you go blind on what we think 3D printing really is."

One participant mentioned a commission department that is set up to put the correct names on things. It is agreed that the overlying name of 3D printing is additive manufacturing. It covers all the different technologies where something is set up, built up automatically, physically, by additive, i.e., a material. Also, 3D printing, by definition, is the most common one.

"That's a bad name for it. I think if you tell someone that you have a 3D printer, who has never seen one before, it's a whole different picture. So, they envision something that comes out in 3D, smack straight away. But if you really see how a 3D printer works then it is really a banal process. It's not that magical really."

One of the participants knew the official definition of 3D printing coming from the Standardization Committee in America. It is all about materials; you have to use materials, and a new process – 3D printing, and design or have a digital model where there are those three; material, process, and digital model, or let's say digital geometry.

Another participant also felt the industry has a poor understanding of the term 3D printing:
"A lot of what we talk about, like 3D printing of concrete, and calling it 3D printing is really not to say that it is an abuse of the term, but I think it's a bit wrong. Because if you look at what it is, it is like a pipe or hose where concrete comes out, instead of someone standing and moving it around manually then you have a management system that moves it around. And is it really 3D printing in that sense? For me it is an automation *process and I think that it is great. Then there is a part of the management*

system and that you have a concrete suitable for that time window and has sufficient strength and all that, which makes it appropriate. But you do not get what was intended or a bit of the point of 3D printing in the first place."

One participant specified that almost all the technology we use for 3D printing was invented in the late 80s. It has also been polished and improved, but there are not many new developments, and we are struggling in many ways with the same challenges we have had all along.

"I'm waiting for a technology to come that makes us see that the last thing we did was the Stone Age or the Bronze Age. We are still somehow in the Stone Age or the Bronze Age. We have become better at making it go faster, productivity is improving, prices have gone down and everything like that. It is not, we do not come at lightning speed with the technology that exists. So, the principles of the technology that exists are tough to escalate much more than we do now. It's going to be a millimetre, while we kind of need something that takes a mile or so."

Several participants mentioned that some of the techniques could be borrowed from other types of concrete works for 3D printing of bridges.

"I think it's pretty interesting to look at because I'm terrified that 3D printing will evolve as a separate technique without taking into account what one has learned from other similar casting methods for concrete products."

With the knowledge or dissemination that has been around 3D printing so far, there is a broad perception that the technology has been around longer than it has, simply because many think it is so super exciting to talk about 3D printing, and so it is spoken about very much. There have been many races: who can build the first house, the largest house, and print the fastest and cheapest. This race has generated a lot of publicity, so many believe that the technology is further ahead than it is now. It is how we might take a step back in order to create a robust 3D printing process

In discussion with the participants about different approaches for 3D printing, several subjects came up:

- Elements
- Equipment
- Extrusion
- Layer by layer
- Software
- Robotization
- Automation
- Industrialization
- Incremental launching bridge
- Segmental bridge building
- Shotcrete
- Slip forming

7.1.2.1 Equipment

"(…) a pump and a nozzle are used, which of course must be adapted to the concrete pumping technology. Except instead of pumping, it's probably a smoother flow."

Under 40 percent of the participants had something to say about the 3D printers that can be used, and 4 participants had an opinion about the nozzle.

Some of the participants envision the process of 3D printing to be executed by a machine that extrude concrete, like toothpaste out of a tube, was the most frequent association to it.

"(...) robot puts out mortar strings and several layers upwards."

One participant considered the distribution of materials for extruders pushing out a formable mass, a fine rate, consisting of cement and very fine aggregate particles. Concrete has particles up to 22 millimetres and consists of 70 percent aggregate and 30 percent binder. One of the participants was involved in a project where an extruder was used where the concrete consisted of 50 percent binder, which can create some disadvantages.

One of the participants mentioned four major types of equipment:

- If you think of a regular desktop 3D printer, the one you may have at home, you can do the same on a large scale. There is a research group in California that started it almost 20 years ago. It is just like a 3D printer but maybe 20m high.
- The second is taller and similar to a 3D printer that you have at home on your desk, but it is very light and bought with rope and motor. It has a very light frame. It is a company in Italy that has become very good at it.
- What is perhaps the most modern technology, is a robot arm that can run and 3D print what you want by moving. The robot arm has been for 30 years, so it is a modern technology that can be used now.
- Many people try drones to 3D print. If you are thinking specifically about concrete, it may not be so good since concrete is very heavy, and then you need great capacity on the drone to be able to lift. With other materials, it fits well, e.g., metal or plastic.

"Robot based printers are based on traditional industrial robots and there is equipment that makes the X Y Z movement."

Jigs were also mentioned, which have been used a lot of steel production.

One participant knew of three types related to what is called 3D printing, and so far, what we think about most is when it comes to 3D printing with concrete. That is the one that Scott Crump invented in 89. He got the idea when he used a glue gun, and he found that, ok maybe if he got to manage that glue gun better than he did with his hands, then he somehow had a 3D printer. Basically, the invention of 3D printing was just a glue gun and a digital guide of that glue gun. If you look at the patented drawings, Crump submitted in about 89, it is the same as all the 3D printers that are still out there, just moving around the various components. So, technology has looked similar for over 30 years.

One participant knew three types:

- Progressive cavity pump - a type of pump that is typically do not pulsate and are available in many different versions.
- Gantry printer, which will typically be used at the construction site.
- Nozzle technology. There are some who work with merely just a nozzle that is, more or less, just touching where the concrete is passed through. And then there are many different versions of these nozzles that can get more and more complicated.

A few agreed that it is essential to know to decide how thick the nozzle, hose, and printer the concrete has to go through. There is a massive difference between 5 or 10 cm in diameter. With a bigger dimension, the coarser aggregate can be used.

One of the participants has worked on adding accelerators in the nozzle so that the concrete hardens faster when it comes out and, at the same time, makes sure that the accelerator does not get into the pump equipment and the hose because if it gets stuck there, it is broken. It requires that one cannot apply the accelerator in the nozzle and mix it with the concrete being filled. Then there are several pipes going into the nozzle with a mixing function. There is no standard or any standard equipment you can buy.

7.1.2.2 Industrialization

"I don't think we're getting without an increased scope of robotization."

The use of robotics and automation were mentioned by over 60 percent and 30 percent of the participants, respectively.

Numerous participants believed there is a potentially rapid development for robotics, and it is coming, it is just a matter of when. Robotic technology is used in the automotive industry and is used in many other industries as well.

Several participants thought about robotization in the context of more industrialization of the construction industry with robots walking on belts and laying concrete, robotization of reinforcement work, binder for reinforcement, robot welding, and similar parts of the processes. Robotization and automation were often used interchangeably in the discussion of 3D printing. Several had suggestions on how robotization and automation could be instrumental in industrializing bridge production. The three following paragraphs are some ideas that were mentioned.

Some pointed out that 3D printing technology has looked similar for over 30 years. And in certain way, an automation can be seen as an intruder. The problem with this technology is that you always must have a support structure, which is one of the major challenges facing bridges, for the bridges to have a reasonably large, free span, otherwise it is not considered a bridge and is more a structure of something. It contradicts the whole thinking about this technology; it must be built up with a support structure because it cannot produce anything from the open air. And then it is a bit like making bridges today just that there is automated material guidance.

One participant suggested if we simplify it , and if there is control first of the reinforcement and where it is placed and should be cast, there is nothing in the way for a machine to do the actual casting work. One would imagine that instead of having 3-4 people walking around with a large hose over their shoulders, the hose could have gone automatically. There would not have been people there if one had the equipment to control the hose on a bridge. Then larger structures could also be cast entirely automatically, but then the material must be very controlled to know that it will be good casting.

The actual casting of bridge decks is a rather time-consuming sequence, and it is hard for the people who work with it, both those who walk around and get the concrete out, whether it is done with bucket or hose, or vibrate and get it between reinforcement. Some participants imagined there is a lot that could have been done more smartly. It is quite clear that if you could have used the large hose and printed with it, and you had a machine that ran it back and forth and e.g., came behind with 3-4 vibrators that went systematically because then these machines always knew where the concrete was, how much was cast, etc., then a quite effective job could have been done because then it works a bit more like they are doing with prefabrication inside a factory.

The incremental launching bridge was also mentioned by several participants, as being part of industrialization. It is with a 'production tent' at the end of the bridge structure that produces the bridge deck and then pushes it outwards.

"(...) things still have to go faster and more precisely, and it does if you do it with automation*."*

7.1.2.3 Elements

“You can create a bridge structure that swivels in all possible directions by 3D printing, such as more bridge beams that have the span that you need. And then you connect them so that you get a stiffness the same way you get stiffness when folding a paper. Then you can really get rigidity in a bridge construction by simply connecting 3D printed bridge beams.”

Over 50 percent of the participants could envision a bridge built from 3D printed elements that could look like they already do today or be shaped in a way they have not been before.

Quite a few considered prefabrication to be a step on the way of creating 3D printed subcomponents that go into a larger process, and structure where they are assembled. It may be faster to imagine that when 3D printing a bridge, you decide which parts of the bridge are suitable for 3D printing and that the actual span widths – the beam systems – can be 3D printed and linked together so you get very resilient structures that utilize geometry as rigidity.

“The problem about robotic work is that when you're out in the open, you know, you're kind of trying to build that thing across some windy ravine. You know, quality control becomes a major problem. As whereas if you're doing it in a factory conditions, you can get the quality control. So, imagine your

robotic work going on now in a factory building a precast component, which is then transported to site and assembled."

Several participants imagined that they would very quickly find that the 3D printed elements you can make will look different from what you conventionally do to be composed optimally or to be produced optimally.

Hollow-core slabs
"Is it possible to imagine that 3D printing can build on the principle of hollow-core slabs as much as what we have seen in a demo that a robot puts out, e.g. strings of mortar and in several layers upwards?"

Some believed the most significant development of old and new technology in the element industry is hollow-core slab production, which is an extrusion of concrete with a machine. It is the most extensive development that has been in this industry, and it is now 40 years since it started.

"(...) it's 3D printing, isn't it? If it's not 3D printing, then I don't understand."

Several thought the process of making hollow-core slabs to be the most automated we have in the concrete industry. Hollow-core slabs are extruded in a machine that runs on a bench that can be over 250 meters in length. Then there are strands on the benches that are pre-tensioned and machinery vehicles over these wires so that the wires go in guide rail through the machine and then stay inside the concrete that is extruded. If it was possible to make bridge beams in the same way with a machine that does the same extrusion process as a hollow-core slab machine, then they would make the beams the same way. There may be a problem with the hollow-core slab elements having only one pre-stressed reinforcement, while a regular bridge beam has a lot of transverse reinforcement. After all, there is no shear reinforcement in the hole slab, it is just longitudinal strands and that is all and it cannot be approved with calculation, it must be approved with testing, so the shear capacity is tested. Part of the reason why the shear capacity turns out to be useful is that the concrete is under pressure so that the shear capacity in the concrete is improved over the strand applying that pressure in the concrete. Thus, there is no shear reinforcement.

7.1.2.4 Software

A few participants thought that several in the construction industry are far ahead on the use of 3D modelling and are demanding the use of BIM in their projects. Efforts are made to incorporate 3D modelling as a completely natural tool, from the sales phase to the finished production and assembly drawings.

Several participants mentioned that 3D printing is based on a computer model, and it can be produced precisely where the drawings show how it should be built. The model is completed digitally, and then the operation is specified for the robot, where and when, and then it will position itself accurately

Another example of software that was mentioned by a participant is the use of computer technology to deliver concrete on construction sites. It is something that maybe a few see and do not think of. For example, in Oslo, a concrete mixer truck is controlled by geofencing which means that when a car passes a certain part of the city the signals automatically go to the factory, saying that truck is either on the way out to construction site or on the way back to the factory, and how many minutes till arrival. There are technology developments that are not visible to everyone, but to the person who sits and controls it at a concrete factory.

7.1.2.5 Shotcrete

Shotcrete is a process that can rationally produce a given geometry. One participant stated that it has been in the industry for 50-60-70 years and explained there are two techniques for this. One is the way we do it with tunnels in Norway, to secure the tunnels, using fibre reinforced shotcrete, which is used in all tunnels. Elsewhere around the world, they are using fibre reinforced shotcrete on walls and stuff like that, with robotic spraying rigs.

Another participant discussed that if the technique of using a shotcrete rig is to work, you must spray against one side. So, either it has to be s on a rock surface like we do in the tunnels, getting a reinforcement layer. Otherwise, if you are going to use it in construction, you have to have a formwork on one side, and then you can have traditional reinforcement you have set up in advance. Then you spray the wall in that thickness and the way you want it. Fibre reinforcement in the shotcrete is used to give the concrete a high tensile strength so that it can hold the rock, and it is also combined with bolting. It is usually bolted after it is sprayed with concrete to keep it all in place. If we know the cross-section, have measured it in and know how thick the spray concrete layer should be, it can be given as digital information to a robot to replace the man who sits in the machine and sprays concrete on the rock. It offers advantages such as saving time, i.e., man work. It also provides a much larger HSE index since moving into an unsafe mountain tunnel is a bit scary, there can be both rock and concrete fallout, but the robot does not care.

Several considered shotcrete to be an application that is quite close to 3D printing. For example, if you are going to build a basement wall, then you can hang a textile reinforcement or similar first. Then you spray it on both sides, being a printing process. Then you could imagine how far it is to make a reinforcing skeleton for a beam, and then you spray a stiff concrete. Some regarded this as 3D printing. The shotcrete is such that there is an accelerator added in the opening of that nozzle. The concrete hardens, it then solidifies in 4 seconds. So, in a way, it is already solidified when it hangs on the wall. If you spray it directly on reinforcement, then it will hang on the reinforcement. Then you can imagine that you can spray it in profile, e.g., a bridge beam. So, taking spray concrete a step further was also a suggestion.

7.1.2.6 Slip forming

A few participants mentioned slim forming as a competitor for 3D printing, or as a process to consider for a step on the way. Although it is not 3D printing, it is a continuous casting of vertical structures. If it could have been robotized as part of the work with reinforcement and casting, then it could be close to a type of 3D printing, according to a participant. Slide forming has done since the 1970s. It is a known technique, but there has not been much development on how to do it, so the industry needs to look at simplifying processes and simplifying execution and whether there are opportunities to automate things and innovate. Slip forming horizontally has been done on not too big items that are on the ground. Middle sections of the road can be cast with a type of paver that slides the concrete over. In connection with all tunnels, many cable channels lie along one side, and some things can be slip formed on-site in the tunnel.

As one of the participants pointed out, slip forming has a dilemma with horizontal things:
"What you can't slip form horizontally is a culvert, because the weight gets too high on top so you can't pull it forward."

7.1.3 Requirements concrete

"The concrete must be compacted in such a way that it does not form voids and such things that can have consequences for both bearing capacity and durability."

95 percent had thoughts on requirements for the concrete. The ones mentioned included:

- Sieve curve – aggregate size
- Moisture content of the aggregate
- Mixing sequence
- Even print
- Stability (segregation and bleeding)
- Compaction and homogeneity
- Flowability or mobility
- Ductility
- Consistency, viscosity, and cohesion,
- Continuity between layers
- Curing method and conditions
- Setting and curing time
- Durability
- Robustness
- Flexural resistance.
- Strength
- Bearing capacity
- Tolerance class
- Quality assurance and control of production
- Quality assurance and control of product

"The size of the aggregate is probably much smaller for it to be able to be pumpable and workable through a machine."

Several participants pointed out that concrete is a material that slightly varies; one concrete load is not necessarily the same as the next load. It is why follow-up and quality assurance of production is particularly important. There must be strict production control, and there must be control over the sub-materials when it comes to continuity, such as sieve curves on the aggregate, the moisture content in the aggregate, that the raw materials are under control and are right for the production process. To get an even cast or print, you probably depend on an even mass and a good mixing sequence. The requirement should be that what comes out of the nozzle is uniform.

A few thought the material composition should be adapted to reflect how thick the hose/printer the concrete it is going through. It must be a very fine-grained concrete, you must have good control over ductility, the viscosity of the concrete, and it must have a particular floating property. If a mould is not used, then there are some strict requirements for stable quality when it comes to moldability properties. Consistency is required for it to retain its shape, so that it does not collapse. There must be minimal variation in consistency and viscosity, i.e., a concrete that is stable and correct.

Some specified that if the concrete is to protect the steel against corrosion, and it should normally do so, then you must have concrete that is compact and has no internal cavity. The concrete should be compacted in such a way that it does not form voids that can have consequences for both load capacity and durability.

Several mentioned that the curing process is fundamental as the concrete must be sufficiently fluid and, at the same time, stiffen at the right time to ensure continuity between the layers. You need to know precisely when it cures and how much it cures, which is why curing time and setting time are important factors. You have to have a solidification and a curing process that ensures that you get a good result in the end.

Numerous participants discussed that there must be a solution to be able to withstand bending while having a certain strength. You probably do not get a concrete like we think of concrete now, with larger and varying aggregates, which also says something about the concrete's strength. It is an issue that pops up quickly, i.e., what compressive strength you get. Robustness over time is vital as the public road network requires a lifetime of 100 years. Tolerances are required.

Quite a few mentioned quality control. An important part is controlling the quality of the finished product, whether you get a homogeneous product where you can use calculation rules for the whole product itself and know that it has the necessary quality.

7.1.4 Challenges

During the interviews, several challenges were highlighted with the use of 3D printed concrete bridges, both in the construction of the bridges and in the construction industry. The challenges were divided into seven subcategories: dimensions and shape, economy, environment, equipment, regulations, reinforcement, and rheological properties.

“Going to 3D printing of the bridge is to skip many links in between. Because there are so many challenges there that we should take it step by step.”

7.1.4.1 Dimension and shape

Almost 70 percent of the participants mentioned dimension and shape as a challenge.

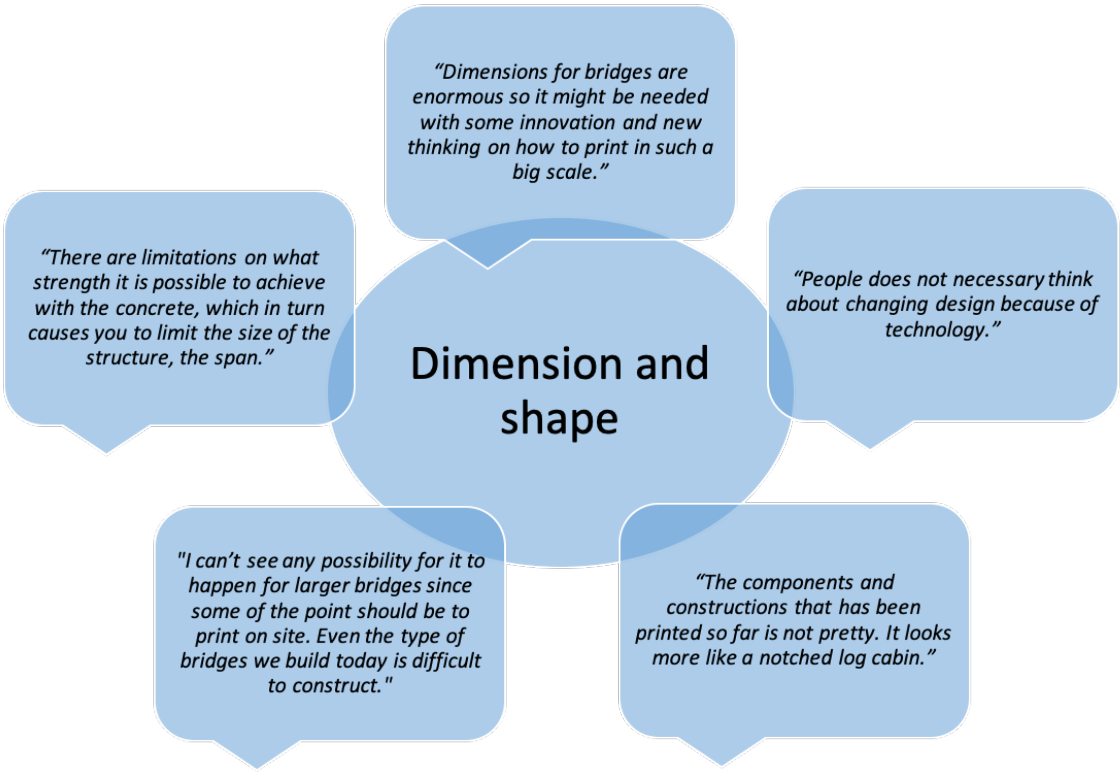

Figure 7.5 Quote Bank: Challenges with Dimension and Shape

The biggest challenges mentioned regarding dimension and shape were:

- How to print it
- Complex shapes
- Geometric tolerances
- Loads
- Transportation and moving elements because of the weight of concrete.
- Aesthetics and geometry, that you can build it nicely enough, acceptable surfaces for the market
- Total design, how to use an put together the different elements.
- Print on-site

One of the participants meant that there is no point in using 3D printing on a straight wall, ceiling, windows, everything is the same as before because then you lose the benefit of using a whole digital thing where you could have optimized, e.g., design, concerning technology or process.

Several pointed out that the bridges should, in a sense, have a reasonably large, free span; otherwise, there is almost no bridge, it becomes more a structure of something. The big challenge for 3D printing technology is the support structure, whereas, for bridges, that is the main challenge. When building the span of the bridge, you have to carry it at the same time building it. Even with the type of bridges we build today, this is challenging to construct, as you have to cast large volumes in short sections, also lift it and collar out and, at the same time, move it forward. Also, the shape of the bridge and the way you have built it are very marked by the construction situation and not so much the operating situation. The bridge has to be shaped in a way for it to be effective.

One participant mentioned how the use of fibre reinforced concrete is fine for some forms, but not for others as it can restrict the shape of the construction.

7.1.4.2 Economy

"I'm a little afraid that the contractors *and construction industry have become so marginal financially that interest in innovation could have been better."*

Nearly 60 percent of the participants regarded the economy as a challenge with 3D printing.

Figure 7.6 Quote Bank: Challenges with Economy.

The biggest challenges mentioned regarding the economy were:

- Investment and development cost
- Risk

Several participants meant that for someone to want to procure this type of equipment, there has to be a market for it. If it is to be a market supplier, those for those who deliver the concrete and who pump the concrete, it will be a pretty significant and costly investment for them. There must be some risk-sharing on the investment in this equipment. So, it must be incremental, maybe with someone starting a pilot project to see its value. A research, development project owned by a public state developer, where this technology can then spread beyond should be started. If one is to see a realistic cost distribution, no private actor today will join unless it is shown that there is already a market. Then there may be someone involved in investing, but there must be some form of cost-sharing and risk-sharing for the time being.

There were many strong opinions on the economy as a challenge for the adaption of 3D printers and also concerning the different actors as the ones to take the risk. One common agreement was the thought of some risk-sharing on the investment on this equipment.

One participant questioned the reason for investment:
"*it will not be profitable to develop a new technology to do exactly the same as before."*

One of the participants had strong opinions on the economy regarding 3D printing:
"First, it must be profitable for people to start investing today. To date, no studies have found that 3D printing is more profitable than the traditional process. Profitable is related to economics so that is one thing, but many people are thinking about sustainability. Winsun, for example, sees that they manage to use smaller materials using 3D printing. I don't remember numbers, but it was very big, Chinese claim. They said they had managed to save 70 percent of the material using 3D printing. There is no study or work to prove it. That is what is very challenging today, especially for the Norwegian industry, that there is no documentation that if you use 3D printing it is faster or safer, or you can use less materials or maybe the house will be better, stronger etc., but no study does, which manages to document it"

Some believed it merely has to do with the business model. If you are going to be a driver of technology, it is also about taking some risk. The cost-sharing between the client and the contractor can become a bit unfair. If the client then expects that some innovation and development will take place in his/hers project but you have to take all the risk, then they are not willing to take it, call it the insurance premium, i.e., the cost of running it.

Several participants considered it to be too high risk for ordinary companies. Those who are sitting and making investment decisions, they will always look at alternative solutions and then, in almost all cases, will choose what is the safest and will give best return during the investment period envisaged. In the construction industry today, particularly in Norway, 3D printing is new and unknown technology, and it will require high investment for those who are going into it.

Investments like a 3D printer were associated with high risk and numerous participants mentioned economy as a specific challenge there must be some form of cost-sharing and risk-sharing. It is difficult to get more substantial investment funds for equipment on projects that are associated with a significant risk. When making investments in new equipment, there are some criteria for risk and for repayment time.

One of the bottlenecks that was mentioned was getting a large company to invest in large investment funds in risky projects, which is not easy. The management must have an extremely firm belief in it and take a risk. But in the regular investment decisions and models, you need to document almost that you can have a repayment time of just a few years to first get investment funds.

Numerous participants mentioned the economy and environment as a challenge that goes hand in hand, where there must be a balance between economy and environment. It was highlighted several times with regards to the material composition. The mortars used today, are based on fairly high cement content, which is unfortunate for the economy and sustainability.

One participant meant that we are at a show-off stage and made an example to illustrate the problem: *"I think, if you talk about productivity and economy and maybe also the environment, regardless of whether they can make a concrete that is so stable that they do not need human hands to have control, then you have to have so much cement paste. The more cement paste, the more variety we can withstand in sales. Extremely heavy cement then, let's say 600 kilos for example, on a cubic, normally 400, we increase to 600 then we know that the concrete goes through it where the 3D printing pump, then we get it but then to think environment and economy so we are far beyond anything."*

7.1.4.3 Environment

Around 50 percent of the participants considered the environment to be a challenge. As mentioned above, the economy and environment are closely associated by the participants regarding challenges, but it is worth mentioning that fewer participants mentioned the environment.

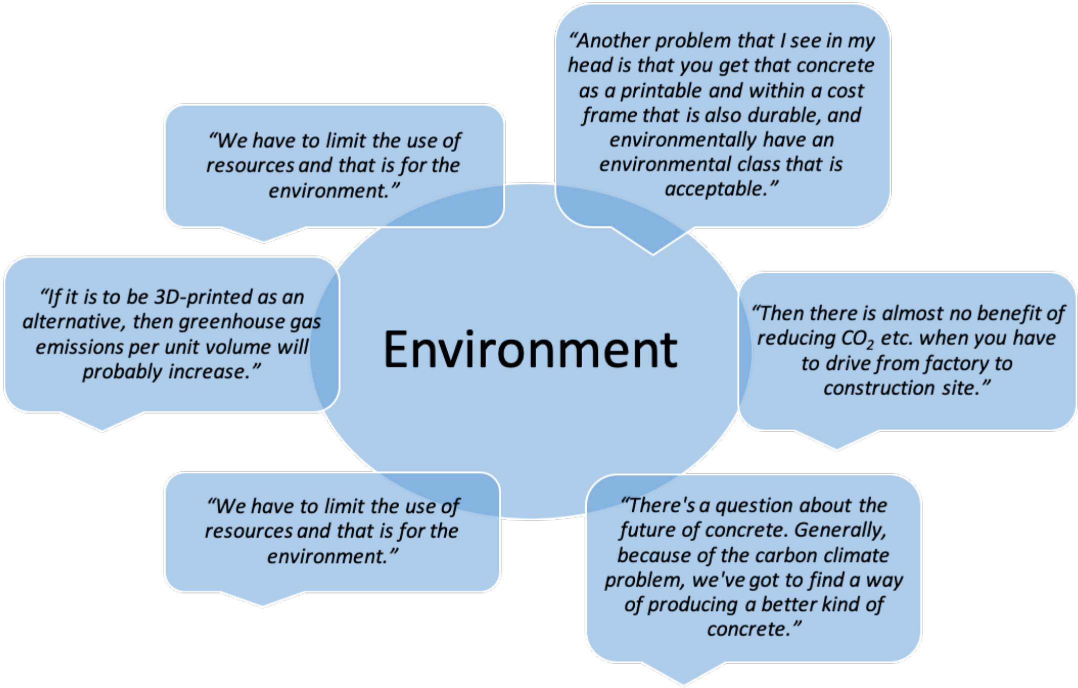

Figure 7.7 Quote Bank: Challenges with Environment

The biggest challenges mentioned regarding environment were:

- Material consumption
- Greenhouse gas emissions

Some believed that, bringing the environment into consideration, there are higher emissions per cubic of mortar/concrete but a much lower amount of cubic. The mortars used today are based on fairly high cement content, which is unfortunate when it comes to economy and sustainability. There are much higher greenhouse gas emissions per unit or kilo per volume from such a mortar than from concrete. Therefore, it must be compensated with less material consumption.

Several participants pointed out transportation as an environmental challenge. Regarding 3D printing of elements in a factory, transportation must be considered.

7.1.4.4 Equipment

Approximately 80 percent of the participants regarded equipment as a challenge.

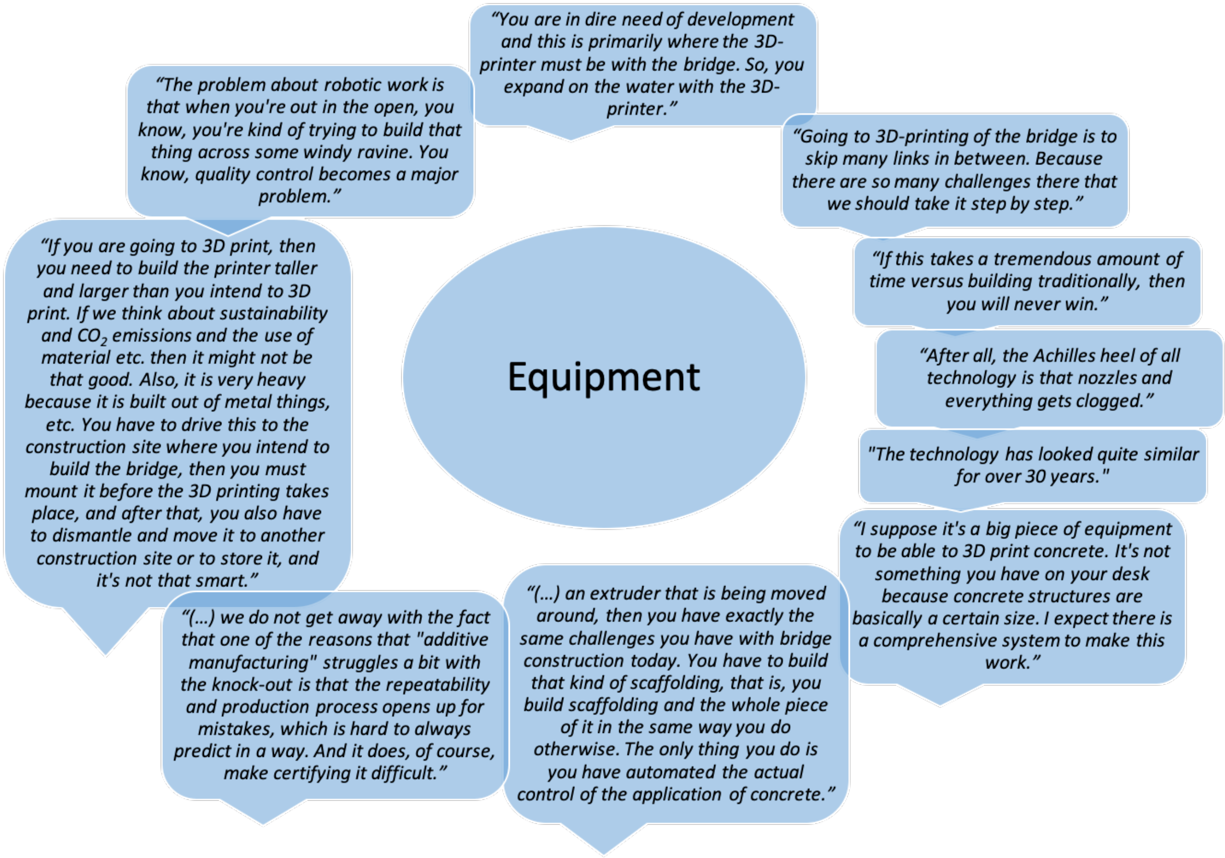

Figure 7.8 Quotation Bank: Challenges Equipment

The biggest challenges mentioned regarding equipment were:

- Size
- Printing speed
- Maintenance
- Quality control

A few participants did not envision how it will be possible to 3D print a bridge as a whole because it was difficult to visualize the type of machine would be able to do it. Others would not see it as 3D printing but more as the industrialization of a process. Several talked about a bridge should be fully 3D printed as a whole or as individual elements to be transported and assembled on site.

One participant stated the whole thought process about 3D printing technology was contradictory, because it cannot produce anything in the open air, it has to be built up with a support structure. And then, in a way, it is just the same way you make bridges today, you have just automated the material feeding. Several participants mentioned the automated material feeding as they could not see the process to be free from people. Some suggested that parts of the process could be robotized or automated but did not believe a bridge could be 3D printed on-site.
Size is a challenge that several participants were concerned about as it needs a comprehensive system to make it work.

Some participants mentioned that something more radical must be done on the technology side as the technology has not really changed for over 30 years. One participant compared the use of 3D printing with information models. The construction industry may not be as far ahead as it was when we started using information models.

A few pointed out, when 3D printing, the printer needs to be built higher and larger than what you are intending to 3D print, which means it will be heavy equipment. You have to drive this to a construction site where you plan to build the bridge. Then you need to mount it before 3D printing the structure, then dismantle and drive again, which means many challenges can occur. If we think about sustainability and CO_2 emissions, then transport in this situation will also be unfavourable.

Some also stated that it is important to develop the 3D printer so that it is scaled up to be able to take proper concrete. So, the success of 3D printing is not only progress and time spent, but it is just as much to use it much more materially where you get smarter, more material-efficient designs.

The nozzle was mentioned as a challenge due to the size of the nozzle when using larger aggregate. A smaller 3D printer does not allow for coarse grain. Larger nozzles were mentioned to give trouble: *You can pump with larger nozzles, but then you will get this pulsating pumping, and we cannot control it if it has to pulse as the big pumps do.* It should be pumpable up to a print nozzle and with a capacity of high pressure without pulsations. One participant stated that all 3D printers make an inhomogeneous material, which is not continuous, and then has internal cavities.

Printing speed was also seen as a big challenge by several. The equipment and the concrete/mortar must be synchronized so the machine will not go too fast for the concrete/mortar to be handled. Also, the process must be fast so it does not harden in the nozzle. If this takes a tremendous amount of time versus building traditionally, then 3D printing will never win.

The production chain was regarded as a challenge by a participant. The production chain for concrete is slightly longer than it will be, for example, for steel.

Numerous participants agreed the maintenance and cleaning are some of the most significant equipment challenges. All of the participants that regarded equipment as a challenge also mentioned maintenance and cleaning. Quite a lot of maintenance is required on the machinery as it has to be kept clean to operate smoothly. If it is a machine through which concrete is being pumped, wet conditions, over time, cause it to become clogged with grout and stuff just in the same way as you have to clean out a ready-mix concrete lorry every day. It is just like any other concrete equipment that needs to be cleaned after use; otherwise, the concrete settles, and with 3D print, it is so extra important due to working with an accelerator because it goes faster. At least some speed is crucial, but that does not mean that it is difficult to clean. It is just like any other concrete equipment that can be cleaned, and you must clean everything. But it is important not to underestimate the cleaning because if the equipment becomes too complicated, it can also be too difficult to clean. So, the concrete can penetrate hooks and gears.

Quality control was mentioned as a challenge by several. Quality control becomes a major problem if you are out in the open and trying to build a bridge across some windy ravine.

7.1.4.5 Regulations

“They must comply with many requirements, standards and legislation."

Almost 90 percent of the participants had some thought on regulations regarding 3D printing with concrete. Over 40 percent of the participants considered regulations to be a challenge for 3D printing. There are no regulations for 3D printing yet, but there are regulations and standards that have to be followed.

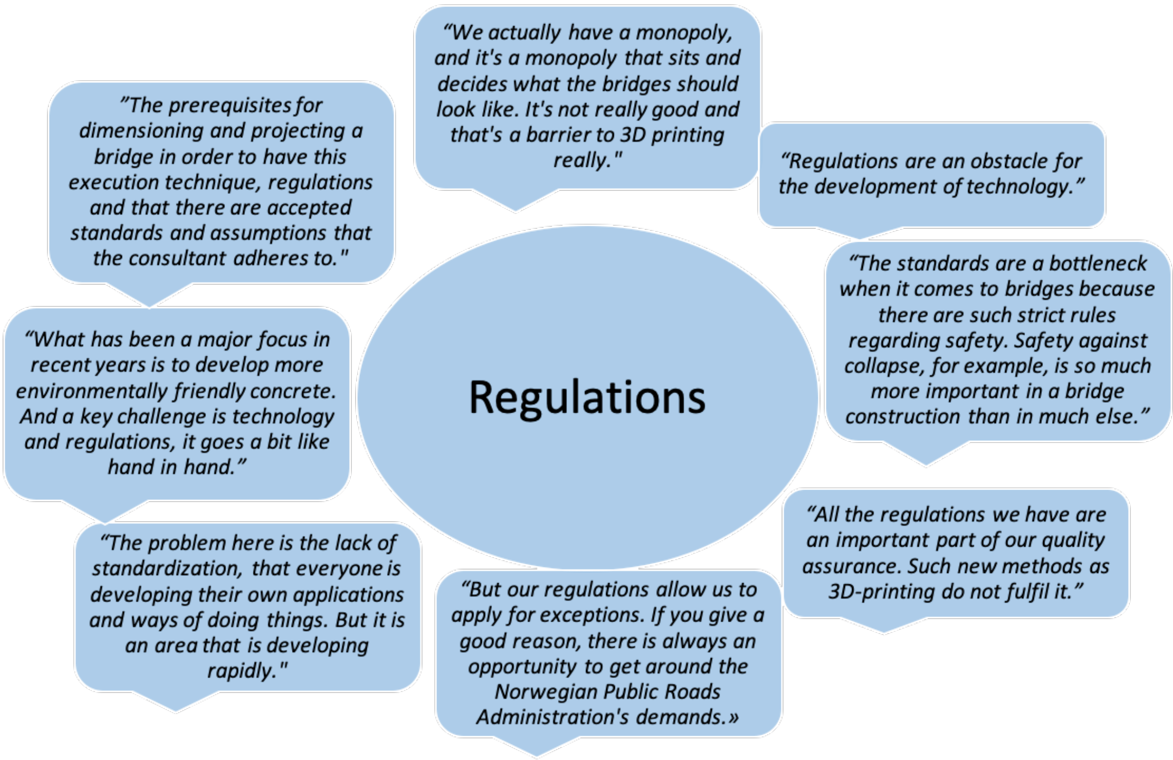

Figure 7.9 Quote Bank: Challenges with Regulations

Several of the participants looked at regulations as an obstacle to the development of technology. It is a European work standard that regulates both the production and characteristics of concrete, and it is not straightforward to start 3D printing. Standards such as concrete type and material properties will be a bottleneck because they are not built for 3D printing. They are made with either prefabrication somewhere or in-situ casting and material properties that are in the solution.

A few participants pointed out that with regards to bridges, the standards are a bottleneck because there are strict rules regarding safety. Safety against collapse, for example, is much more important in a bridge construction than in anything else. It is a risk assessment, and the consequence for bridges is more significant. The rules will be an inhibitor. All the regulations are to govern and are an essential part of our quality assurance. Such new methods as 3D printing may struggle to fulfil it. 3D printing other designs may have lower risks or smaller consequences of one or the other. Bridges are one of the areas with the strictest rules, and it does not have the same boundary conditions as 3D printed houses. There are requirements in the standards that must be complied with geometric tolerances. However, it depends a bit on the application and safety measures in question.

Some participants mentioned that the Norwegian Public Roads Administration sets requirements for their concrete for bridge structures. In a public context, i.e., a public road network, bridges in Norway are required to have a 100-year service life and are based on off-shore concrete technology. It was also mentioned that the municipalities and the public road administration require paper for the archives. Therefore, it has been challenging to have a "paper-free" project. The public systems are not completely in development.

A few pointed out that the entire standard system, the EN system, has some limitations that exist today because an element of this must be adapted to the regulations. If the regulations are not in place, then few will apply it. You can see this in the context of other areas also such as ultra-high-performance concrete, the regulations are not sufficient yet so many people say that they do not dare to use it. Then it is important that the material composition of the concrete is printed, is following EN standards 13670 and 206, meaning it is only the production process that is challenging. Regarding the material composition, it should have a concrete used today, that meets the requirements given in the EN standards. Then only the production technique is different, and it is easier to handle. Then you can create a system that deals with what is in the standards. Standards are relatively open when it comes to opportunities, but at the same time, they require that everything is documented, i.e. that there is sufficient compression, etc. This is exemplified in the last section of this chapter.

Several stated that rules are an obstacle. As we have been considering fibre reinforced concrete, which is relevant to 3D printing, one could not have used it because it was not part of our regulations and calculation rules in order to execute to the standards required. Then you can imagine that if you say that a better casting technique is a technology, then the standards become a limitation, as you could not cast the concrete just as you wanted to get the properties.

The standards have several functions. One is that if there are several competing for the same project, you must follow the same guidelines. That is one reason for standardization, and why one is eager to standardize. Then, of course, it is to get safety in order and maybe also that it will not be too expensive. With a standard, it is a little challenging to try to find something new that is not in the standard, so it works against you. You try to standardize so that everyone has equal business opportunities, and everything is safe. Some of the very large companies or organizations are very true to these standards and find it difficult to get away with things outside of them. Americans are a bit better at testing, at practice, and if they make it, then they say it is okay even if some theorist says it is not.

It is a European standard work that regulates both the production and the design of concrete, and some things indicate that it is not straight forward to simply start 3D printing. One participant concluded that it can be done, but 3-4 points need to be explicitly addressed. It goes into workmanship competence, because it is a completely different way of producing and a completely different competence is required for those who perform it. Also, compaction and homogeneity must be considered, as it says in the standard work that the concrete must be compressed in such a way that it does not form voids, which can have consequences for both load capacity and durability. The third point is geometric tolerances, which are somewhat dependent on the applications and safety considerations in question. Still, there are requirements in the standards that a bridge must comply to. Then there are hardening conditions that must be taken into account.

Numerous participants agreed that it is concrete standards that will be the limitation. Concrete standards will be a bottleneck because they are not built for 3D printing. They are built for either prefabrication somewhere or in-situ casting, because you end up with a combination of conventional reinforcement and fibre reinforcement or such solutions when 3D printing. There are still some bottlenecks in the standard in the way, for example, post-tensioning or coupling with fibre reinforcement. Thus, the standard is a bottleneck when it comes to bridges because bridges are so large and have strict safety rules. Safety against collapse, for example, is so much more important in a bridge construction than in a residential wall. It is a risk assessment, and the consequence of bridges is more significant. The regulations there will be a stumbling block as bridges are one of the areas with the strictest rules.

One participant specified that 3D printing must meet many requirements, and one cannot check that it meets the requirements after it has been designed because then one cannot change it. The creation process is very important upfront because once you have designed the bridge, then you need to get approval from the environmental authorities, the road association, etc.

A participant mentioned standardized methods for bridges as a challenge. That is a challenge for bridges in general and not just an issue for 3D printing.

One participant considered that some have made robust methods, but with some assumptions, specific equipment with one particular prefabricated material that you have to print at a specific temperature. It will go right every time, but it is not flexible in experimenting with new concrete types, etc. Robustness and simulation are also some of the keywords.

A few pointed out that if you are going to develop more environmentally friendly concrete, then there is an important point: you must reduce the cement content. But at the same time, there are limits to how far one can go because one must look after the concrete properties. It should still be durable and safe to use. In this industry, we have a framework that puts a lot of limits on what we can do, as part of the standards. It is the cement standard (concrete standard 206), and they are there first and foremost to assure the community that the concrete that is produced and built with is safe, so that one can be assured that the constructions being built will not fall down in any year. It sets a framework for what we can do. Much of the development work we are doing today is about adjusting and expanding these frames so that we can develop new concrete materials. Then there are openings in the concrete standard, for example, so that you can document other rules than those set up in the concrete standard. In the national annex, it is allowed, for example, to add extra fly ash to the concrete to make it more environmentally friendly. In practice, how much fly ash you can add is set up with some limits on the k-value you can use and what durability classes you can use. The standard, and the national annexes, allows you to document correct k-values and a more considerable amount of fly ash. It is, after all, an example of how we can drive development by providing a space within the standard to at least document itself to more favourable rules. The rules set in the standard are quite conservative, and they must be. The fact that through the documentation you can get more liberal rules then opens the industry up for technical development is very important, and something that we have been quite aware of and good at in Norway.

7.1.4.6 Rheological properties

"you probably don't get a concrete like we think of concrete now, with larger aggregates and varying aggregate size."

Nearly 90 percent of the participants mentioned rheological properties as a challenge for 3D printing.

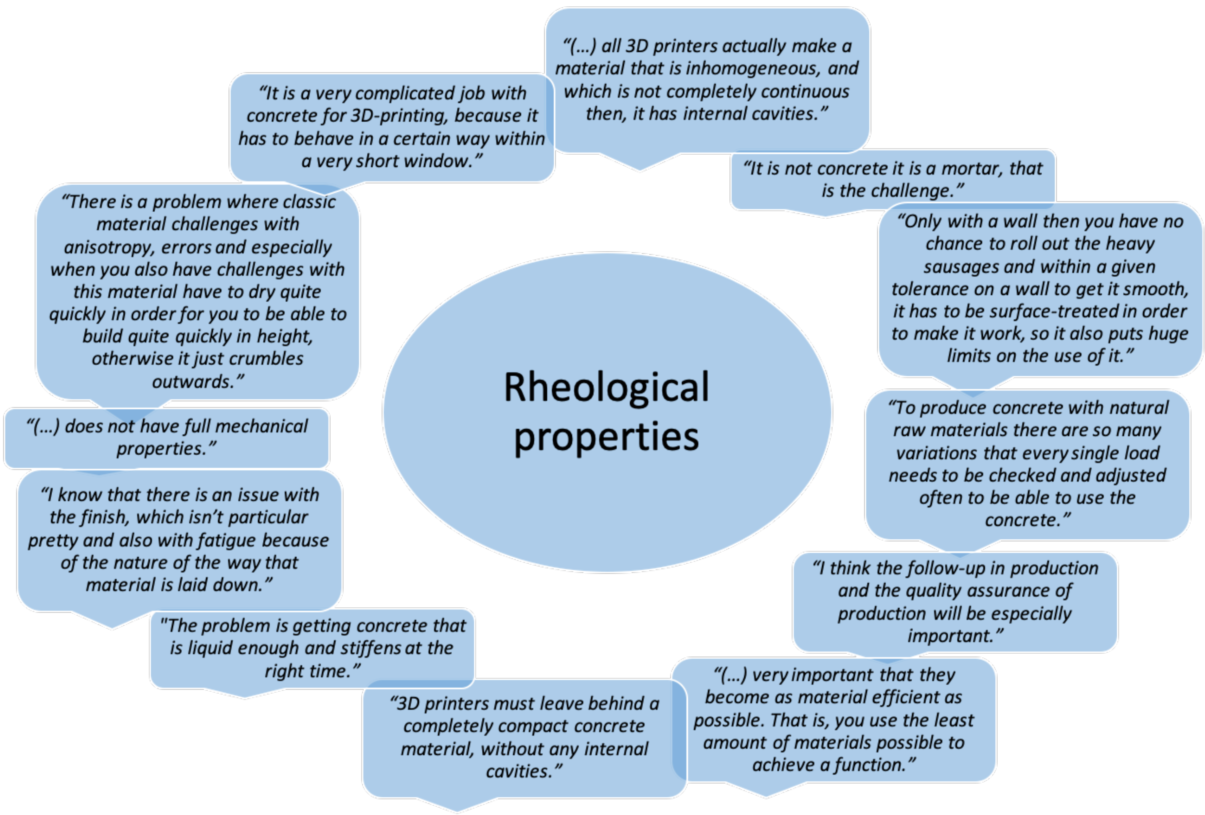

Figure 7.10 Quote Bank: Challenges with Rheological Properties

The biggest challenges mentioned regarding rheological properties were:

- Quality
- Mortar vs. concrete
- Raw materials
- Material composition
- Loads
- Pumpable

- Even print
- Consistency
- Capacity
- Durability
- Vibration
- Durability
- Moldability
- Resistance

Several participants shared the opinion that opportunities for making things easier and faster are there, but because concrete is so complicated, we have not come any further.

The type of concrete that is printable is seen as quite different from regular concrete, and some participants stated that it is not technically concrete but mortar, like those so-called mortar prints where you use very small stone size, it is technically not concrete you print with but mortar. If having concrete that is pure mortar-like paste, without coarse aggregate, is a weak concrete with today's technology. It will have too much shrinkage, too much creep, and relatively weak mechanical properties because what gives the concrete its high E-module and its high strength, i.e., in mortar, you often get concrete structures with cracks.

Participants mentioned how the quality of the concrete is affected. The materials you have to print with, are simply not good enough. On a purely physical level, how does this print have to happen on the project for it to work and to have a predictable quality of what you produce?

Environment, as in surroundings, was a challenge mentioned by several. If you are going to have a bridge, then you have to look at what environment that bridge will be in e.g. if it should be in a marine environment, or should it be standing dry. Because there are very special requirements for concrete compositions in different exposure areas for a bridge, so it is important to have an environmental class that is acceptable.

Some participants meant that a 3D printed bridge could not be heavily loaded, neither with a static load nor environmental load. The balance between having a lifetime exposure to the environment such as frost and water should fit with 3D printing effectively. It was mentioned that tough stressed constructions would probably require a material technology in the concrete that makes it difficult to 3D print. We have a number of bridges that are located in quite heavily environmental areas. A lot of road salt is used, and we have some bridges in the coastal environment that are exposed to chlorides.

Also, questions were asked about *how to fix it on a construction site out there in the open* and *how in all days you should get to 3D printing in the rain?*

One participant meant that when you are going to 3D print, we will go in the opposite direction to what we have done in the latest environmentally friendly concrete. There the concrete consists of little fines and binders, and a lot of coarse aggregates which has been the trend in so-called environmental concrete. The 3D printer goes a bit the other way, and it is imperative to emphasize material consumption.

The participants had a different saying in material consumption. Some participants were worried about producing concrete with natural raw materials, as there are so many variations, meaning every single load needs to be checked and adjusted often to be able to use the concrete, like looking at sieve curves on the sand, the moisture content in the aggregate, and having control of the raw materials. Some were also concerned about the raw material supply, such as fly ash, which can be difficult to get.

Several thought that the challenge is to produce a concrete that is stable and correct; a load of concrete is not like the next load necessarily. So, the follow-up in production and the quality assurance of production will be especially important. Very strict production control is essential, and you have to have a lot of control over the material you are going to use to get concrete that meets all the requirements such a production process as 3D printing will demand.

The material composition was discussed by several participants. It included aspects of segment-rich, binder type, additives, and aggregate. Also, to be as material efficient as possible, it must use the least amount of materials possible to achieve a function.

One participant mentioned a challenge from their projects where the composition of the material used in the project was almost twice as high as normal cement consumption. It is not possible to have coarse aggregate grains, and thus you get too high cement consumption.

Pumpability was a challenge to be mentioned by many - they must have a tailor-made material that is first and foremost pumpable. The size of the aggregate was a big part of this.

For some, the embodiment is a little unknown, and to what extent the finish affects the final product in terms of density, and how homogeneous the concrete structure becomes. Concrete is not a homogeneous material, so you must have incredibly good control over the material you send to the printer. 3D printers must leave behind a completely compact concrete material, without any internal cavities.

A few participants looked at vibration as an issue because if you do not vibrate the concrete, it can have consequences for both bearing capacity and durability. In a bridge, or a large construction, it becomes especially important that it is well connected which is why one does the vibration job on ordinary bridge cast. When, for example, vibrating a shape, the mortar forms an outer layer and tends to have a high water/cement content and thus creates a high shrinkage. Therefore, the concrete inside is stiff and does not fade as much, and the upper surface fades, so it cracks.

The consistency was regarded as a challenge by quite a few participants. If you have something that is a little too fluid, then you can only 3D print 2-3 layers before it floats out. If it is too hard or dry, there is nothing between the layers that is connected or glued together – so is able to turn up or down, floating or not. It must achieve a sufficiently fast strength for it to carry the next layers printed on top. When we then extrude the concrete, it should like to find its shape immediately after.

Some stated that the biggest problem lies in the setting time and the adhesion between the layers. If there is too long left between the layers, it can dry to the surface, and then no proper adhesion will come. The concrete is not continuous because it is laid out in small thin strips, leaving open space in-between. You get a delamination effect because you only put a partially molten material on top of each other. If you squeeze a little on the side, you will see that it bursts into layers. You will see that then you get an anisotropy.

The concrete strength and durability were discussed by several. There are restrictions on what strength you can achieve with the concrete. When reducing shear strength, and compression, it will not have full mechanical properties.

Gravity was mentioned as we have a problem when we print with overhang because it affects everything on the previous layers of printing.

Concerning 3D printing an entire concrete bridge, one participant stated that dimensions and loads would be the biggest bottleneck.

Quality control and quality of the finished product were frequently mentioned and to control how it is cast or printed.

The finish was also often mentioned; no one accepts these waves instead of smooth surfaces.

A few mentioned how small the success window is in terms of speed, accuracy, and problems may occur along the way. It is a very complicated job with concrete for 3D printing because it has to behave in a certain way within a very short window. When we work within the success window, we are somewhat in doubt whether we have been on the outer edge of the window or been in the middle. It is necessary to know that this is not trial and error to create a robust method as it has been widely followed on many fronts.

One of the participants tried to start a project with 3D printed concrete 20 years ago, but it stopped after they had enquired with the concrete industry. After talking to actors in the concrete industry, it became very clear that this was a pretty big quantum leap. It was talked about that there was a potential with lightweight concrete, but still, there were problems with the curing time. Looking at 3D printing of houses and as far as 3D printing of bridges, and as it is today, the challenge is on the material side.

Several participants thought of concrete as the wrong materials to use, that steel or composites would be better.

7.1.4.7 Reinforcement

"The more complicated a construction, the more complicated it is to also reinforce."

Almost 80 percent of the participants envisioned challenges with reinforcement.

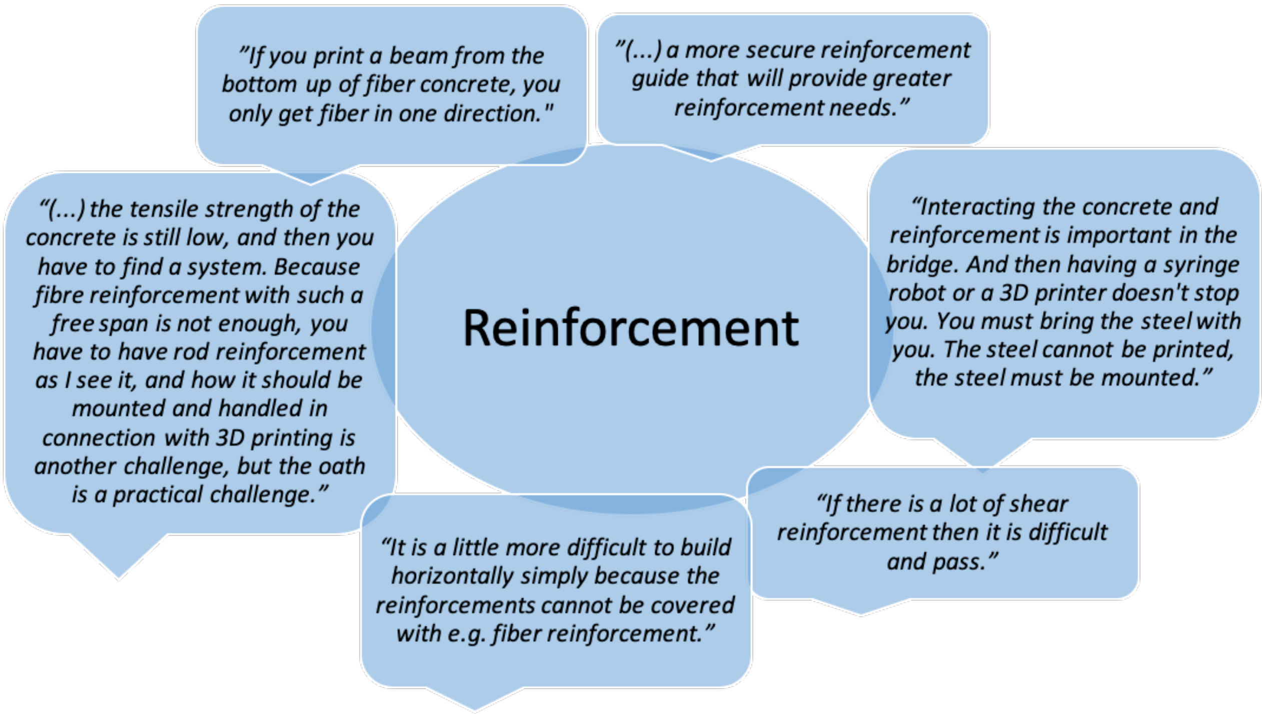

Figure 7.11 Quote Bank: Challenges with Reinforcement

The biggest challenges mentioned regarding reinforcement were:

- Reinforcement handling
- The amount of reinforcement
- Complicated reinforcement
- Fibre

Complicated reinforcement was mentioned as the more complicated a construction, the more complicated it is also to reinforce.

It is a general view that the need for reinforcement is a challenge. After all, we will need more reinforcement because we will not be able to position the reinforcement optimally because the robot will not succeed in doing it alone. A more secure reinforcement guide would provide greater reinforcement needs.

Reinforcement handling was discussed by several, like secure reinforcement, how to get reinforcement building if you have a robot, and should the robot also take care of the reinforcement or another process? If there is a lot of shear reinforcement, then it is not easy to pass. If we are to get good enough reinforcement, then it should be crossed, as usual reinforcement does. Then it must go through the structure, and then you may need to insert the reinforcing iron first, or the reinforcement, also you have to print around and everywhere. And then you are not far from having formwork, and then you are left with automatic control of such concrete. There must also be a way to design this to compensate for the disadvantages of reduced shear capacity and provide a little more of asecure reinforcement guide bracket, which will trigger a greater need for steel. There might be a need for more reinforcement if we are not able to position the reinforcement optimally.

A few specified the strength. If you have a lot of tension, e.g., at the bottom of a girder, it could be a real issue.

Types of reinforcement were a discussed subject by many. It was stated that you could not get reinforced structures with only non-pre-stressed reinforcement. Bridges often require pre-stressed reinforcement. Fibre reinforcement with a free span is not enough. It has to carry pre-stressed cables too, so you have to produce a piece forward, and then you have to tighten up a section to be carried in the next section.

Using fibre reinforced concrete is more frequently mentioned as an opportunity, but over 30 percent of the participants saw it as a challenge. The challenge most mentioned is when you can have fibre reinforced concrete, and if you lay out thin layers on layers, then you do not get continuity in the fibre layer. In a way, the fibre layer only lies horizontally for each layer, and no fibre bridges the individual layers. Fibre was also mentioned as affecting the character of the shapes, and the forms we can produce because fibre reinforced concrete is fine for certain things, but not for others. Until recently, it has always been such that one could not use fibre because it was not part of our regulations and calculation rules and execution in standards.

Types of fibre were also up for discussion. Those who produce non-metallic reinforcement or polymer fibre, claim that steel is rusting, but was stated not to rust if done properly.

It was discussed if the reinforcement process should be part of the process or done separately before or after the 3D printing. If it is to be printed around the reinforcement or should the reinforcement be part of the printing with fibre, it is possible to do something with fibre, but you do not get any special reinforcement amount with fibre.

New ways to reinforce things were also stated to be a challenge around 3D printing.

7.1.5 Opportunities

During the interviews, several different opportunities were highlighted with the use of 3D printed concrete bridges. The opportunities were divided into six subcategories: approaches, dimensions and shape, economy, environment, reinforcement, and rheological properties.

"I think the possibilities are many, and that is basically the imagination that sets boundaries and is not enough, something you can hear in the discussion right now that I'm talking about the things we already know."

7.1.5.1 Approaches

"What I've been really unsure about is what's right, is it to 3D print building elements that are put together or is it to 3D print entire constructions? That is really what I'm most uncertain about and what the future will show."

Different approaches were considered by 12 of the participants. The group of participants did not agree whether 3D printing was most suitable for customization or standardisation.

The biggest opportunities with regards to approaches were:

- Elements
- Standardization
- Industrialization
- Incremental launching bridge
- Segmental bridge building
- Shotcrete
- Slip forming

Starting with a bridge, should you 3D print the bridge, or should you 3D print the bridge elements? It is possible to create a bridge structure that rotates in all directions through 3D printing, for example, several bridge beams that span over what is needed. And then, they connect so that stiffness is obtained in the same way that you get stiffness when folding a paper. Then you can get stiffness in a bridge construction by directly connecting 3D printed bridge beams. One participant imagines that to succeed, it is much quicker to decide which parts of the bridge are suitable for 3D printing. It may not be what you are walking on because it may be mounted afterward, whether it is wooden beams or other. Still, the actual span widths - the beam systems and such can be 3D printed and linked together, so you get very airy and resilient structures that utilize geometry as rigidity.

"If one could have a robot near the bridge site that can produce 40 different or 40 similar 3D printed elements that are mounted continuously. I think that would have revolutionized the way to build just the structures. Being able to 3D print in the field will give much greater flexibility and adaptation to the geometry."

Elements

"Prefab could be a step on the way, making 3D printed components as a part of a bigger process."

Elements were mentioned frequently. The participants did not agree whether 3D printing was most suitable for customization or standardization, but either way, elements were considered.

Several participants saw the potential to use the element industry to drive the development to make this work due to controlled indoors conditions. Then it is entirely possible to produce elements that are assembled at the construction site. Opportunities for producing indoors were mentioned, as there are controlled production conditions, and you can control both temperature and humidity and everything that might be with the curing chamber, etc. Then it is quite possible to make printable concrete.

"I think it might pay off, rather than complicate the actual casting process, I think it's better to think in elements, at least in the beginning. It may be that when we enter the fully automated construction site it looks different, but we are not there yet."

One participant mentioned that there is a big market in relatively short span bridges such as motorways over bridges, for example, which could use identical components. So, it could potentially be an opportunity for a company to set up a robotic assembly line to produce identical components or with small variations to create a kind of family of bridges, a sort of off the shelf pitch system, like, pre-cast t-beams, such as pre-stressed t-beams type of construction, to be a product you can buy off the shelf.

Hollow-core slab production was mentioned by numerous participants. It was suggested that one could borrow some of the techniques one uses on other types of concrete work over to 3D printing of bridges, comparing a 3D print of bridge with the way you build hollow-core slabs. The hollow-core slabs span x number of meters, with post-tension, and are casted horizontally out of a large pasta machine. In the production of hollow-core slabs, there is a very narrow range, and it is an example of how to utilize pre-stressed reinforcement.

"I think many times we go blind in what we think 3D printing really is. I think it is quite interesting to look at because I am terrified that 3D printing is being developed as a separate technique without taking into account what one has learned from other similar casting methods for concrete products."

One participant envisioned 3D printing of precursor sections. They did a lot of bridges with pre-cast components, precursor segments of bridges, post-tension, or kinds of construction where you have a series of components to be assembled on the site. Now, clearly it could be possible to use robotic construction with 3D printing to build those pre-cast elements components in a factory somewhere.

Segmental bridge building was mentioned as a possibility for 3D printing. In recent times, there has been something that casts the entire bridge cross-section in full width and put in small lengths of 2.5 to 3.5 meters. Then, hang it on the bridge site via a rig and tighten up with tendons to take the tension on the underside, so that the cables are tensioned.

"If there are small bridges then it is easier to imagine, but again I have to imagine that 3D prints are small elements that are put together in place"

Some participants considered standardizations of elements as an option.

"No bridges that looks the same, it is possible to imagine that something can be standardised which can probably be done to a greater extent than what is the case today."

There is a big market for relatively short span bridges such as motorways over bridges, for example, which could use identical components. So, it could potentially be an opportunity for a company to set up a robotic assembly line to produce identical components or with small variations to create a kind of family of bridges, a sort of off the shelf pitch system.

Standardization

"It should have been a standard item, so a concrete element should have a specific design, and that is it."

One participant suggested that if one had standardized and made the same elements so that the elements were the same, one is always in stock and can be swapped if something happened. It is often the case that if an item gets damaged, you have to swap out just that item which involves finding drawings and shapes for that particular item, tailor-made and entirely from scratch.

One of the participants has participated in some projects that looked at repetition in construction, by repeating the same things over again to improve efficiency. In particular, the tunnel element was a typical thread, and a typical concrete material where one could have done a lot more repetition, made more efficient while saving a lot of money and time by having things in stock, and operating it becomes much more manageable. It is the same with some bridges, at least some smaller bridges like pedestrian bridges, , could also have been simplified and made easier with repetition, so that those who are casting, those who will run them, those who will calculate, and those who will approve the calculation are all together demonstrating more you could standardize, the easier and faster it would have been—the easier product you would have received.

"It is really strange we have no more standardization of bridges."

One of the participants talked about a major road project where they used standardized bridge details. *"It is a way to standardize without really standardizing*." If you have details on what the columns should look like, how the bearings should look, how the joints should be, so you can reuse those details and insert them, then it is easier for advisers to describe and draw it. The architects did draw the bridge first, but when the consultant does it, and the person who is going to check and approve gets it in and sees there are standard solutions, we do not have to reckon anything special because it is standard. Those who are going to do it have done the same solution many times, and those running it see that it is the same solution and components that must be replaced in the same way. Then you get a very good solution. That is what is laid out from the Public Roads Administration's standard bridge solutions, where there are details that are similar but not the bridge itself.

It was suggested that if one has e.g., ready-to-print bridges that are easy to carry, not too big, and which are pedestrian bridges where one can almost lift them in place somewhere, then it would have been an effective way to install. You do not have to stop traffic for more than one night to install them. Should anything happen, like several people ruining these bridges because they drive a trailer or a big boat over it, destroying these bridges and they have to be replaced effectively. It is clear if these types were standardized, if you can swap it or print quite fast, it is a brilliant solution because once it is damaged for some reason, you only need to start a printer and switch it in a very efficient way. Then we talk about the smaller bridges so they can be transported and handled. Nye Veier thinks a lot about to standardizing bridges. Still, then again, we talk about small and straightforward bridges, such as transitional bridges, bridges that cross a motorway, for example, a shorter smaller bridge.

Industrialization

Some of the participants did not envisage 3D printing to produce a bridge by itself and thought industrialization of building bridges as more realistic. It starts with robotizing the simple before it goes further, and the robot technology evolves to become more and more advanced, in every possible area. There are a whole host of operations that can be replaced, where robotization can replace manual robotics work. One can imagine that robotics technology is being developed step by step showing where there is potential. Whether it is a reinforcing robot or a casting robot, it must be ensured that there is a concrete delivery at night. It also stands as a casting robot and casts a traditionally closed wall. It is conceivable to industrialize and robotize formwork work. It must not be moulded without formwork, even if it is to be industrialized. It is conceivable to have robots that do all the operations that we do today if it is simple enough.

A couple of participants viewed an incremental launching bridge as an approach to industrializing the production of a bridge. That one builds a small production workshop at the construction site that there are a continuous production and relocation of the finished bridge. Then it is adapted to have a production line at the construction site.

The incremental launching bridge was explained to be a beam bridge with a continuous beam that is produced on land and pushed over pillars and support structures. One of the participants was been in a project where an incremental launching bridge has been produced. They had a factory on land where they built the bridge, and as they produced section by section in conjunction with the previous one, they pushed the bridge across the river. First, they built the pillars, and then they pushed the bridge over the pillars while building it. It is a type of production technique that is possible to robotize and automate. Spraying processes could have been attractive, where you have the production and the robot standing in one place, and it is the bridge that moves. Since the mould is standing still and the concrete is pushed over, the steel placement must be focussed on, it must be continuous throughout, and it can be mounted with a robot. Then, it is possible to have a printer that places the concrete in such a way that it encloses the reinforcement, casts, straightens, and smooths the surfaces completely to how it is expected to look like the concrete structure. So, then you avoid some of the problems that 3D printing has: the concrete must be free. It must be a reasonably horizontal bridge, with no significant height differences, nor can there be substantial curvature on it. For example, if you are going to cross a fjord crossing where there is plenty of space on both sides or there is relatively shallow water, so that it can be put on pillars, this type of solution is very well suited. It is a very attractive construction form, but one relies on a builder or client who believes that it is a rational way to build the bridge. Experience from this is that it is an excellent way to build. It provides high quality, high security, reliable progress, and provides very robust performance, i.e., a robust way of ensuring progress. It is the production process that is most suitable for industrialization.

Two participants thought that the printer could move along with the bridge. If possible, you can turn it around and do the opposite from the incremental launching bridge and produce equipment that is mobile and so light that you can directly produce on the spot-on print outwards and over the crossing. Thus, a robot that is standing on an already printed structure and is printing a new structure ahead of itself, as it was cantilever construction. The idea is a structure that kind of grows out of the ends by a robot.

One of the participants talked about shotcrete as a way to produce and be part of the industrialization of the process with robotization.

“3D printing is a name someone has come up with, slip forming is also a name, but the features are not completely different.”

Several participants talked about slip forming as a technology base that could be the base of 3D printing and further built on. Slip form is a known technique, but there has not been much development on how to do it, so there is potential to look at simplifying processes and simplifying execution, opportunities to automate things, and innovate.

7.1.5.2 Dimension and shape

"Shape is important for aesthetic reasons but also because the shape can affect the design ability to handle loads."

Almost 70 percent of the participants thought 3D printing could give opportunities in dimension and shape.

The most significant opportunities regarding dimension and shape were:

- Design
- Complex and free shapes
- Aesthetics and geometry
- Size

Quite a few participants believed that if you want something that is an unusual shape, then 3D printing technology can be a solution. Because one can, perhaps to a greater extent than with the traditional construction method, obtain forms that one would otherwise not have created without spending a significant resource on intricate formwork systems, etc. It is possible to aim at niche constructions with spectacular or other forms than what we are otherwise used to. 3D printing offers a greater opportunity for flexibility - geometric customization, and a more exciting geometry with 3D printing than with prefabricated concrete. The bridges in the landscape can be adapted differently - create curvature, make designs for roadways, etc. to a much greater extent than what prefab does today.

Several imagined that it has to be an entirely new way of thinking. It has to be suitable for printing and to be structured suitably for the flow of loads. They must look outside what they conventionally do. For example, columns and beams may look different when printed in 3D. The bridges will have a different expression. It may be that some of the limitations of design may be dissolved somewhat because there is a possibility of a free design that can be put into use in this regard. Many bridges are standard construction concepts. It may well be that we are going to see some more individual solutions to use constructions that, at least in the projects including 3D printing, you can see something that is produced in a new way that is also reflected in the design.

Participants also mention small scale bridges. That is, small bridges have some distinctive character that is appropriate to make it a 'one-off'. Thus, a bridge that is not desirable to be made using standard elements. If there was the opportunity to deviate from the standard solutions that you tend to fall into, then you could get bigger, more customized solutions than we might have today because we have been freer to design.

One participant mentioned a solution to get a more elegant aesthetic finish by dragging a shape behind the printer that could rectify the waves that often occur with 3D printing.

“ (…) it depends on the bridge type whether or not this is going to be attractive.”

Several participants envisioned that smaller bridges and culverts could be a solution in the first place, slightly smaller and simple objects.

Pedestrian bridges were mentioned for two reasons. One is that they are very visual examples, so it is a construction that is easily accessible to people and used as an example of how it can be done - the first phase of 3D printing. Bridges are constructions people can touch and look at to show that this is possible so that they are scaled up in the next turn. It is really like demo projects to show that technology is possible.

Several participants saw opportunities for 3D printing with concrete for other structures than bridges, structures with lower risk and smaller consequences, as well as structures that do not have a static or environmental load. It might be smaller components, constructions, or objects, e.g., tunnel elements. Others believed in would be suitable for niche production, that we must refrain from thinking traditionally about concrete structures. One can imagine that parts of the bridge could have been designed this way, and if there were parts of the bridge that had special requirements, one could fix it with a 3D printer So 3D printing might not be necessary for the whole bridge, but it may be appropriate for parts of it. Or those smaller things like culverts and manholes if you are in a place where it is not easy to get this transported and make more minor things. For example, when you build a power plant in the forest, and you need something a little unusual and may not have it on-site or be able to get organized to find a solution.

One participant believed it could only be used for tables and chairs, or where it is on a superior level where an architect can use it to brag.

7.1.5.3 Economy

"If you manage the technique and get the quality, then it is just the imagination that puts limitations, so it is a huge opportunity. There is a huge opportunity to improve productivity and reduce construction costs if you overcome all the practical challenges.”

Over 50 percent of the participants could see possibilities for the economy with 3D printing.

The biggest opportunities with regards to the economy were

- Productivity
- Cost reduction
- Material efficiency

One possibility mentioned by several participants is that 3D printing can lead to minimal labour and, therefore, reduce labour costs, which helps to reduce total costs.

"So, the success of 3D printing is not just progress and time spent, but it is just as much to use it much more materially smart."

3D printing can influence us to use fewer materials by using concrete more optimally, and numerous participants agreed. Now we use a lot of concrete because it is cheap, so we concrete in areas where it is not necessary. If you print, then you can certainly create the shell construction, which is very material optimally so it can help the construction industry to use less materials, which leads to a lower cost. The bridges are typically minimal constructions to some degree and 3D printing has the advantage of being able to place material where it is needed meaning 3D printing can lead to more competitive competition. If someone manages to print the beam layer very cheaply, then the other actors need to upgrade themselves, either introducing similar technology or improving their current technology. When those who made post-tensioned flat slabs came on the market very strongly for a while, they became a notable competitor for the prefabricated industry. Then the prefabricated industry had to optimize its beams even more to be competitive. When we then get solid wood as a strong competitor into the construction market, then it means that concrete must become more environmentally friendly than before. Therefore, one must enter with low-carbon concrete and such things. So if 3D printing comes as a new successful product, perhaps the most important thing is that it increases competition.

Participants believed that 3D printing would make it more competitive in an international market. If successful, technology cost is universal, and virtually equal everywhere so it will increase the competitiveness between the concrete element factories.

It was pointed out by a few, if 3D printing comes as a new successful product, it can also increase competition against other materials. When massive timber comes as a strong competitor in the construction market, it means that concrete must build-up to be much more environmentally friendly than before. Therefore, one must enter with low carbon concrete and such.

Another possibility that was mentioned by only a few, is to use these bridges as good examples of circular economy with some reuse of these segments, and the elements. It was explained with an example from one of the participants. There is a factory in Europe that has built a bridge out of elements. It is not 3D printed, but it could be suitable. It spans up to 25 meters as a road bridge. The elements are 2.5 m long and 1 meter wide and approximately 1 meter high, square with a hollow core. There is quite a lot of reinforcement in them. They were mounted at the bridge site and clamped together, then they were mounted tightly together, and then it gets tensioned. And that is something they have developed to use as a circular economy bridge, to reuse future bridges. So, it has been mounted, and it has also been disassembled, it works great. 3D printing could have been used to produce these bridges. There are small and straightforward elements compared to segments that often become 30-40 tonnes, because the total width of the road bridges is large, and there is a vast cross-section even though the length is only two to three meters.

7.1.5.4 Environment

"Bringing the environment into consideration is that one accepts that there are higher emissions per cubic, but much lower number of cubic meters."

Almost 30 percent of the participants mentioned environmental opportunities for 3D printing.

The most significant environmental opportunities were

- Material consumption
- Location and transportation
- Carbon Capture and Storage
- Green concrete

Several participants imagined that if it is to be 3D printed as an alternative, then the greenhouse gas emissions per unit volume will probably increase due to the concrete composition. Then material consumption must go down by, e.g., 40% or so that one has material consumption from it. Ideally, the 3D printer should be able to handle the concrete materials we already have, which has low cement consumption, and leaves a compact material, and gives the minimum cement consumption concerning the environmental impact of the cement.

"What it takes is getting the right total design, using and putting together different elements and taking the overall assessment on the environment."

Some believed that thinking of an environmental concern starting to enter the construction industry, then one of the significant challenges are the logistics and transport to and from the site. And the more production you can have close to the site, the better it is as a production. If you look at a prefabricated or segment-based project, where you can start production at the site rather than production at the factory, then it can be a profit or gain.

The industry has been working hard to reduce the environmental impact, and a lot has been done in recent years, and there is more to come. A few participants believed that the problem may be out of the world in a short time. If we start with Carbon Capture and Storage, which is likely to come within a few years, then suddenly, concrete is a perfectly acceptable product to use in an environmental context. It will help highlight the issue that we use concrete types that give a larger carbon footprint, such as a 3D printed concrete may do.

One participant suggested that being able to develop a kind of greener concrete that deals with wood fibre inside concrete is a win-win situation for all of Norway. It is a good economy and greener for the concrete itself, but it can also use what is not currently used in the forests, resources, or wood resources.

7.1.5.5 Reinforcement

Over 60 percent of the participants had suggestions on opportunities for reinforcement.

The biggest opportunities with regards to reinforcements were

- Stirrups
- Pre-stressed reinforcement
- Pre-tensioned reinforcement
- Post-tensioned reinforcement
- Steel wire

- Fibre

Some participants mentioned a type of reinforcement has to be a type of stirrups which solves critically exposed areas in practice, that one can put into the construction.

Several participants thought pre-stressed reinforcement could be a solution as it becomes a slightly different system than usual. You do not need as much reinforcement if you use pre-stressed reinforcement and strands in this. Depending on which direction you print in relation to the force, the two things can go in the same direction, and you can insert tension cables along the way while printing.

Some participants thought that a possibility could be pre-tensioned products where you tighten a wire and build the concrete around it instead of post-tensioned, making pipes in the concrete that you put a strand in afterward you tighten up.

Others suggested automated reinforcement processes. In the case of standardized bridges, one can imagine that reinforcement can also be made: you have an automated process for making reinforcement or adding reinforcement. You could still pull machines over the reinforcement, but then it must be a robot that makes the reinforcement in advance.

One of the participants has looked at TU Eindhoven, who have experimented with printing steel wires or steel cables into the printing process, so they put a thread out while they print. It is also interestingly combined with post-tension, where elements are eventually joined together. It can be a combination of different reinforcement methods where you can have pre-stressed structures.

Over 50 percent of the participants could see fibre reinforced concrete as an opportunity with 3D printing. Several thought that the biggest possibility is whether you can use fibre reinforced concrete. Then you can get viscosity and properties that are necessary and very important for 3D printing. But otherwise, you need reinforcement for bridges that have much bending, and concrete is good for compression but not so good for bending. Fibres are mixed in, e.g., shotcrete and in ordinary concrete which has started to be used in load-bearing structures, not just in flooring. If you have a material that can be used with fibre and have a system for it, it can open up great opportunities.

"Then we save 40 percent of the ribbed bars if we can use with fibre reinforced concrete."

Several participants mentioned the combination of fibre reinforced concrete and pre-stressed systems to be the best opportunity for 3D printing. Some meant that using fibre in the mortar could be the primary reinforcement, while others believed fibre would not be enough to be itself.

"Combinations of fibre reinforcement and pre-stressed reinforcement can work with 3D printing."

A couple mentioned material choice in fibres could also be wood fibre or composite material.

7.1.5.6 Rheological properties

"Ideally, we should have had the 3D printer that would be able to handle the concrete materials we already have. It has low cement consumption, which leaves a compact material and gives the minimum cement consumption, concerning the environmental impact of the cement."

Almost 60 percent of the participant had something to say about opportunities for rheological properties of the concrete.

The opportunities with regards to rheological properties were

- Stability
- Compaction
- Ultra-high-performance concrete
- Flowability and mobility (Curing and setting time)
- Durability
- Environmentally friendly concrete
- Other materials

Several of the participants were concerned with durability as one of the significant advantages of concrete. Although it has a substantial climate footprint, it lasts a long time, which is an advantage. Now we have good practice to get good durability with today's concrete.

One participant thought a more protected bridge structure will be easier to get safe enough concerning the degradation mechanism. Now it is possible to finish all 3D printed designs to ensure that they are frost resistant with e.g., various surface treatments.

One of the participants saw opportunities for stability and mobility by having some concrete technologists looking into whether we can use normal cement or fast curing cement or ultra-fast curing cement, which is to be developed. Measures should be developed that are sufficiently fine so that they do not separate in the blending process, the extrusion process, and the printing process. And it should harden quickly so when the next layer comes on, it does not collapse together. Similarly, one has the solidification accelerators when it comes to consistency.

It was mentioned several times that by moving production indoors, you have controlled production conditions and can control both temperature and humidity and everything to do with the curing chamber, etc. Then it is quite possible to make printable concrete.

"Do you lay down your printed concrete within a mould in the same way as you do conventionally? I have not seen that. There is no particular reason why you should not have achieved the finish that you wanted in the first place."

Several participants saw it as an excellent opportunity if it is possible to make a concrete mix that has the necessary properties to withstand bending or if one gets a good and efficient way to print high-strength concrete with fibre reinforcement.

Numerous participants mentioned that having a concrete that is compact and has no internal cavity is important if the concrete is to protect the steel against corrosion, and it should do so normally.

One of the participants has been a part of an experiment where they have 3D printed concrete around the reinforcement. Thus, some have bulged reinforcing irons in different patterns that those printed around it, to analyse how well the fastener has been on the reinforcement. Of course, this requires a relatively good attachment so that one should print closely on the reinforcement.

The concrete used for 3D printing has been discussed if it is concrete or if it is mortar. One of the participants said it is possible of concrete being printed and referred to two examples; in the U.S. Army Corps of Engineers, they have made some trial print, and COBOD in Denmark has made some prints with concrete.

Several participants did not see any problem with printing concrete. They believed that if you combine someone that knows concrete technology with someone that knows computer and robot technology, then they will solve the printing itself.

A couple of participants thought that 3D printing was better suited for materials other than concrete. Among other things, it was said that it could have been much more effective or used much less if you had used another material, such as steel or maybe even wood, but at least 3D printed steel.A bridge with 3D printed steel from MX3D in the Netherlands was mentioned which was thought to be much thinner and finer to look at. It is certainly much easier to optimize when working with steel than when working with concrete. A steel material or plastic material is more of a homogeneous material, which, thus has fewer challenges in obtaining it in the right way e.g. it is easy, and also more manageable, or that there are composite materials that replace what we traditionally think of as concrete. But once you start with composite materials, and not just composite materials, but the material properties should vary over a building component, it can get very complicated. And it might be possible if things are standardized and you are going to create the type of components on a large scale or many, i.e., you have a large production, this has to be repeated many times, then it is probably possible to get.

7.1.6 Future with 3D Printed Concrete Bridges

"I have no doubt that 3D printing will affect the industry, and it will affect it most quickly as contractors adopt the technology."

When the participants were asked about the future of 3D printed, there were many different answers. It was registered 17 positive participants, but also 13 participants that are negative, which means there are several participants in doubt.

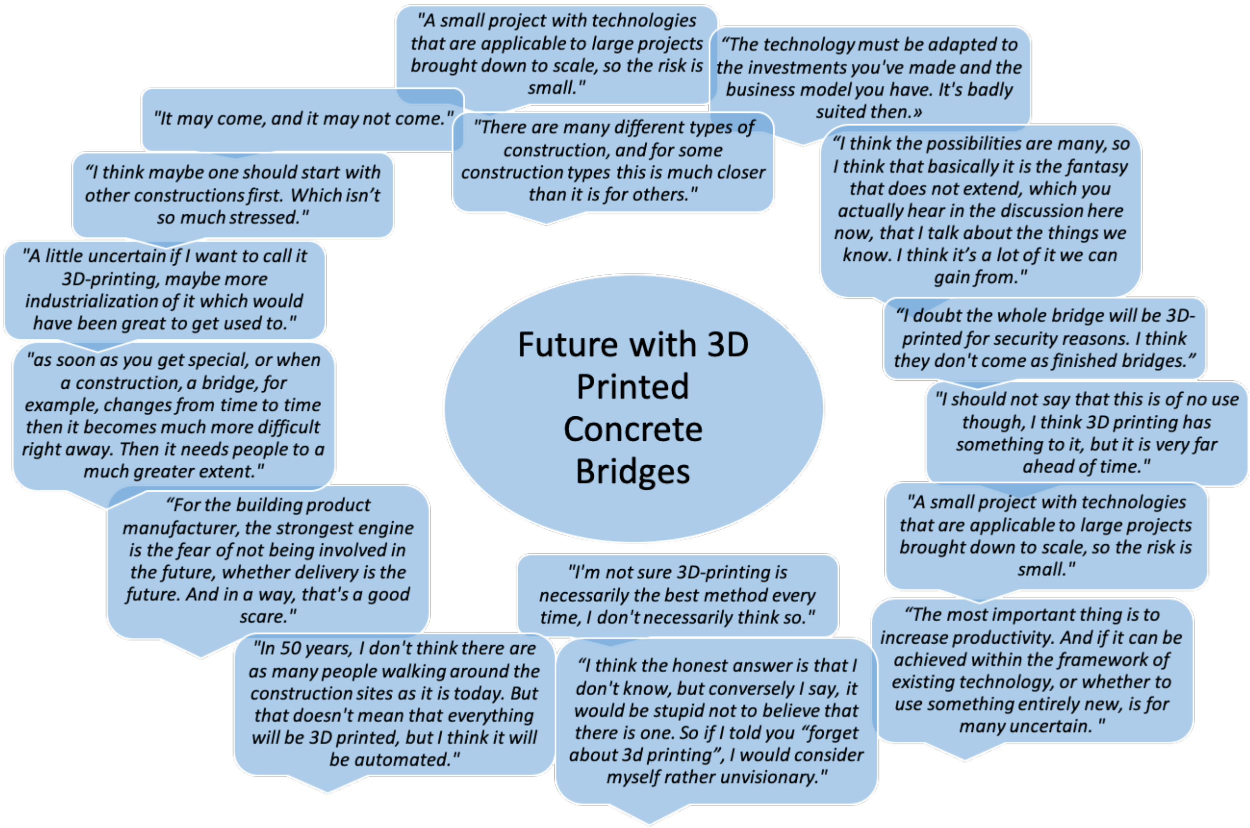

Figure 7.12 Quote Bank: Future with 3D Printed Concrete Bridges.

Some participants thought that 3D printing has an incredible potential for revolutionizing the whole way we build because it means that we get higher productivity, but it also has a significant impact on how things will look.

A consensus among several of the participants was to start on the small side first, and the parts that are manageable in weight and length with lifting equipment and such, so the technology that is behind the 3D printing can come into use. Some saw a future where small bridges can indeed be relevant. Then one has to think a lot about the possibility of getting the firmness up fast enough so that the concrete can carry itself. We may get so far at one point that even the large constructions can be 3D printed.

Several could see great opportunities, first and foremost, on standardizing items. If one could have a robot near the bridge site, where you build a bridge can be set to produce 40 different or 40 similar 3D printed elements to be mounted continuously. It would revolutionize the way to build just the structures.

Some saw tremendous opportunities with mass customization considering the needs of end-users as the highest potential for getting started with 3D printing. Seeing completely new expressions or brand-new types of bridges, and completely new ways to design, bridges have emerged because you see other methods and a freer form of production.

A few thought that we should refrain from traditionally thinking about concrete structures, that we are more into fibre reinforced solutions or composite materials that replace what we traditionally think of as concrete. Opportunities can open up if you get a good and efficient way to print high-strength concrete with fibre reinforcement.

As many pointed out, the future of 3D printing depends on the challenges being resolved, most on the material side, and with reinforcement.

Several highlighted the optimization of concrete bridges by being able to place the concrete where needed and thus help the construction industry to use fewer materials.

The thing about innovation is to change the way we do stuff. Some considered the future of concrete. Generally, because of the carbon-climate problem, we have got to find a way of producing a better kind of concrete. But having done that, we can then print it just like any other kind of concrete. We need to find the material, which is this low carbon, workable and printable, with the durability that we need to have.

Several of the participants were positive that 3D printing has a very bright future. Because it is labour-saving and makes building processes faster and certainly cheaper in time, this can have a significant impact on cost-effectiveness and productivity in the industry. It can produce without mould cost and with fewer working hours.

One participant stated that it may be worthwhile not to take large steps at this time, not think that this will solve all problems but start a little slow and develop step by step. Many participants mentioned that 3D printing is an excessive quantum leap for the construction industry.

It is generally a scepticism because people will see it working in their production and whether they will be able to create more or less the same things that they have always done, only 3D printed. There comes a compromise where the producers also open their eyes and think a little differently than they did yesterday. There should be some pressure to show some new opportunities, and that is where the architects are essential. And then we also have to get a little into what sort of world you are in when you are a concrete element manufacturer. There is good access to the concrete material, and it is by far the cheapest material in the world. It cannot cost much per kilo, so it will cost more with 3D print; it is tough for the industry. It is not the world they are in.

Some pointed out it must also be profitable, even if you save a mould and maybe labour, there are limits to what the concrete can cost. We do not know how big the scope is, but it is important to include it in the assessment.

"We know that, for example, in the offshore industry that we talk about all the time, shouldn't it be easier with spare parts. But very much of what is laid out in offshore is that those who make things for offshore, make money on maintenance and replacement of wear parts. If Equinor had taken over all that and only produced spare parts on-site, then the whole bottom falls out to those who have delivered solutions to them. So, with them, the resistance is partly quite big. And similarly, it is easy to imagine the construction production as well, that not everyone sees it as a gift from God to the world.

In the beginning, everyone will be cheering on this, saying "wow how wonderful it is", but in a way, when you introduce such a disruptive technology, then there will be resistance to it, naturally enough. Because it threatens an existing one."

Some thought 3D printing must happen in factories, and then it is natural and logical to see that this is the next development step for element manufacturers. Others thought that element manufacturers would initially try to increase productivity with the traditional moulding methods.

Some could see a brighter future for other materials than concrete.

Negative

There were several who could not see a future with 3D printed concrete bridges. Some of the reasons were:

- How to benefit from it on economy and propulsion
- Static load
- Environmental impact
- It is easy to get the desired shape of concrete already and 3D printing will not provide better opportunities
- There is too much uncertainty around material and hardening
- Safety

7.2 3D printing market

This chapter is based on research on how capable the construction industry is in handling technology and how the market is for 3D printing.

Market in this context is not limited with regards to economy, but about how the construction industry is able to adopt new technology. Market reports are included to show how much is invested in AM and 3D printing today, and what is estimated for the future to illustrate where we are, and where the industry is heading.

7.2.1 Adopt technology in the construction industry

The building and construction industry are providing us with tomorrow's building and infrastructure. According to KPMG Global Construction Survey 2019, only a few of the actors will be able to drive the industry forward [62]. The international survey from KPMG shows that only 20 percent of the construction industry actors are prepared to meet new customer needs [62].

There is little doubt that a lack of manpower, low productivity, increasing material costs, fragmented supply chains, and major prestige projects that flop make the construction industry ripe for conversion and disruption [62]. Developments over the last couple of years show that sustainability, digitalization, and technology are the new way to go for industry actors. 83 percent of industry leaders say they want to become more data-driven by introducing routines for using data, analysis, and predictive modelling in project planning and monitoring [62]. 59 percent expect that extended and virtual reality will naturally be integrated into most projects over the next few years, while 69 percent are confident that they will meet new actors soon who challenge traditional business and delivery models [62].

The survey shows a growing demand for actors with expertise in climate-conscious and data-driven solutions, and the most capable actors in the field can showcase it, not just at the construction site [62]. These businesses rationalize and streamline corporate governance, investing in technology, building culture, gaining a diversity of expertise, and measures result at all levels of the organization.

KPMG's Future-Ready Index shows that the leaders included in the panel, only 20 percent of them prioritize - and therefore, can benefit from such enhancement of competence in the staff functions [62]. KPMG surveyed 223 top leaders in the global building and construction industry, creating a benchmark for the industry. Based on the responses they have provided, the respondents were then divided into three categories [62]: *Innovative leaders* (top 20 percent), *Followers* (middle 60 percent), and *Behind the curve* (bottom 20 percent). The survey reveals an imbalance in the industry, where businesses in the lowest-ranked segment face significant challenges when it comes to adapting quickly enough not to lose considerable competitiveness [62].

Other important findings from the survey [62]:

- Invest time and resources in strengthening control and management functions: 66 percent of companies ranked as *innovative leaders* complete their projects on time and budget, while very few percent of the *Behind the curve* leaders do the same.
- The leadership segment of businesses has a much higher propensity to launch pilot programs for new technology, to turn the entire organization into testing innovations, and to recruit new resources with specific technology expertise actively.
- Future-oriented companies consider the recruitment of new talent as their second most important challenge, while other respondents rank recruitment in fifth place.
- Diversity is not just about recruitment: The majority of all respondents express that diversity is important, but only 20 percent in the top category prioritize to measure diversity at all levels of the business.
- The *Behind the curve* leaders spend most of their time chasing short-term revenue growth and spend little or no time investing in technology.

The construction industry has lagged in realizing the enormous opportunities that lie in technology and digitalization. Still, the report puts numbers on how few companies drive the international industry forward [62].

Transfer of competence from other industries becomes vital for the industrialization of the construction industry. The construction industry has traditionally been regarded as a craft industry, but more people see the benefits of transitioning to more industrialized construction production [63]. It applies to several levels in the value chain. The benefits include more than just cost reduction for the actors. A report from SINTEF [24] summarizes the research in the field and shows how the Norwegian construction industry can extract the benefits that lie in industrialized construction processes. Examples of such conversion are already developed themes such as Lean.

There is a great potential for automation in the construction industry, especially for subcontractors [63]. Small and medium-sized businesses can leverage today's advanced automation technology.

Going from crafts to industrial processes requires that the company do the following [63]:

- Find the optimal degree of automation
- Focus on IT infrastructure as important as the equipment in the value chain
- Involve the craftsman in the development process
- Training of operators and operational management

The transition from manual to automated processes is closely linked to the discussion about the future workplace and employment. In the report from SINTEF, some developments have been identified that can take production back to or near the construction site. For example, technology trends such as 3D printing and robotization enable on-site industrial production [63]. It creates new opportunities for combining local labour and production with industrialized processes.

According to the report, there is an intimation of a trend shift from the fact that industrialization is associated with end products that have a standardized appearance, to industrialized processes are associated with end products that have experienced a high degree of adaptation and variation [24].

In Norway, there is a strong drive for digitalization, but there is a great need for more and faster adaptation of new technology [25]. According to a report from the Boston Consulting Group, the impact of digital technology in the construction industry can reduce the project's lifecycle cost by up to 20 percent, thus improving completion time, quality, and safety [64].

The use of digital technology demonstrates excellent potential along the value chain from planning, design, projecting, and the construction phase of the project [25]. The use of digital transformation in different phases of the project provides better structure and collaboration between the design and the project phase, optimization of construction, and smoother operation [25].

Digitalization in the design and engineering phase helps create robust designs and blueprints [25]. It allows engineers, architects, and other project partners to identify similar dependencies and quickly re-evaluate design. It promotes structure and high collaboration between departments despite the large size of the project. Digital transformation also enables data-driven design by utilizing big data analysis. For example, people's behaviour and infrastructure environment contribute to optimizing the design decision by combining different data collection methods by including surveys, opinion polls, and more.

Digital design improves the efficiency of the construction phase by identifying distractions and discrepancies, thus optimizing the construction [25]. The biggest challenge in the construction phase is to give all stakeholders - from suppliers, subcontractors, clients - the right information at the right time. The effect of not having the correct information during this phase leads to delays in communication. Thus, the overall project has errors in construction, delays in the project, and cost overruns. Digitalization also contributes to computerized construction planning and Lean execution, enabling companies not to spend time on meaningless activities such as waiting, moving personnel, transporting materials, and equipment.

The operation phase benefits from digitalization, mainly from design analyses carried out during the design phase, where the building information is collected during the construction phase [25]. For example, the inspection data collected from handheld devices can be effectively shared with key stakeholders or project owners in the corporate office without data loss. With the help of integrated and interconnected systems on-site, continuous monitoring of project status will help organizations perform predictive maintenance. It will reduce the number of manual checks, thus significantly optimizing costs. Digitalization also provides the opportunity for on-site project management with full access to inventory-level information of equipment, building materials, and spare parts [25]. It makes it possible to notify the purchasing department earlier to avoid overloading the warehouse.

The digitalization of work processes is changing our working lives. Stedje [65] discussed with leaders in the construction industry about how digitalization affects their own company and the industry. Stedje concluded that leaders can be placed in three groups. In the first group, some leaders have had success in working traditionally and who do not consider it worthy of investing in new technology. In the second group, some leaders recognize that digital solutions simplify and improve processes, but they have no clear plan for how this will help their own company. In the third and final group, some leaders understand that digital solutions are just a tool, and it is crucial to use the tool [65].

According to Statistics Norway, construction is one of the industries with the lowest investment level in research and development [66]. It states that actors in the construction industry have seen little of the benefit of improving existing processes. Here, interaction with other actors in projects probably plays a central role.

A construction project is complex to manage. If overruns are to be avoided, the challenges must be resolved before they occur at the construction site [65]. It requires three critical steps: (1) First of all, it will be advantageous to create a prototype of the building and test it before the building is built. (2) Second, several areas of expertise must contribute to problem-solving during the planning phase. It, in turn, requires that a collaborator shares their knowledge and devote time and resources before the physical job starts. All participants must be involved and actively contribute to the planning to make this interaction work. The goal is to increase the sum of the total to each individual's independent contribution. (3) Third, clear leadership is needed to bring everyone together and work toward the same goal. Getting everyone to understand the bigger picture, and what their contribution can be, requires a steady hand. [65].

Digital tools today enable interaction between actors in projects that are likely to turn the industry upside down [65]. It is not an unknown phenomenon that new actors are flourishing as new technology changes traditional ways of working. Whether this will also happen within the building and construction sector, only time can show. Tomorrow's winners in building and construction are the actors who [65]:

- Ability to get participants in projects to interact effectively.
- Master digital tools.

- Facilitates a culture that wants to share insights across disciplines.
- Are good at practical problem-solving.
- Sees the benefit of investing in digital tools and expertise where you may not be able to count your investment directly in your own business.

7.2.2 3D printing market

The World Economic Forum (WEF) has together with the Boston Consulting Group (BCG), developed an industry transformation framework (Figure 7.13) listing 30 measures that are supported by case studies of innovative approaches and practices [36]. The measures are divided into different levels. Companies can adopt some on their own, while others require collaboration with other companies along the value chain. The government can adopt some of the measures as both regulator and major client.

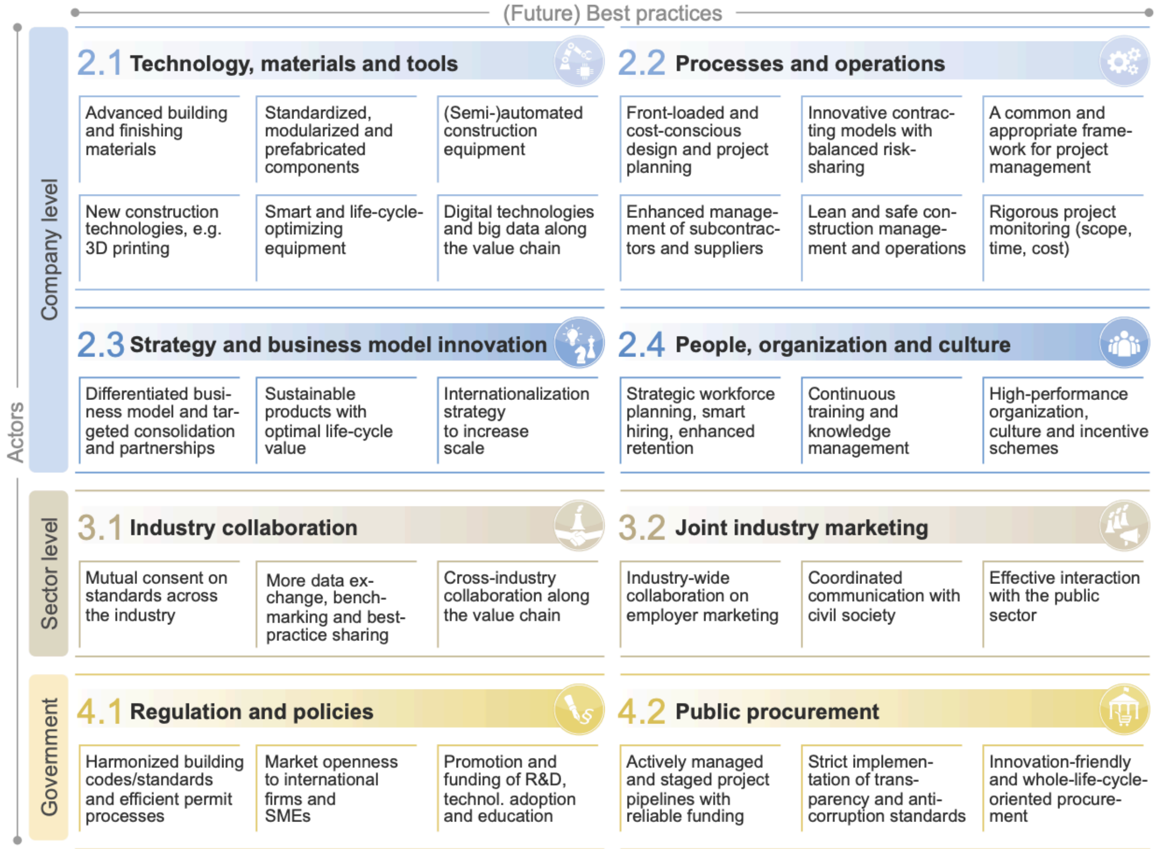

Figure 7.13 Industry Transformation Framework [36, p. 17].

The industry has societal, economic, and environmental relevance. Construction is determinant for nearly the entire world population's quality of health as it influences health and well-being. All other businesses rely on construction for infrastructure, plants, and accommodation. Today, more than 100 million people worldwide are employed in construction, and there is expected to be a considerable growth with estimated revenues of $15 trillion by 2025 [36]. The construction industry is the largest consumer of resources and raw materials in the world, with approximately 50 percent of world steel production and three billion tonnes of raw material to manufacture building products. [36]. The construction industry is also responsible for 25-40 percent of the global total energy use, thus contributing a lot with greenhouse gas emissions [36].

The WEF and BCB predict that the industry's future will be shaped by some megatrends (Figure 7.14) that can be divided into four categories [36]:

I. Market and customers
II. Sustainability and resilience
III. Society and workforce
IV. Politics and regulation

Figure 7.14 Megatrends Shaping the Construction Industry's Future [52].

The industry must confront internal challenges. Underlying causes for low productivity improvement might be lack of innovation and delayed adoption, informal processes or insufficient rigor and consistency in process execution, insufficient knowledge transfer from project to project, weak project monitoring, little cross-functional cooperation, little collaboration with suppliers, conservative company culture, or shortage of young talent and people development [36].

> *"Looking at construction projects today, I do not see much difference in the execution of the work in comparison to 50 years ago."*
>
> \- John M. Beck, Executive Chairman, Aecon Group, Canada [36, p. 15].

There is a widespread perception that the construction industry companies are not adequately progressive as it operates in a conventional environment [36].

According to WEF and BCB's rapport, the industry is mature and capable of transformation and has excellent potential to be used. Technology, materials, and tools are in development each day. New construction technologies, such as the development of 3D printing, are expected to disruptively influence the construction industry and promise productivity gains of up to 80 percent for some applications [36].

Based on a survey conducted as a part of the *Future of Construction* project, transformation areas of the industry are listed and ranked according to performance in Figure 7.15.

Figure 7.15 Importance of Different Transformation Areas for the Construction Industry [36, p. 49].

All stakeholders in the value chain should contribute and take action. Private companies should actively shape transformation. The industry unitedly should improve coordination and cooperation in the value chain with shared goals and standards. The government should build a fertile environment for change [36].

The *Future of Construction* project survey resulted in a matrix (Figure 7.16) illustrated the impact and likelihood of new technologies, materials, and tools in the construction industry [36]. As it illustrates, 3D printing is just below middle on both axis, likelihood and impact, while integration of BIM which is already happening to a great extent has extremely high impact and is extremely likely.

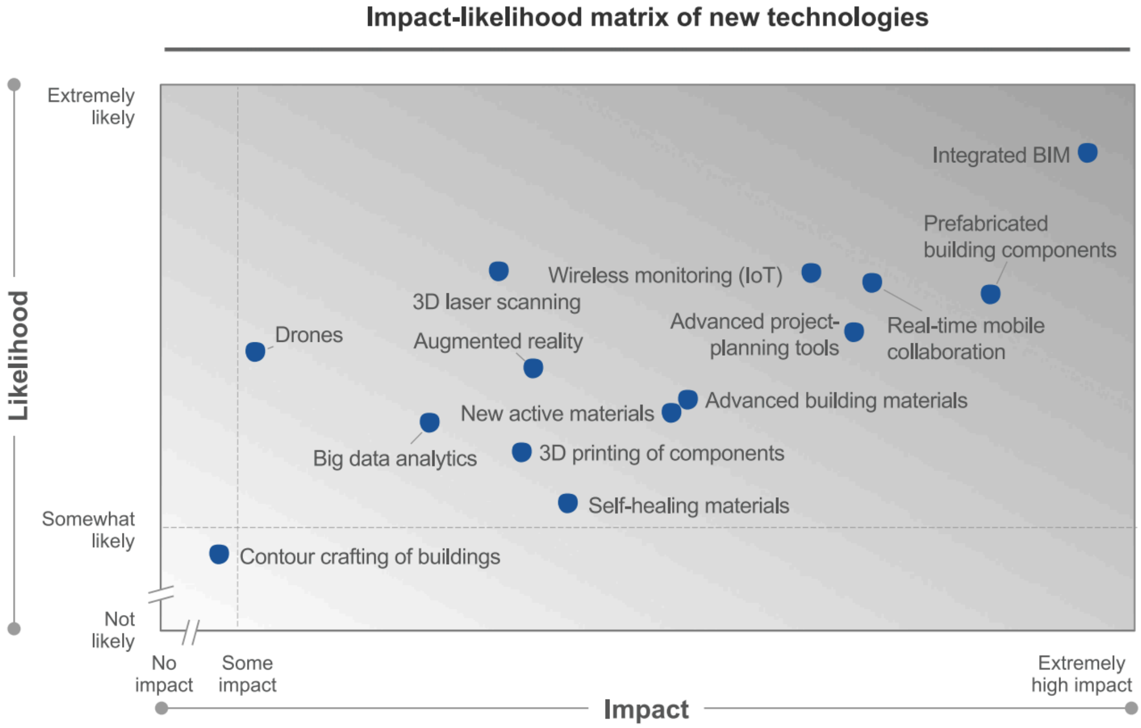

Figure 7.16 Future Impact and Likelihood of New Technologies [36, p. 53].

In 2018 SmaTech published a report predicting the AM, including 3D printed, construction industry to have considerable growth [67]. They expect an increase in revenue to go from $0.07bn in 2017 to $40bn by 2027. Some bold predictions for the AM market were made in this report. The predicted total revenue of $40bn by 2027 is made up of $150M in material, $3.5bn in machinery, and $36bn from applications and services [67]. Figure 7.17 shows the forecasted market revenue.

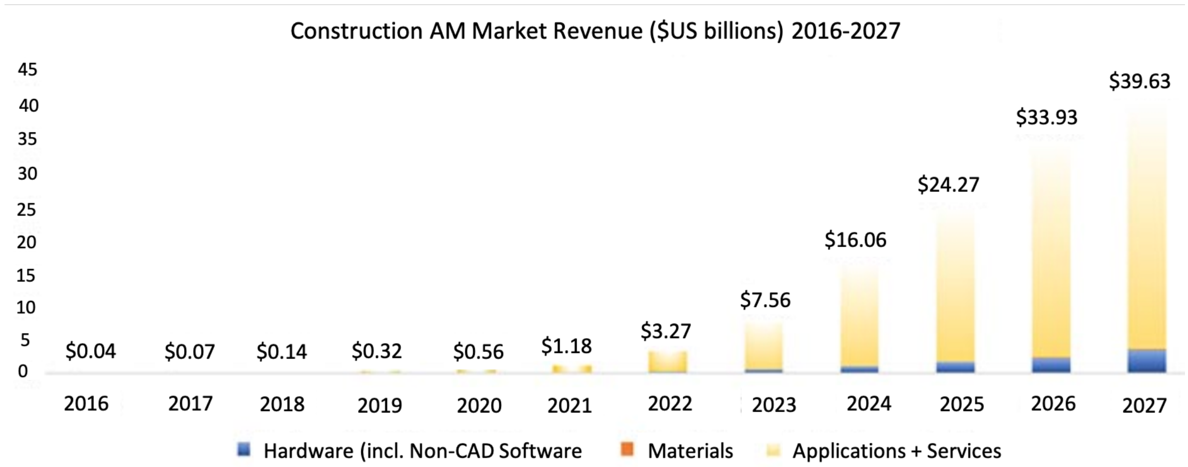

Figure 7.17 Construction AM Market Revenue 2016-2027 [67].

Several factors can explain the predicted growth of 3D printing in the construction industry:

- **Political factors**: Politics and regulations promote the implementation of 3D printing in the construction sector. These public sector initiatives often address issues such as resource and energy efficiency and can provide potentiality for technologies that maximize resource use, like 3D printing. Policies can directly support 3D printing, e.g., the UK's national additive manufacturing strategy, that predicts 3D printing to generate more than $1bn to annual GDP and create fifteen thousand jobs in the construction industry by 2025. Public institutions outside Europa are already planning to use 3D printing for house building and some have succeeded. It can provide important market opportunities for EU construction companies [31].

- **Economic factors**: As the 3D technology develops, the cost will decrease with improved efficiency. Also, the expanded awareness of 3D printing can lead to more R&D investments and economies of scale [31].
- **Market demand factors:** 3D printing provides more options for design, to be constructed on-site or off-site, and are stated to be reducing costs compared to traditional methods. Also, it is more predictable and can shorten the construction time [31].

The report indicates that 3D printing will most likely cause drastic changes to the construction industry. The 3D printing technology responds to numerous concerns related to the industry; low productivity, labour shortage, building material costs, environmental impacts, recycling of construction waste, and resource efficiency [31].

The HINDCON project investigated the market during their research [41]. One of the challenges with HINDCON is to see how it can further be developed in the market. The idea was to synchronize with the market early in the development, which has many questions related to it because many parts of the technology need to be more developed. For example, the production capacity of the HINDCON robot unknown today, taking all parameters into account. The maintenance level is essential, especially if there is a wish to sell the robot, and the final price is unknown. The user's needs are very open, and the market for 3D concrete printing is relatively new. There are also many questions about the standards. The construction sector is highly regulated, but the evolution of the standards is just starting.

Even with all those questions and uncertainties, a business model for the income company was created. All the project partners were included in a workshop to share their experience to look at the business model [41]. A focus group was created with the idea of doing interviews with professionals. Small companies, craftsmen with five employees, and also some big companies with more than 1000 employees were included. A macro-economic study was made, a considerable analysis around 3D concrete printing in the world. An internal property analysis was also conducted, because, with this type of project, one of the questions is the repetition of the intellectual property. Hence, it is essential to analyse and imagine the management of this kind of intellectual property in a company [41]. Another focus group was created to see if the professionals from the other focus group and this one would have the same results, point of view, or not. Finally, the business plan, the marketing strategy, and the market analyses were to be made.

The business plan included the following steps [41]:

1. Market analysis: market forecast, competitors, user's needs.
2. Company strategy: in a competitive context and emerging market, define a strategy to penetrate the market.
3. IP Management and R&D Strategy: understand how HINDCON's intellectual property is distributed and anticipate future R&D.
4. Financial forecast: to develop a HINDCOS company supposes investments, jobs, expenses, and sales, etc. to imagine the financial forecast.

5. Marketing strategy: Who is our client? What do we sell? How? For what income?

A vast market study was used with the analysis. Looking at the all additive manufacturing market in the world, in 2018 it was close to $10bn in the world and is going to develop very rapidly and will in 2022 get close to $27bn [41]. The 3D concrete printing sector is small, $23M, but it is going to develop a lot because in 2029 it is estimated to reach $200M, which means there will be a market [41]. Looking at the geographical repetition, North America is the leading market close to 40 percent and will keep the proportion for the next ten years [41]. The second largest markets are in Europe and Asia. With the focus on Europe, the leading countries are Netherland and Germany, followed by the UK and France, but Netherland and Germany are pushing the technology [41]. The 3D concrete technology nowadays is more for parts for the residential market. It is 30-35 percent, and it will keep this proportion, followed by architectural projects, and finally, commercial and infrastructure are very low [41]. By product, mainly walls, roof, and floor are mostly used.

Regarding the two focus groups. A synthesis of three kinds of results was made [41]:

a) First, the idea was not to speak of the technology but to speak about the main problem of the construction sector in day-to-day work. Three main issues appeared:
    i. Poor preparation on construction sites: many problems are discovered on the construction site, which costs money and time. Many elements are discovered on-site, which causes problems of quality, security, and delays. The construction sector is the last sector to be industrialized and finally the risk of that is that each project is a prototype.
    ii. Climatic problem: More and more off-site construction is developing, which can be a way of handling the climate problems. Weather is one of the major factors of uncertainty and can cause a lot of delays and, therefore, money.
    iii. Difficulty finding skilled workers: building jobs are difficult and unattractive jobs. It is hard to keep or fin people with good skills. Robotization of the sector can be a solution.
b) Second is the expectations of 3D concrete printing technology:
    i. Reduce dependence on the worker
    ii. Increase production rates
    iii. Avoid error and improve quality
    iv. Reduce the hardness for workers
    v. Developed new forms, new architectures
c) The third result was what applications would be useful with 3D printing:
    i. Automated manufacturing of complex parts specially to avoid the cost of formwork
    ii. Manufacture of ornamental pieces: facades, concrete ceilings, etc.
    iii. Indoor or outdoor furniture and street furniture.
    iv. Build a whole house.

It has been adapted a strategic vision for AM to develop further, and to make sure the progress did not stop after the HINDCON project. AM-Motion is a strategic approach to increasing Europe's value proposition for AM technologies and capabilities, with a final goal to contribute to a rapid market uptake for AM technologies across Europe [30]. AM Motion has four focus areas: (1) Technology development, (2) Technology transition, (3) Market barriers/industrial implementation, and (4) Communication and networking [68]. This strategy concerns the construction industry and several other industries, e.g., aerospace, energy, automotive, etc. It is a united project with no single technology/solution, but seven process categories, with subcategories using different materials for different sectors. Production is not a single step; it is needed to consider the complete chain/integration process (Figure 7.18). From idea, design/engineering, simulation, materials, process, post-process, quality control, the final product [30].

Figure 7.18 Steps of AM Value Chain [30, p. 8].

Building confidence is also necessary to find the right process for companies. Is AM or traditional manufacturing the right thing in this period. To determine when and how to apply AM, organizations need to assess the market strategy, supply chain, available equipment/materials, cost-benefit, business model. AM-motion vision for 2030 is for Europe to take industrial leadership in AM with high social, environmental, and economic impacts in target sectors [30].

7.3 Conditions for 3D concrete printing

7.3.1 Technological solutions

There are mainly three large-scale AM processes targeted for construction: Contour Crafting, Concrete Printing, and D-shape [69]. Contour Crafting is based on extruding a cement-based paste against a trowel building up layer by layer [70]. Dr. Khoshnevis developed it in 1996 concerning the 3D printing based on the extrusion of concrete [71]. It can address the issue of high-speed automated construction and for minimum use of material. It has the potential for automating the construction by building whole structures or sub-components that can have different design [71]. Concrete Printing is based on extrusion of cement mortar and has retained 3D dimensional freedom. It allows for greater control of internal and external geometries, compared to contour crafting, as it has a smaller resolution of deposits [71]. D-shape is a process using powder deposition, which is hardened using a binder [71]. Table 3 compare the three processes.

Table 3 Comparative between different 3D printing construction processes [70, p. 255].

	Contour Crafting	Concrete Printing	D-Shape
Process	Extrusion	Extrusion	3D Printing
Build material	▪ Mortar mixture for mould ▪ Cementitious material for build	In-house Printable Concrete	Granular material (sand / stone powder)
Binder	None (wet material extrusion and backfilling)	None (wet material extrusion)	Chorline-based liquid

Nozzle diameter	15 mm	9-20 mm	0.15 mm
Nozzle number	1	1	6 300
Layer thickness	13 mm	6-25 mm	4-6 mm
Reinforcement	Yes	Yes	No
Mechanical properties	Tested with zero degree (0°) of layer orientation, which means the force was given from the top of the printed surface		
Compressive strength	Unknown	100 110 MPa	235 242 MPa
Flexural Strength	Unknown	12-13 MPa	14-19 MPa
Print Size	> 1 m dimension	> 1 m dimension	> 1 m dimension
Pre/Post Processing	▪ Reinforcement per 125 mm vertically ▪ Backfill the mould with a cementitious material per 125 mm height	▪ Reinforcement after printing	▪ Compression of the powder for next layer by a roller with lights pressure prior to the deposition ▪ Removal of unused material
Pros.	▪ Smooth surface by trowel	▪ High strengths ▪ Minimum printing process: deposition & reinforcement	▪ High strengths
Cons.	▪ Extra process (moulding) ▪ Weak bonding between batches due to segmented backfilling batches by one-hour intervals	▪ Limited printing dimension by the printing frame, 5.4m(L)x4.4m(W)x5.4m(H)	▪ Slow process ▪ Rough surface ▪ Limited printing dimension by the printing frame ▪ Massive material placement ▪ Removal of unused material

The Gantry Solutions were the first to be developed for concrete extrusion in 2001 and was patented under the name Contour Crafting [72]. Later on, Concrete Printing, also referred to as Freeform Construction, emerged in 2007 from a research group at Loughborough University. It focused on constructions fabricated in one piece, such as full-scale construction components (e.g., panels and walls) [73]. This system had a CNC machine to move a printing head digitally along the X-Y-Z axes in the Cartesian coordinates. Using gantry solutions can quickly turn into a very complicated task with several cranes and nozzles, and requires a considerable amount of energy for transportation and installation [69].

Twente AM, a Dutch start-up company focused on architectural 3D printing, unveiled at the beginning of 2020 its latest large-scale 3D concrete printer [74]. The machine was developed and assembled at the company's research and development centre in Nelson, Canada, just days before it was displayed on screens at the 14th annual *Big 5 International Building & Construction Show* in Dubai [75]. The central role of this large printer will be to build a framework for the construction of concrete houses to be built in British Columbia. Twente AM's goal in their debut year was to develop a concrete 3D printer placed on a building-like structure capable of moving ten feet in width and five feet in height. A typical 6-axis ABB robot attached in place has a print footprint of 42 m^3. With the addition of being able to move vertically and with translation, an 8-axis robot is capable of printing 181m^3 [75]. Finally, a ninth rotational axis brings the machine's working capacity to 391m^3 [75]. The extensive range of the concrete printer combined with its advanced articulation allows for detailed forms and artistic structures that would otherwise be impractical with traditional formwork. Parametric CAD software is directly connected to the machine, and the shapes are controlled by algorithms [75].

Twente AM presents six different 3D printing technologies (Figure 7.19) related to material extrusion and architecture [27]:

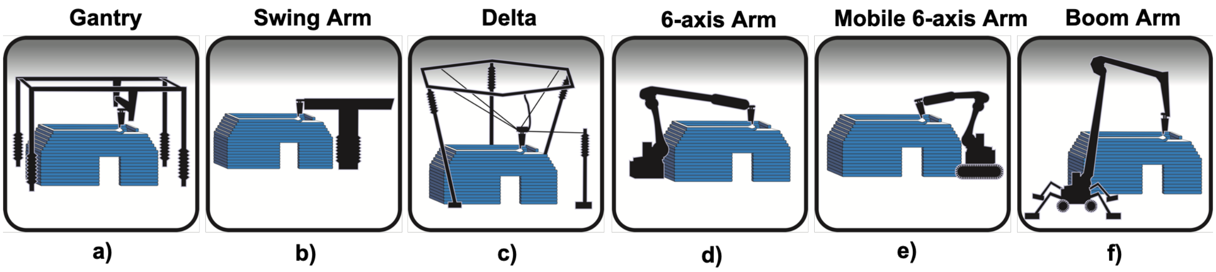

Figure 7.19 3D Printing Technologies Related to Material Extrusion [27].

- **a)** **Gantry** is the most typical 3-axis computer numerical control machine using a cartesian coordinate system [27]. The Gantry is a well-contained equipment; the programming uses simple movements, it is easy to expand, easy to create safety perimeters and is basic maintenance on moving parts [76]. The negative aspect of this type is the complicated set-up for on-site usage, as it requires a foundation for footing for rigidity, and it is difficult to move printed parts away [76].
- **b)** **Swing Arm** is a 3-axis computer numerical control machine using a polar coordinate system [27].
- **c)** **Delta** is a parallel robot consisting of 3 arms capable of fast 3-axis motion [27].
- **d)** **6-Axis Arm** is a robotic arm with 6-axis or degrees of motion [27].
- **e)** **Mobile 6-Axis** is a 6-axis robot arm usually mounted on an additional wheeled axis [27].
- **f)** The **Boom Arm** is a boom arm mounted on a mobile vehicle [27].

The Swarm Approach is very different from the others as it consists of several smaller and mobile robots instead of a big fixed frame. One of the benefits is the ability to be used in environments where payload and transportation considerations are critical [69]. This approach was introduced with robots able to build and climb tubular structures. The ability to climb is essential for this approach as it enables the building all dimension and heights. Researchers from the Institute of Advanced Architecture of Catalonia have developed three small robots ("Minibuilders"), which are a foundation robot, a grip robot, and a vacuum robot [77].

Cable Suspended Platforms have been developed based on the Cartesian system but have improved the system's transportability. They consist of an end-effector attached to an external frame using multiple cables. The end-effector is controlled by motors that can adjust the cables. The cables can be attached to the end-effector from below, or since 2008 the cables could be mounted from the top, both parallel and crossed [69].

The benefits of cable robots are many. The advantage of using cable-supported platforms is the provision of larger workspaces and they are easier to transport, disassemble, and reassemble, easier to reconfigurable, and they are also less expensive [69]. A larger workspace made it possible for large pieces. Furthermore, the technology of cables and winches has been developed in the construction sector for years, so all components are already established and studied. They have been put together to a cable robot. Therefore, it can have a high dynamic with strong winches and payloads. Because there is such a large workspace of several meters and also meters of height, the only real comparison machine that is out there is the Gantry system, and compare to them, this cable robot has a lower price for the same performance.

7.3.1.1 HINDCON

The robot that was developed for HINDCON is a cable robot. Cable robots consist of a mobile platform, wherein the case of HINDCON is the extruder, then the extruder can be moved around using cables. Cable robots are parallel kinematic machines that use cables as transmission elements (kinematic chains) [78]. Winches adjust the cable lengths; thus, it is possible to move the platform. Suspending a mobile platform with seven or eight winches allows for six-degrees-of-freedom manipulation [78]. For HINDCON, there were eight cables, so it was fully constrained, therefore it is possible to control both the position and orientation of the platform. There are other configurations e.g., when the system is hanging, there are only four cables, which also have its benefits and other applications. The eight cables are controlled by modular winches, which are positioned in the corners of the room, and through them, it is possible to control the length of the cables accurately [78]. The benefit of the HINDCON cable robot is that it can be reconfigured relatively easily. The winches can be mounted in different positions or change the mobile platform fairly quickly.

The first step for the robot is to plan, design, and simulate [78]. It is possible to design and optimize cable robots, analyse workspaces, detect a collision, and also e.g., the stiffness analysis. All hardware component of cable robots was designed and produced. Calibration and control software were also used. With the control software, the cable robot can be commanded manually or programmed, or with G-code to generate the printing trajectories [78]. For smaller cable robots, there is also force control and admittance control. To achieve a high accuracy, the system's initial calibration needs to know all the winches' dimensions and the mobile platform's position. Furthermore, there were integrated safety concepts, and a fence around the robot so the humans are safe during operation [78]. The lessons are that good printing quality can be achieved with cable robot system, and the robot's stiffness could be improved to reduce vibration [78].

In the development of the ultra-high-performance concrete (UHPC) 3D print-head, it was necessary to have a strong emphasis on good collaborations with partners [78]. The cable robot gives much freedom but also many constraints for the print-head due to the controlled environment where the robot is placed, which is not necessarily an easy thing because there are very different actions, and shapes are different. It has to be mixed in the right quantity and continuously, which is a challenge, in terms of control. A progressive cavity pump was used, which is commonly used in the construction sector to pump concrete, but it had to be used in a way suitable for AM [78]. It means precise control of the doses or having the correct mix and in order to put the right amount of concrete in the right place. A primary pump on 100l was used together with a smaller pump on 4l, which will add the additives to be fully compatible with the concrete element [78]. It is then again blended in a mixer. The main pump used for HINDCON (Figure 7.20) is based in a motor system that pumps concrete, located in the tank, through a typical commercial progressive cavity pump [78]. Second is the dynamic mixer, which has nothing different from a traditional mixer which can be bought commercially; the only problem is the weight issue on the entire system. There is an infield for the additive and another one for the mortar. Everything is mixed inside and is located with the head, which gives a good concrete shape. The auxiliary pump is the tank that holds the additive [78].

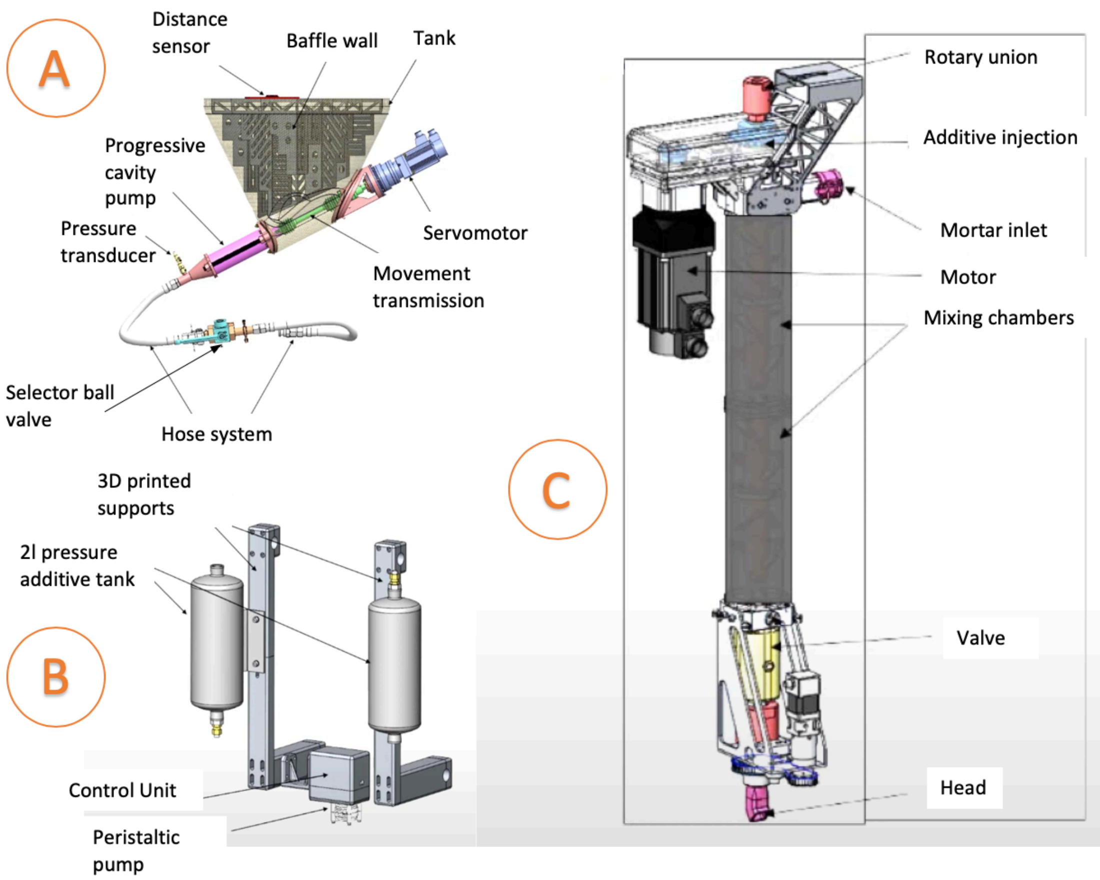

Figure 7.20 A is the Primary Pump, B is the Auxiliary Pump, and C is the Mixer [78].

The structure design (Figure 7.21) is crucial [79]. The weight was one of the main concerns during the design of the actuator, so it made extensive use of carbon fibres on different composite materials, basically made of mostly plastic unions and carbon fibre tubes [79]. A risk analysis was conducted to make sure it had the right resistance, because there is no visible deformation in the parts before having a total breakout. Another problem in the design is that on one side there is a big pump that pumps very quickly, creating a lot of vibration. The deposition is wanted to be as accurate as possible, which means that deformation needs to be avoided. The support of the tank and the structure which hold the rest of the elements are built around it to avoid that problem [79]. The tank has no physical attachment to the parts beyond it. Based on Von Mises- criterion results of the calculation, no parts seem to suffer from plastic deformation [79].

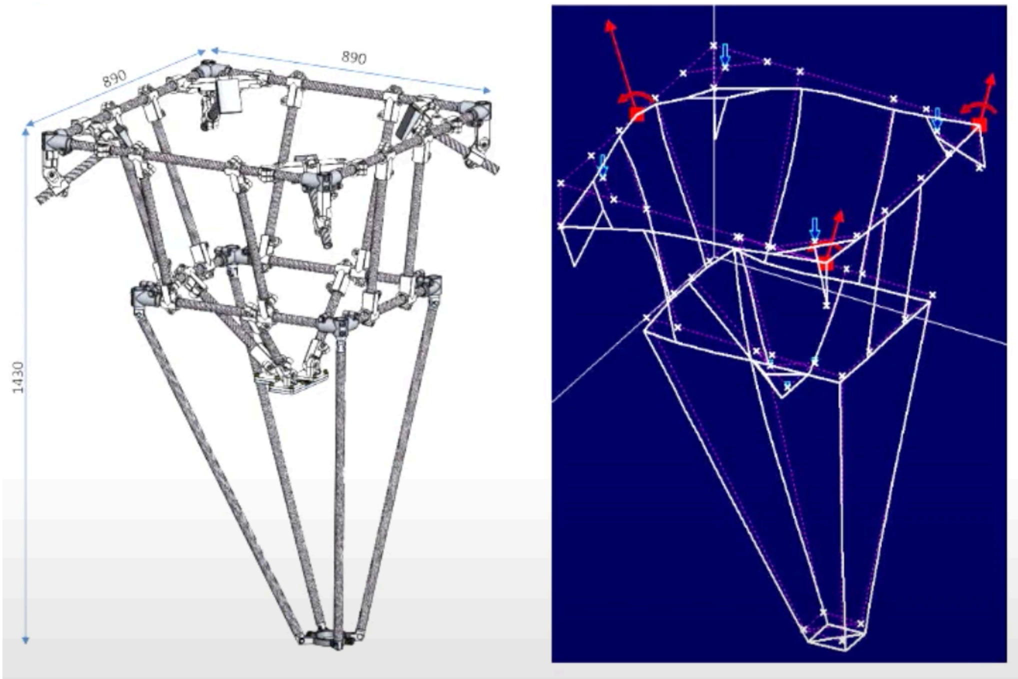

Figure 7.21 HINDCON Structure Design [79].

The main tank, the core part of the extruder, is the one with the most responsibility because the main motor of the main pump can lead to a torque up to 90 Newton meters [79]. To save as much weight as possible, a mix of carbon fibre on aramid, which is mostly known as Kevlar, was chosen. It also used some glass fibre parts in the tank to add rigidity. Another problem for the main tank design is weight loss and the gravity centre movement [79]When concrete is printed, the mass inside the tank is reduced, which means the total weight is reduced, and it makes a displacement in the z-axis of the gravity centre that is unavoidable. If the platform is not correctly calibrated and a displacement of the platform's gravity centre occurs, it will cause the cable robot to tilt. Therefore, everything is designed around the main tank, as the main tank as the central part, however this creates a problem for the tube[79]. If the tube was placed in the front, the platform would have been desecrated, which would have added displacement. Experimental measurement of the displacement of the gravity centre was made, and the displacement is less than the nine centimetres which was seen as acceptable [79].

Temperature and pressure sensors were used during printing, and it was seen that a chemical reaction was taking place inside the mixer for post-print printing. The reaction is not linear for a long time because there is one sensor at the entrance of the chamber and one at the output [79]. The increase in temperature is related to the rise of the pressure of the system. When the pressure exceeds, there is a heat-up that will influence the reaction of the concrete. During the setting of concrete, it is an exothermic reaction, and it gets warmer [79]. The pressure sensors' values have a quick rise as the reaction begins, of the pressure, and then it gets back. The decrease is due to the tank. The concrete is not static; it gets down little by little doing the full printing. The RE (Rare Earth) elements start to precipitate in the bottom of the tank, so the end concrete has less RE than the beginning of the concrete [79]. It changes the entropy of the concrete and is the reason for decreasing the pressure at the end of the printing [79].

There was also a development of the subtractive process technology in the HINDCON project [80]. The objectives were to realize polishing, milling, drilling, and engraving. For that, some cutting tools mounted on the arm manipulators were necessary. The mechanical integration, software integration, and to control functionalities into the "all-in-one" machine was also a big step. Constraints for the subtractive tool were the high weight, rigidity, stability, and repeatability. Preliminary trials consisted of machining testing, time of concrete drying, with/without compliance, with/without a load balancer, a study of vibrations, horizontal and vertical trials, maximum load [80]. Subtractive manufacturing includes different tasks. The polishing and sweeping strategy make good surface aspect quality and works even if the concrete is set. A force controller needs to be used to make sure not to break the robot or the structure. Milling with a chamfering carbide milling cutter was also used. The sweeping strategy was developed as well to get a flat surface and shaped corners. Engraving was used to write on the surface. It achieved a good readability of engraved words. The depth could be adjusted to adapt to different contrast. Holes were also manageable with drilling. For the smaller holes, a drill of desired size was used. It was drilled for large holes, and then a large carbide cutter for the contour was used. All the SM technologies reached good quality between 3-6 hours of drying, after the composition of concrete [80].

The all-in-one machine is a hybrid 3D printing machine that is the result of integrating various, different and very innovative technologies such as the cable robot, AM and SM tools, printable cement materials, and also the control software, not only of the single printed element but for the overall prototype [81]. It consists of several different parts (Figure 7.22).

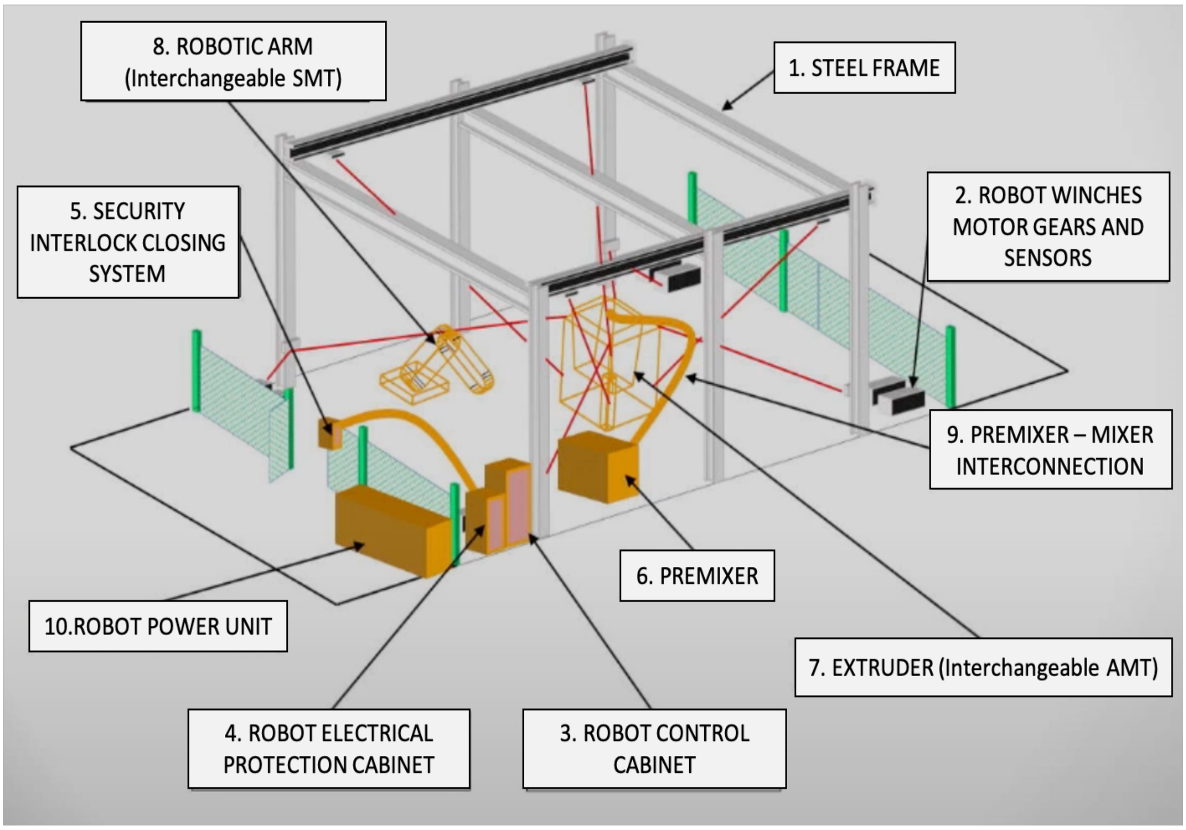

Figure 7.22 All-in-one machine. Elements of the Prototype (AM) [81].

The demonstration of all-in-one machine was done through four steps [81]:

1. Scenario proposal: Test scenarios and boundary conditions were defined. Each scenario included different typologies of construction elements and different strategies to maximize production. The integration of the prototypes in the all-in-one machine only started once machines (AM, SM, robot), materials, control software, and other necessary elements had been developed and tested at the laboratory level.
2. System prototype installation and test: The first setup was the installing of the frames, pulley elements, and preparation for safety switchers. The second set up was the installing of eight winches and control cabinet, following commissioning and testing of winches and drives, as well as cable robot installation and configuration. Next was the final setting if cable robot and simple testing to know that it worked fine. Then, AM and SM tool installation and tests of the prototype in an operational environment were conducted. The system is calibrated before each manufacturing operation to get good performance. During the first setup, it was also necessary to fix the cable platform location using a laser station.
3. Specific use case development: New designs to be manufactured by the HINDCON all-in-one machine. There was a process to transform the design in BIM to G-codes, the commands that the machine needs to print. G-codes were generated and validated. There was a manufacturing strategy to maximize productivity and tests to check that the new designs could be manufactured. Manufacturing process monitoring was a part of this step as well. The testing schedule was followed up every week with a meeting with all partners.
4. Validation of results: in conclusion, different specific use cases have been designed and developed. Very good results in operational conditions have been obtained. Analysing the performance and the validation of all results finished on time.

7.3.1.2 Netherland - Nozzle

The 3D printed concrete bridge in the Netherlands did thorough research on the type of nozzle as they incorporated a steel wire through the nozzle while printing.

Generally, a down-flow nozzle is used for concrete printing (Figure 7.20a),d)). The project conducted in the Netherlands used an integrated reinforcement cable and had to adjust the nozzle. To begin with, a down-flow printing nozzle had an incorporated cable, but the cable sliced the filament when printing and resulted in an insufficient connection between the concrete and the cable [49]. As a result of that, a back-flow nozzle was developed (Figure 7.20 b),e)). The concrete is coming from the top, the cable wire is coming from the front and unites the cables with the filament of concrete before it goes out of the nozzle from the back. This solution tolerates the incorporation of the cable into the layer without separating it. The angle of the concrete flow is the same as the cable direction movements, making it easier to place the cable. An improper design of the nozzle can have a cataclysmal impact on the interface bond between the filament layers because of the lack of fluid pressure when placing the concrete [49]. The bonding between the adjacent layers when using a back-flow nozzle is poor due to the sidewalls shaping and taking material away from adjacent printed layers. This irregularity was rectified by composing a hybrid of the down-flow and back-flow nozzle. The bond between the layers in the z-axis were enhanced by removing the bottom surface of the back-flow nozzle, making it a down-flow nozzle. (Figure 7.20c),f)). The front wall surface of the back-flow nozzle was the same for placing the reinforcement tube through where the cable penetrated the layer. The tip of the nozzle was detached so that the material from the already printed layer is not removed when printing the adjoining layer, and by that, enhanced the binding of the layers in the x–y plane [49].

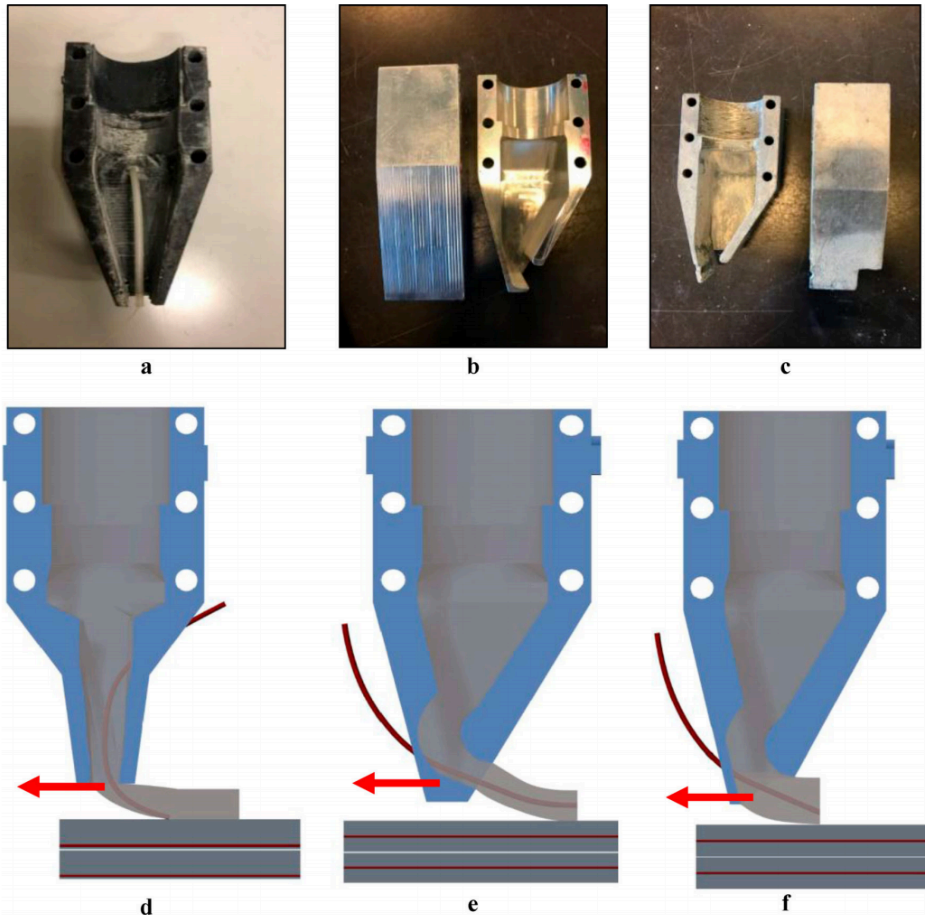

Figure 7.23 Nozzle design and concrete flow [49, p. 229].

The pump motor frequency, which controls the pump pressure, was set at 150 rpm and the speed 80mm/s [49]. It is important to have a consistent pump pressure. A change in pump pressure will influence several parameters as material rheology and internal friction of the system [49].

The print speed is adjusted after the sharpness of the curves. If the pump speed remains the same, it will result in an inconsistent layer dimension for the curves. In regards to corners, there will be more concrete in the inner side of the corner than on the outsider side due to the variance in path length. Furthermore, this will create a difference in the height (z-direction) of the filaments and can cause failure during printing [49]. Also, smooth curvature is important for this issue. This issue has been used in the design rules for the bridge [49].

7.3.1.3 Smart Dynamic Casting

Another major digital concrete technology is Smart Dynamic Casting (SDC), also known as Adaptive Slip forming. Due to the number of participants mentioning slip forming in the interviews, it was further but shortly studied.

Smart Dynamic Crafting is an adapted way of slip forming. DFAB HOUSE used SDC for automated prefabrication of concrete load-bearing concrete mullions and defines SDC as [82]:

"Smart Dynamic Crafting is a continuous robotic slip-forming process that enables the prefabrication of material-optimized load-bearing concrete structures using a formwork significantly smaller than the structure produced. In this automated process, a dynamic formwork is continuously moved at a velocity which allows concrete to be shaped during its delicate phase, as it changes from a soft to a hard material."

Slip forming is a competitive production method that has proven to be effective in building vertical structural components such as bridge towers, silos, towers, industrial pipes and stair/elevator shafts in tall buildings [83]. The construction method has been dominant when constructing concrete platforms offshore both in Norway and other countries. Slip formed structures in the North Sea have proven to have good durability, which underpins that the desired quality in these structures can be achieved through thorough planning and execution. Slip forming has developed further to be SDC and has kept the benefit from traditional slip forming. SDC has advantages on reinforcement, surface quality, and smooth interfaces. Previously a challenge with this technology has been the limited shape of freedom, which is now solved to a certain extent. One of its limitations it that it can be used for prefabrication only [84].

To eliminate basic sources of failure, SDC structures should be adapted to the construction method already at the design stage. Collaboration on buildability between execution and design is required, especially on demanding slip forming operations with heavily reinforced and possibly pre-stressed structures [83]. The requirements for competence and experience of the executive must be adapted to the complexity of the execution of SDC for the particular construction. In particular, plans for logistics of materials/concrete and a rigging plan must be in place before start-up. The actual execution must also be described. The challenge often lies in how to organize and carry out different activities for the different actors. A suitable concrete is an important prerequisite for a successful casting. The concrete properties will affect how a sliding layer is formed between the slip form and the concrete itself. This sliding layer consists of the concrete matrix (fines, cement, and liquid), and the matrix in the sliding layer affects the sliding ease of the concrete, especially during the period before and during the solidification [83]. Managing solidification is a key issue. The setting time must be in accordance with the desired speed of the slip form. The surface quality of the concrete is crucial for the durability and design life of the construction, especially in harsh marine climates [83]. SDC requires expertise and experience to ensure that the operation is carried out safely and with the right quality.

7.3.2 Concrete properties

Figure 7.24 summarizes all the important requirements for concrete properties for the concrete.

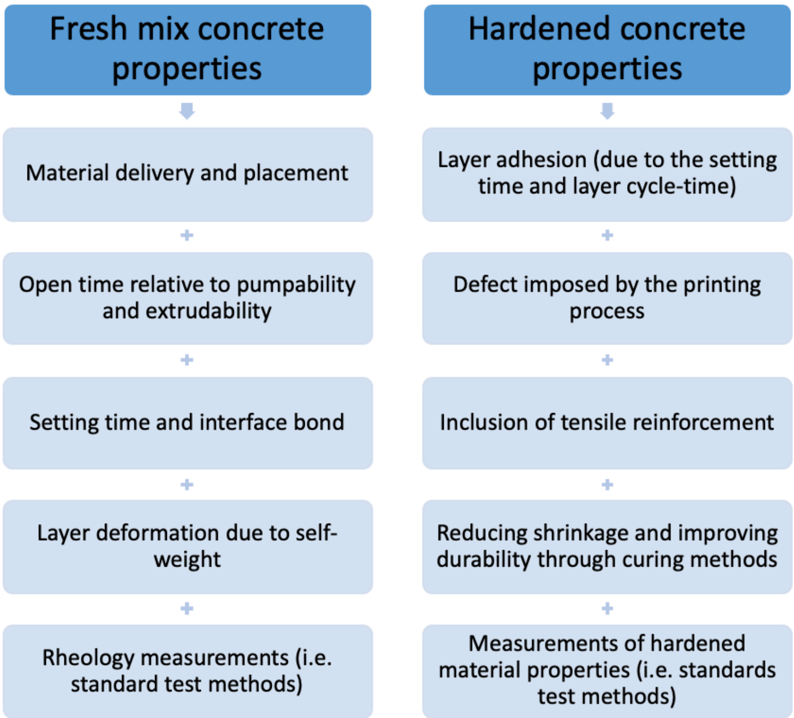

Figure 7.24 Summary of Concrete Properties Requirements [85] [84]

Fresh mix concrete properties

Compared to traditional casting concrete moulds, 3D printed concrete is associated with multiple parameters management [42]. Understanding and managing these parameters is necessary to achieve the desired quality. The fresh concrete mix needs to be printable, pumpable, and buildable within the open time. Lim et al. defined the four factors as [70, p. 266]:

i. *Printability – The ease and reliability with which material is moved through the delivery system.*
ii. *Pumpability – The ease and reliability of depositing material through a deposition device.*
iii. *Buildability – The resistance of deposited wet material to deformation under load.*
iv. *Open time – The period where the above properties are consistent within acceptable tolerances.*

Printability, pumpability, and buildability must be balanced in the open time zone, which is also referred to as a window, where all properties are consistent within acceptable tolerances [86]. Figure 7.25 shows an illustration of the graphical depiction of different fresh mix requirements relative to the hypothetical window (open time) made by Bentz et al. [86].

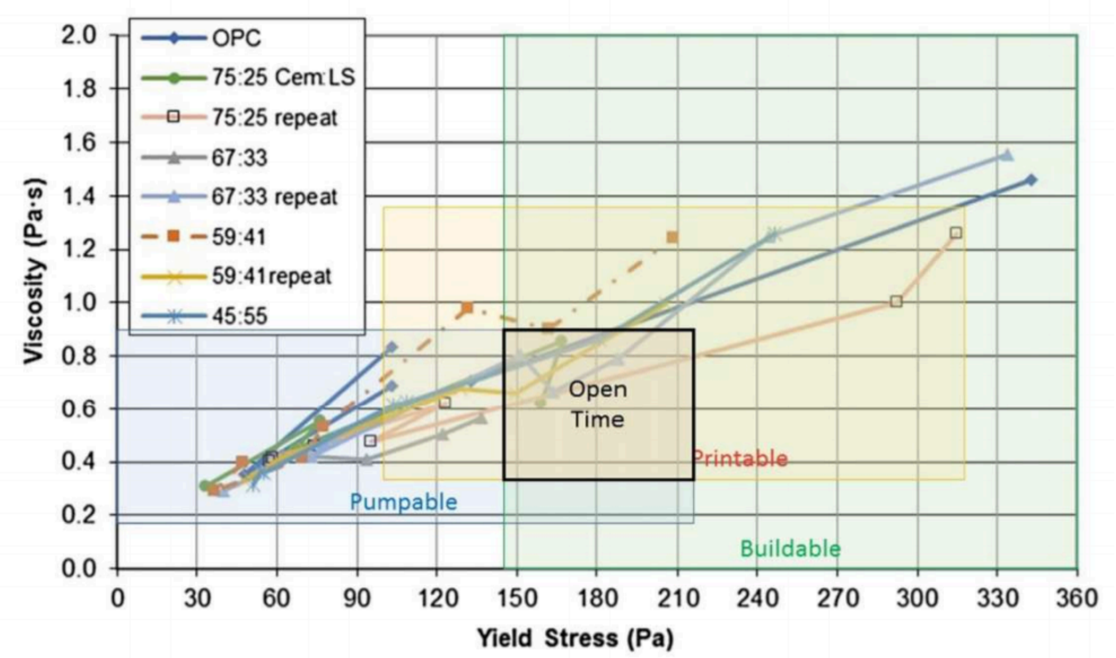

Figure 7.25 Schematic showing hypothetical open time window [86, p. 217].

The concrete - when leaving the print nozzle - should stand on its own, i.e., do not collapse, which in itself constitutes a paradox to the desired pumpability [42]. The setting time, cycle-time, and the total time elapsed between layers are essential factors. If the setting time is faster than the cycling time, there will be a cold joint between the layers. But if the cycle time is faster, it can lead to deformation and possibly create instability [85]. The concrete can then build a fast strength to carry the next layers, which will be printed on top in a relatively short time [42].

Hardened concrete properties

Density, compressive and flexural strengths, tensile bond strength, and drying shrinkage are important hardening properties for 3D printing [87]. The hardened concrete properties are affected by interfacing bonds between layers, voids, geometry, tensile reinforcement, curing, shrinkage, and durability [42].

The concrete must avoid rapid drying so that no adhesion and moulding between the layers is achieved [42]. The layer adhesion can be affected by several variables but, most importantly, printing time and material setting time [88]. The balance of the two variables is decisive for the overall performance of the concrete, so it will not be reduced [85]. The bond between filaments and between layers influences the hardened properties of concrete components [87].

Material stiffness is essential due to the ability to support the following layers of concrete [85]. For material stiffness, the setting time is crucial because if the printing is too close, the initial setting time may cause tearing and voids, so the parts have to be sufficiently dense [87].

Tensile reinforcement is vital due to concrete, naturally being weak in tension. Larger construction applications that need to withstand tensile stresses due to various loads are dependent on tensile reinforcement [85].

For the concrete to gain strength and properly hydrate, it is important to have the right time and method for curing [85]. It is essential to find the most suitable approach to inhibit the evaporation of surface moisture, hinder shrinkage, and enhance the concrete's durability.

7.4 Challenges with 3D printed construction

There are several areas of intervention in regard to 3D printing Technologies: Certification, Skills and education, Communication, Safety, Financing, Standardization, Cross-regional and international cooperation, and Intellectual property [30]. Figure 7.26 shows the categories for the main challenges.

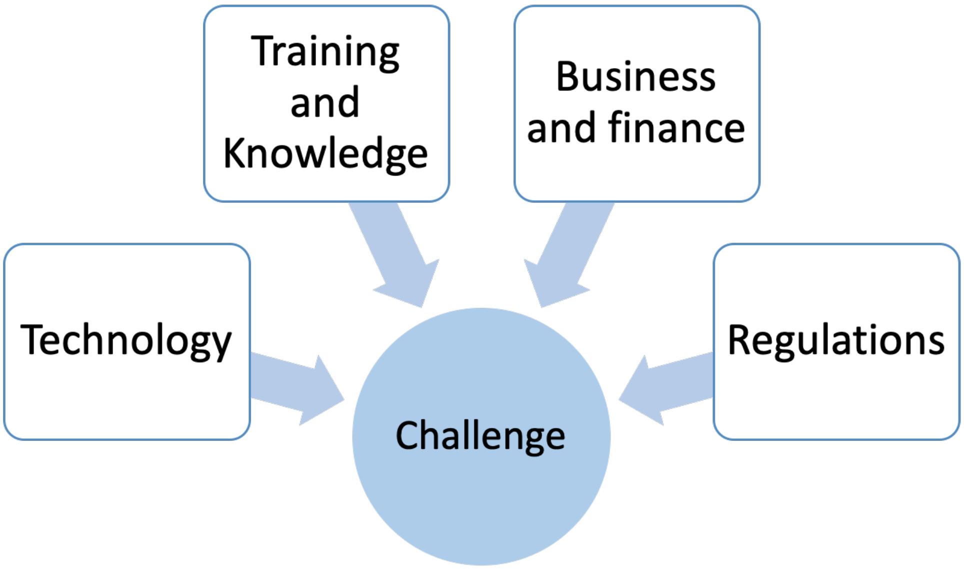

Figure 7.26 Challenges with 3D printed concrete structures.

7.4.1 Technology

Challenges with technology include new materials, better material quality and reliability, faster and cost-effective production, and cyber implementation [30].

One of the greatest challenges facing additive construction is to up-scale existing additive manufacturing technologies [69].

The size of the equipment can be a challenge in different ways:

- Storage of the printer on-site [89].
- Transportation – moving the printers to-and-fro the site [89].
- Moving the printers around with heavy, rail-like cranes is expensive and time-consuming [32].
- A trade-off between scale and speed as large printing remains slow – their size constraints standard 3D printers [36].
- Resolution problems (rough, uneven results) [36].

- A large workspace is wanted to print large parts and also a high printing accuracy. A problem to account for is a collision between the printed parts and other objects in the environment, e.g., a cable robot must deal with cables coming from different corners of the frame.

The weather and climate on a construction site are, to a certain extent, an unpredictable factor. The robot has to withstand the conditions on the construction site. I should be robust enough to handle precipitation, drought, frost, and wind, etc. It can also create assets that improve resilience against e.g., natural disasters [36]. Extra time may be necessary on-site if the units are printed in-situ [89].

There is a higher risk because any errors in the digital model can result in severe consequences on-site during the printing [89]. It is challenging for quality control to be perfect [26].

Challenges with the robots are the bearing payloads which depends on whether the concrete tank is full or empty, and the difference in the payload can be significant [78].

One of the significant challenges is that printing with concrete is an entirely new and radically different way of using concrete [42]. The majority of projects around the world using 3D printed concrete use a trial and error approach, i.e., one tries to achieve a good result and perhaps obtains a suitable method for a concrete printing for a specific task. Of course, this is not appropriate in all construction projects. Several of the 3D printers that have been developed so far have been for a certain type of material. A limited number of materials can be used for the same printer since it might not be able to print the required various materials [89].

The biggest challenge for the concrete properties is to fulfil all the requirements (Figure 7.24). There are several challenges related to 3D printing for concrete in a fresh state. The time during a material to be used and its influence on pumping and extrusion is a challenge. The concrete must not be bleeding [70]. The setting and layer-cycle time, the time required for one build layer, vertical build rate, and deformation as successive layers are added [85]. There are also some issues related to geometric conformity in regards to minimum feature size and tolerances, hatching, and creating fully dense components material and process modelling and simulation; and creating overhangs [85]. Surface finish, the ribbed finish, is also a challenge [70]. To control this, it is also essential to evaluate the printing speed [70]. Poor printing could result in a lower density with voids located principally at the intersection of filaments [87].

Filaments must bond together to form each layer. The bond between filaments, as well as between layers, influences the hardened properties of concrete components. The bond strength between the layers is critical, creating potential flaws between extrusions that cause stress concentrations, but is greatly reliant on the adhesion. A careful balance is required to keep the materials adequately open for adhesion but develop enough rigidity to support its self-weight. The tensile bond strength has been tested and is unavoidably reduced as the printing gap between layers increased [87].

There are several challenges related to 3D printing for concrete at hardened state. Bulk density and under-filling, tensile reinforcement, shrinkage and durability [85]. The layering process can introduce small linear voids in the interstices between the extruded filaments, meaning the layered structure is likely to be anisotropic as voids are formed between the filaments, weakening the structural capability [87].

High strength in compression and flexure, and tensile bond, is a central goal in developing the printable concrete [87]. The hardened properties are inevitably affected by any anisotropy in the layered structure of freeform components. A reduction in compressive strength depends on the orientation of the loading relative to the layers. The lowest strength occurs when loading in planes parallel to the layers [87]. In terms of tensile properties, the flexural strength has been tested to significantly higher than the mould-cast control when tension was aligned with the extruded filaments, but the flexural strength was significantly reduced when loaded to cause tension between (perpendicular) the layers [87]. A similar trend has been observed in the measurement of direct tensile strength [87]. Also, a low shrinkage is crucial as the freeform units are built without formwork, and that could accelerate water vaporization in the concrete and result in cracking [87].

Rheology measures, measurements of hardened material properties, and quality control are significant challenges at all stages [85]. As weather and climate is an unpredictable factor, it makes the control of cooling or setting of materials difficult.

Adding reinforcement at part of the 3D printing process is not easy, but it is important. The steel will influence the diameter of the layer thickness, and so the extrusion diameter, which again turns into a domino effect where important factors are affected [85]. Reinforcement may also be necessary perpendicular to the print layers, which is a more significant challenge. Placement of reinforcement is a big challenge, particularly when bespoke geometries are required [90]. Also, the incorporation of reinforcement is a challenge with this technology as steel rebar must not impede the movement of the printer head [84].

In some cases, fibre reinforced concrete is used to improve the ductility of the concrete [91]. Fibre reinforcement faces several challenges. First is even application of fibres into the concrete, lack of which could lead to clogging, segregation, and non-uniform distributions (amount per volume and direction). The second is ensuring the effectiveness of fibres across interface boundaries. Enhancement of the bulk material properties makes little sense if the governing interface properties are not equally improved [90].

Using fibre reinforced concrete faces challenges in post-processing and porosities. Post-processing needs to be done to remove the support materials and maintain dimensional accuracies. The presence of porosities inside or on the surface of the part leads to more stress concentration and eventually reduces mechanical strength. Raster angle, infill speed, layer thickness, and nozzle temperature have a significant effect on the porosity level, shrinkage, and microstructure of the material. These process parameters have a direct impact on the ductility, toughness, Young's modulus, and strength of the material [92].

Having a cable wire together with the extrusion of concrete from the nozzle could increase the tensile strength in the vertical direction. Still, it will be demanding to manage the force of the steel staple penetrating the filament. The fresh concrete could be destroyed or deformed if the force of the penetration is too large. Then again, if the force is excessively little, penetration might not happen at all [91].

Both embedding reinforcements and post-tensioning reinforcement bars are added manually. Printing structures that have straight hollow voids for the post-tensioning reinforcement bar would hinder the flexibility of the design [91].

7.4.2 Training and knowledge

3D printing in the construction industry is still at an early stage of development [36]. For 3D printing to be implemented, the construction industry has to be prepared for it. Education and training are essential, and there should be appropriate modules for curricula and training in the job [30]. Cross-regional and cross-sectorial collaboration in AM should be encouraged for smart specialization [30].

There is a need for an architectural paradigm shift. Current construction design approaches must be upgraded in response to the new capabilities offered by additive construction [71]. Also, it is a need for a holistic design process. The design process must promote synergy facilitated by real collaboration between architects, engineers, and clients [71]. Also, there is a need for rational designs. The design process must adopt a rational approach to the opportunities available and the new constraints governing building design, structural engineering and the construction method [71].

Many of the architects and designers have shown little interest. The construction industry is tradition-bound and does not quickly adopt new concepts such as additive manufacturing. Even when architects and designers are innovative and produce new designs, it still has to be built, and many construction engineers face a challenge [26].

One barrier to innovation is the conservatism of the industry that creates difficulties for new technologies related to regulations, investment, and attracting clients [36]. The transformative technology is facing scepticism from project developers, designers and end-users. It seems too good to be true for those with a conservative mindset [36]. The scepticism can be worked on by trying to educate the market and providing vivid proof through creating prototypes [36]. An opportunity to "fight" the conservatism is to engage in various collaborations. An interdisciplinary team of experts in concrete printing and 3D design can together revolutionize parts of the industry with creative thinking. It enables partners and collaborators to extend their knowledge by exploring and developing solutions [36].

7.4.3 Business and finance

With regards to business and finance, using 3D printing technology demands a new and successful business model and business collaboration strategies [30]. Currently, 3D printing is mainly adaptable to low-volume, high-value parts [36]. It remains to be seen how fast companies will overcome the primary technological difficulties, and whether they will be capable of bringing down costs and gaining economies of scale [36]. Project delivery can be a challenge because for large scale construction projects there have to be a reduction in time, cost and uncertainties [52]. Affordability can be a difficulty as the printers must lower the costs to generate inclusive communities [52]. Industrial access to technology at a lower cost is important, in particular for small and medium-sized enterprises (SMEs) [30]. Lifecycle performance can be considered as a challenge because it has to increase total value across the entire lifecycle and reduce cost [52].

3D printing is not as well suited for all projects. If an uncomplicated standard bridge with straight lines and a simple steel plate is to be built over, printing will probably not be worthwhile [54].

Conventional manufacturing companies and plant leasing businesses could endure as their products are no longer needed [89]. 3D printing could reduce the number of employee numbers in the industry since the 3D printer does most of the work [89].

It can be a hurdle to generate end-user orientated assets that enhance well-being and are flexible for changing property [36]. Intellectual property rights (IPR) can be a challenge due to ensuring protection and market opportunities [30].

7.4.4 Regulations

Standardization in the industry and certification is a challenge [30]

A significant impediment is the lack of specific regulations for 3D printing. No testing standards currently exist to specify quality assurance or quality control procedures for measuring concrete properties. Most standards and building codes do not mention 3D printing. [36].

Bureaucratic factors have been hampering the adoption of additive manufacturing in construction with slow establishment into building standards and broad regional variance in regulations [26]. Many potential customers are not informed or unconvinced about the safety and durability of 3D printed buildings [26]. It can also have something to do about user engagement [30].

Authorization is absent. The government could be involved at the beginning of the design phase to enhance the dialog but also ease the review process [36].

7.5 Opportunities with 3D printed concrete bridges

There is great potential in automating the production of concrete structures using concrete printers. First of all, there are some exciting productivity improvements. 3D printing in construction projects, whether it be bridges or other types of structures with different materials, has excellent potential.

Figure 7.27 below compares 3D printing with the traditional construction and demonstrates the advantages it could give when the obstacles are overcome [26].

		3D-printed vs. conventional construction	
Costs	Labor	Slightly lower	Overall savings as 3D design becomes easier and as onsite workforce is reduced
	• Architects, designers, engineers	Slightly higher	Need for training to adapt to the new technology, methods, and possibilities
	• Installation	Significantly lower	Printers' ability to work autonomously, so less supervision is needed, but initial training is required
	Equipment	Equal	High cost of 3D printers currently, but reduced need for heavy construction machinery
	Materials	Slightly lower	Expensive specialty concrete mixes and materials, but fewer materials are needed and far less waste is generated
	Logistics	Equal	Need for transporting printer to the site, offset by reduced use of other machines
Non-cost factors	Delivery	Significantly lower	Printers' ability to operate 24/7; avoidance of delays related to deliveries and coordination
	Environmental impact	Significantly lower	Avoidance of waste and reduced need for materials
	Project risk	Slightly lower	Technology risks (e.g., interruptions) but fewer hitches related to workforce, delivery, and coordination
	Accidents and safety hazards	Significantly lower	Fewer accidents, thanks to autonomous construction process with little human involvement
	Quality issues	Significantly lower	Increased accuracy of 3D-printed construction and enhanced appearance as the technology progresses

Significantly lower | Slightly lower | Equal | Slightly higher

Note: The comparison assumes that 3D printing technology has reached maturity and is included in building codes and regulations; accordingly, approval and testing costs are not included.

Figure 7.27 3D Printing in Construction Offers Many Advantages [26].

7.5.1 Technology

The integration of AM technologies in the construction sector has many advantages [71]. Algorithm-based or generative software can be used to optimize the design, whether it is buildings or components as lightweight beams [52]. For faster and accurate construction – a 3D printer transfers the digital model into a physical one; errors that arise can only be due to faults in the digital model or the materials used [89]. Using printing robots gives the possibility for real-time control and predictive maintenance [30]. 3D printing makes it possible to create three-dimensional components by automatically applying layers upon layers of material based on digital models [44]. There is total process control while manufacturing layer by layer any structure. It can be checked at any second of all variables of the constructive process [71].

The introduction of concrete as base material gives extra durability and strength, and large-scale 3D printing makes it possible to create parts with total freedom of form and design [44] like the manufacturing of new structures, complex shapes, integrated channels with flexibility, and adaptability [71]. It produces concrete structures that are something more - and can do more - than today's standardized concrete structures produced on assembly lines [42]. 3D printing in controlled environment of a precast factory simplifies automation [49]. With 3D printing, it is possible to build more accurately and with a better final appearance [71]. The most promising solution for a representable finish of printed structures is to supplement the additive process with a conventional subtractive process like surface milling [26].

Moving the printers with heavy, rail-like cranes is expensive and time-consuming. Light frames that hold the printers up with cables have therefore become a preferred solution [32]. Small, lightweight printer robots can climb the structure as it is being built. As the printers move, the technology can be applied to larger constructions.

3D technology makes it possible to create parts for architectural and urban design that have previously been impossible. 3D concrete printers provide completely new architectural solutions - where technical and sustainable challenges lead to a higher degree of construction and, thus, architectural expression [42]. The technology also makes it possible to 'scan' memories and then make accurate copies that can be made available to most people [44].

7.5.1.1 Concrete

The potential advantages for 3D printed concrete structures are many. The coupling of a layered construction process with solid modelling techniques will give greater design freedom [93]. Printing concrete has the advantages of both self-compacting concrete and sprayed concrete to meet the critical requirements of a freeform construction process. The performance is dependent on the ability to extrude consistent filaments. The use of wet-process concrete principles can ensure that fresh concrete is moved effectively through the system without blocking [93].

The developed 3D printed concrete bride in the Netherlands was given the name Weber 3D 115-1, was considered as a mortar. The mortar's material properties did not fulfil the standard concrete designation (C30/37, etc.). Hence comprehensive research was carried out: compressive, flexural and uniaxial tensile strength, modulus of elasticity, density, and directional dependency [49].

HINDCON created a range of concretes for AM [94]. The formulation strategy development started with self-placing mortar, which is very fluid and easy to pump, and then to modify it by adding an additive just before the extrusion to make it printable. Concrete behaviour was studied for each formulation, as illustrated in Figure 7.28. It is possible to start characterization early to know if it is printable or not. Characterization was done during the first minutes with a scissometer test, and after with a compression test. It made it possible to know all about the concrete behaviour during the setting time and to know how to print, in which speed, and for how long, with the mortar [94].

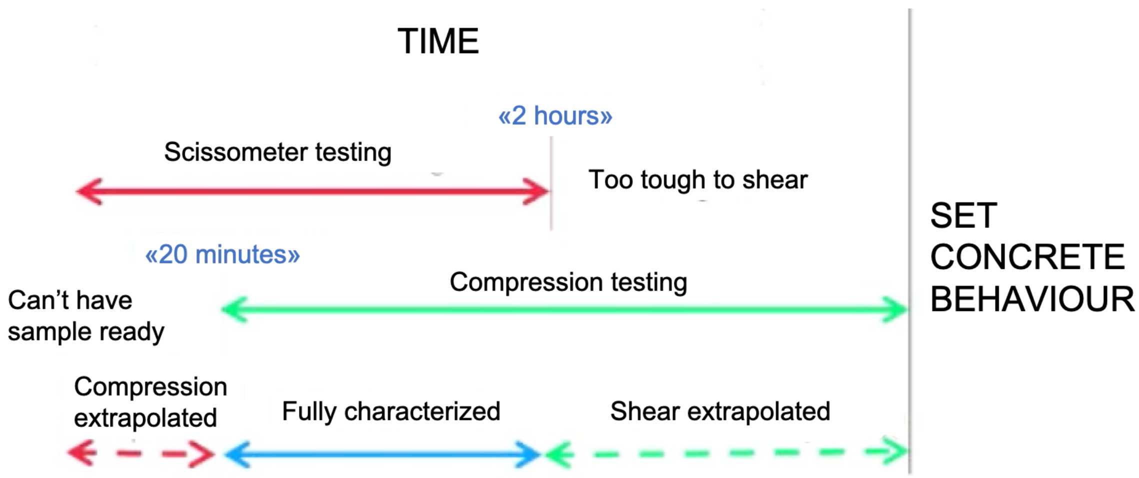

Figure 7.28 Young Age Characterisation [94].

Another test to characterize mortar is the Pull-out test, which tests the influence of waiting time between two successive layers [94]. Results showed that, with an accelerator agent, if it is waiting for more than 15 minutes, it will have a conjoint between the two layers; it can create a lack of addition between the layers [94]. Instead, with the viscosity modifying agent (VMA), the second type of additive, there is more time to deposit the second layer. With this test, it is possible to design the right concrete depending on the speed [94]. So, you should use an accelerator for high speed and VMA for long printings. Also, with the 4 points bending test, it was found that: strength and modulus are globally preserved for longitudinal samples but significantly reduced transverse direction (decohesion between layers) [94]. Formulations were implemented with an accelerator but developed with a VMA as well, so mechanical properties and structuration COULD be de-correlated [94].

For the HINDCON project, various axes were considered (insulating concrete, support material, depolluting concrete, etc.) [94]. Tests had been made on carbon fibre reinforcement, but those materials could not be implemented in this version due to the robot's extrusion head. It was a strong focus on UHPC based, C60, and low-cost concrete. UHPC had the most demanding applications in terms of production rate and shape complexity, it has small particles for a very smooth finish [94]. The tests reached at least 100 MPa in compressive strength at 28 days and a very high level of early-age strength development [94]. The shear resistance after 30 minutes was 38 kPa (Figure 7.29).

A UHPC was successfully developed for a digitally controlled printing process that can build architectural and structural units without formwork [87]. The mechanical and thermal performance of UHPC is considered superior to standard concrete [91].

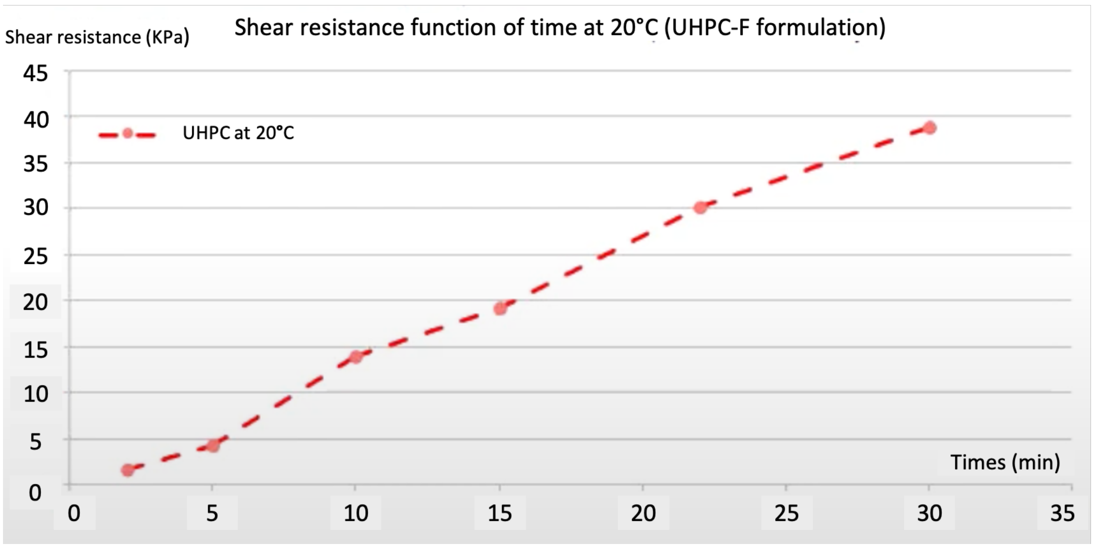

Figure 7.29 Shear resistance, UHPC [94].

The C60 concrete developed for the HINDCON project had a more ordinary grade of mortar with larger particles. It is suitable for any application with moderate aesthetic and performance standards [94]. The level of compression strength was tested to be around 60 MPa, and the shear resistance after 30 minutes was only 16 kPa (Figure 7.30) [94].

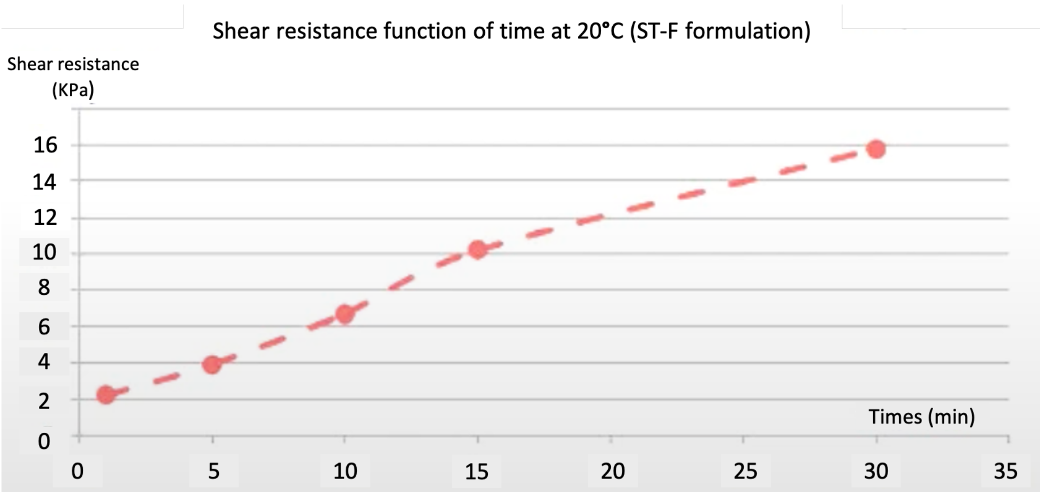

Figure 7.30 Shear resistance C60 [94].

The third concrete in the HINDCON project was the low-cost formulation, which is a cheaper and more environmentally friendly formulation [94]. It was not tested in the HINDCON robot because of the larger particles that can break the extrusion head. It had a low performance around 20 MPa ultimate strength, and the shear resistance after 30 minutes was almost 16 kPa (Figure 7.31) [94].

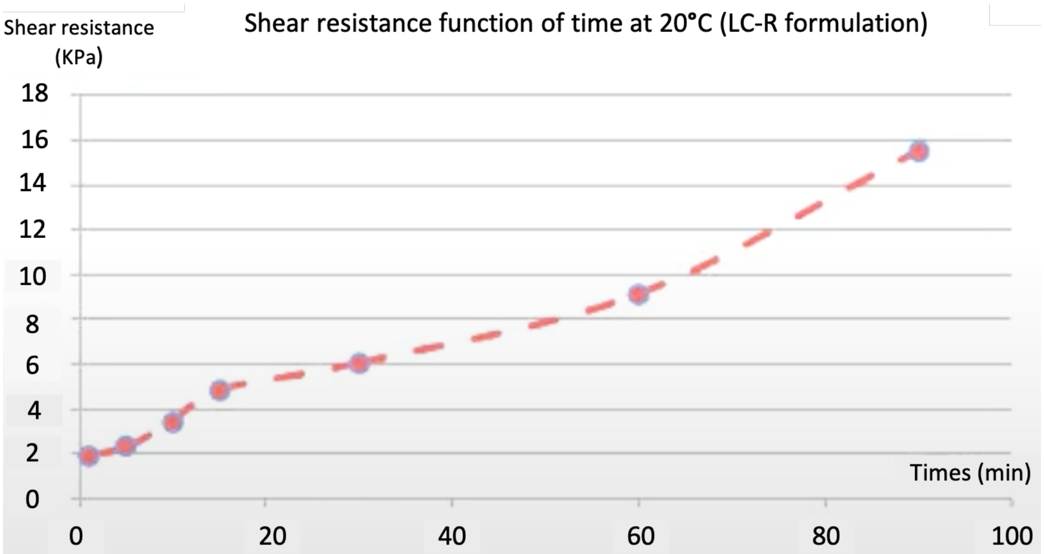

Figure 7.31 Shear resistance, Low-Cost Formulation [94].

Another research project testing hardened properties of high-performance printing concrete showed that the concrete in the mould-cast state had high strength (107 MPa compressive strength and 11 MPa flexural strength), low drying shrinkage, and a density of 2250 kg/m3 [87]. The printing process increased the density with 100kg/m3. Increased density might be due to the moderate vibration of the concrete container, and the little pump pressure in the extrusion process that seemingly reduced the number of voids [87]. The high density is further associated with the grading and homogeneity, resulting in great strengths and low shrinkage [87].

7.5.1.2 Reinforcement

There are several opportunities from reinforcement to be implemented with 3D printing using integrated reinforcement or print outer shells to use as mould formworks.

The filament direction can be used to reinforce along tool paths, which can be designed to act in the most optimal direction, which may not be in a traditional grid format [85]. The arbitrary creation of form is a key value-added driver for the technology. So computational methods that can analyse and optimise structural capacity will need to do so within the constraints of manufacturing methods that incorporate reinforcement [85].

The issue of reinforcement can be approached by printing hollow structures to install rebar afterward, with infilled concrete creating the attachment to the printed structure. It renders the method as basically a stay-in-place formwork production system [84].

Integrated reinforcement as fibre reinforcement and wire is an option. 3D printing can initiate a completely new area of utilization for steel fibre reinforced concrete [84]. Steel fibre reinforced concrete can be infilled, or channels to enable reinforcement by post-tensioning can be printed [84]. It is possible to use the extrusion to orient fibres to align with the filament, thus increasing its tensile capacity [85]. Mechanical tests reveal that using glass fibres can effectively enhance the flexural and compressive strength while reducing flexural deflection. The alignment of fibres to the printing direction have been observed and can additionally increase the structural performance [95].

The direct in-print entrainment of reinforcement cable into the concrete filament during printing is the most advanced method of reinforcement [96]. With a wire reinforcement into the extruded bead, it avoids additional automation of placement with the layer as it is extruded [85]. The reinforcement wire coil would provide longitudinal tensile strength and ductility through the layer interfaces [96]. The reinforcement cable should be sufficiently strong and ductile, but also highly flexible to allow it to follow all 3D free form lines that can be produced with the concrete filament [96].

Research on 3D printed steel reinforcement for digital concrete construction is ongoing, with varying results, but the overall performance could be rated as satisfactory [97]. It can be a solution to the reinforcement problem if one can print the reinforcement before the concrete is printed.

The concept of directly entrained cable reinforcement is a feasible reinforcement method that can achieve performances similar to conventional reinforcement in cast concrete [98].

3D printing can be combined with traditional construction methods [52]. Conventional reinforcement can be implemented with post-placement and post-tensioning [85].

For the 3D printed concrete bridge in the Netherlands, the 3D printed elements were rotated 90° and pressed together by post-tensioned pre-stressing tendons to optimize the section design and overcome the poor bending moment resistance of unreinforced concrete [49]. Pre-stressed tendons were placed in the opening of printed components, stressed anchored in the ends before it is released. Simply compression remains in the section, and no supplementary reinforcement is needed, hence the lack of tensile strength is solved. Furthermore, the tensile capacity becomes irrelevant as it depends on the interface interval time and it could be lower than the bulk material tensile strength [49]. The cross-section is stressed in compression only at the design load in its entirety [49]. The principle is illustrated in Figure 7.32.

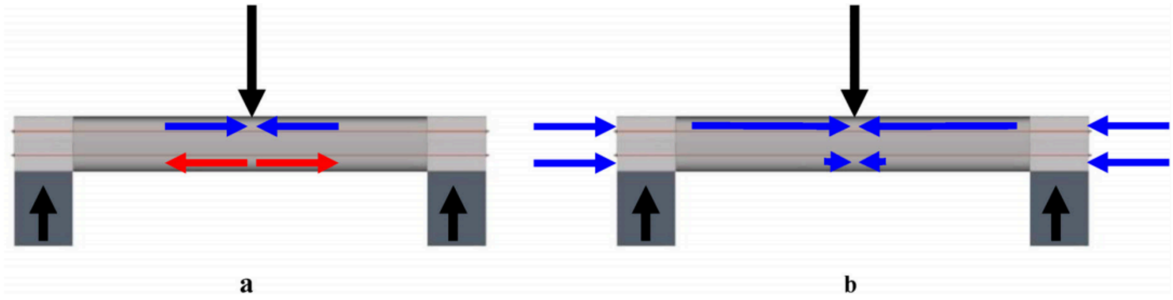

Figure 7.32 Principle of pre-stress applied to a structure loaded in bending. (a): no pre-stress, only bending, (b): pre-stress and bending: the tensile stress in the bottom of the structure is eliminated [49, p. 224].

The compressive strength was especially significant for this project because the pre-stress force controls the bending moment resistance. The shear resistance of the concrete cross-section must be known to withstand the external shear force [49]. The design with integrated reinforcement cables can operate as stirrups. However, their presence is not assessed in the shear resistance yet since their implementation regarding shear resistance has not been identified. The shear strength is derived from the tensile and compression strength based on a Mohr–Coulomb failure criterion, and not from a direct shear test [49].

The concrete stiffness must also be known. Pre-stress loss occurs when the structure shortens under pressure. Stiffness of the section controls the amount of shortening, hence the section area and modulus of elasticity. Shrinkage and creep must be compensated for as it slowly diminishes the pre-stress load over time [49].

The final cross-section of the bridge is 3440x920 mm [49]. As a result of relatively low tensile strength, structural calculations revealed a necessity for sufficient shear capacity, which resulted in the cross-section shown in Figure 7.33. b) is the final design of the cross-section, which was optimized after the testing of the cross-section in a). The print path length was reduced with about four percent, hence the printing time and material use as well [49].

The unique production method of 3D printing means that the concrete structure's design can be done differently than with traditional casting. Among other things, rounded corners can take up the compressive and tensile forces in a completely different way [48].

The cross-section consists of a top and bottom flange, curved and straight respectively, and grants the bending moment resistance with the pre-stress force. The share force and bending moment is taken care of by having a series of connected bottle-shapes type of design in between the flanges with a combination of a connecting straight line at the underside (Figure 7.33) [49].

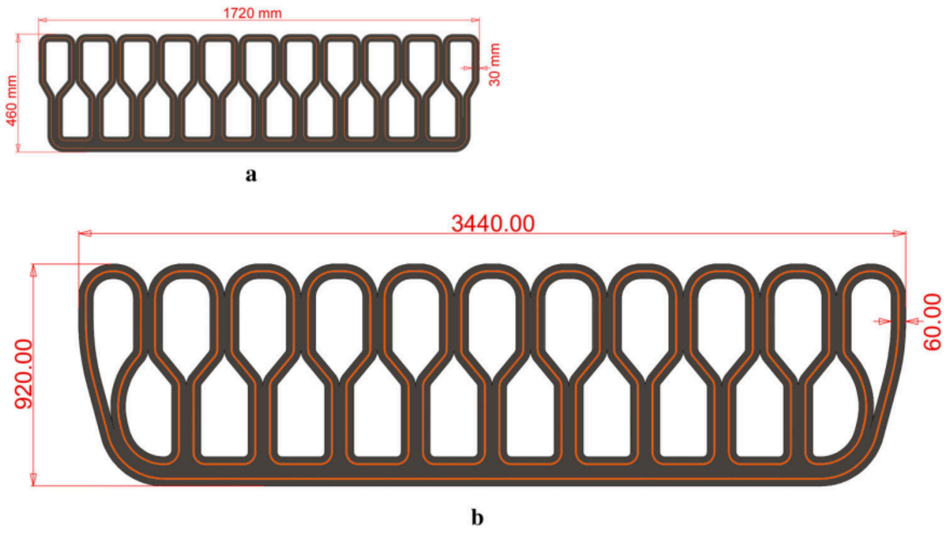

Figure 7.33 Print paths of the 1:2 scale model for testing (a) and the actual bridge section (b). The optimised pattern of the latter with regard to the former saves 4 percent of print path length [49, p. 226].

The pre-stress load was managed for the complete section to stay in compression under the design load, also in the ultimate limit state. The centre of gravity of the tendons is just beneath the centre of gravity of the concrete section to counterbalance the impact of the self-weight. The tendons can be re-tensioned later if creep and shrinkage pass the studied values. Hence, the required degree of pre-stress can continuously be managed [49].

Acknowledging that the design is the main goal and that the materials support the realization of the production, the vision is to motivate and guide up-coming research efforts in 3D concrete printing [85].

7.5.2 Business and finance

There is great potential in automating the production of concrete structures using concrete printers. Fully integrated digital construction models and tools contribute to a highly precise method of producing structures with minimal costly rework and waste [36]. The technology can be used for unique and demanding building constructions, it can be used in façade work, and in general, this technology works very well with BIM. This means that you will have unique opportunities to make both the planning and production phases in construction projects a fortune [54]. 3D printing technology involves predictability and speed of delivery [26]. Decreasing the manufacturing and production time, with a manufacturing process automation, obtained functional structures faster with a lower cost [71]. Production time for some buildings could drastically decrease from weeks to days [36]. Once the technology is developed and matured, customized concrete structures can be printed at a significantly lower price than today [42]. For project owners, including government and industry clients it is increasingly important to reduce costs [31]. It is important to note that these are tailor-made concrete structures - concrete structures that can potentially do more than, e.g., today's standardized concrete elements. Compared to these, the price is hard to compete with. The custom-made concrete structures take advantage of some of the new possibilities of 3D printing [42].

Customized components could be provided at a much lower cost with 3D printing [36]. No mould shall be produced, which may be expensive to build in the case of unique manufacture. The form does not cost (with 3D concrete prints) more money. The more free and exciting design gives new architectural possibilities and a more individual construction [42]. 3D printing allows for the creation of purpose-built shapes that cannot be provided by any other system. It assures productivity gains of up to 80 percent for some applications [36].

More considerable material savings are possible. In moulds, massive structures are typically cast. But with a printer, you have the opportunity to put out material only where it benefits. i.e., it is possible to work with cavities in the constructions, which makes it easier, cheaper, and, above all, makes material-saving constructions. It is also possible to think of optimal structures, where only material is laid out where the forces flow in a structure. Also, it gives the ability to embed more functionality into the concrete by printing complex surfaces, such as acoustic and thermal properties [42]. At the same time, 3D printed concrete in the construction industry opens up huge savings on building materials [42] and offers the capacity to use recycled materials [31].

3D printing can lead to reduced labour cost as a 3D printer undertakes most of the job with minimal human effort [89], which, in all means, is to maximise resource use [31]. It also means it can lead to reduced health and safety risks, and labourer's accident hazards due to the increase of automation by replacing dangerous jobs on site with printing processes [89]. At the same time, it generates skilled jobs, increased employment, and entrepreneurship forming a knowledge-based economy [30]. 3D printing will also form customization and human-centred approach that induce a better quality of life and inclusive societies [30]. Other believe that 3D printing can address the concern of lack of labour observed in several European countries, i.e., it can generate more jobs than today [31].

Interdisciplinary research has fundamental value and is extremely important. 3D concrete printing will require intense teamwork with architects, materials scientists, roboticists, and structural engineers. Notable progressions in 3D concrete printing can only happen when every part brings the constraints imposed by their respective fields to the table, and a realizable solution is put forth [84].

7.5.3 Sustainability

3D printed concrete is more environmentally friendly than conventional reinforced concrete [36]. Using 3D printing enhances a better environment and circular economy [30]. The technology uses less energy and are resource efficient and also reduces the amount of waste that is produced thanks to the recycling of raw materials [44]. Also, recycled products can be used to produce the construction materials used in 3D printers [89]. By following the circular economy concept, 50 percent of the ink material can be derived from construction waste or mine tailings [36].

3D printing can reduce environmental impact during construction and operation [36]. Also, it has decreased energy consumption and waste products obtained while manufacturing [71]. The affordable solutions for energy lead to pollution reduction, green mobility, and low carbon economy [30].

According to TU Delf, by optimizing shapes causing material savings, the 3D printing technology appears to be the most eco-friendly technology in a life cycle assessment (LCA) if the weight reduction is at least seven percent [52].

If one can create new solutions using knowledge of 3D concrete printing is, e.g., minimizing material consumption with the same performance as conventional products. It is like a design studio that always develops projects based on a sustainable mindset, which is a clear market advantage in the global market [42]. The result is that 3D printing of concrete results in less concrete consumption, and therefore, the contribution to the construction's climate accounting becomes very positive [48].

7.5.3.1 Example: Environment and economy

In terms of life cycle assessment, one question was: "Is HINDCON any better environmentally than traditional construction?" To answer that question, a pillar designed by XtreeE (Figure 7.34) that was printed during the project, was chosen as a case study. It had the following properties [99]:
Height 4m; ø base=1.52m; ø top =0.68m; Volume = 619 L; Area= 6.8 m^2.

Figure 7.34 3D printed pillar [90].

Because of the size, the idea was to print it in four pieces, where each piece is hollow. As an example, transport to the construction site was set to be 100km. At the construction site, parts are assembled, reinforced, and cast with concrete to fill them [99].

The 3D printer printed the pillar. For the LCA manufacturing, production of all the elements and all the machinery needed to produce a 3D printed element, has been taken into account (Figure 7.35) [99]. For the LCA study, there are different components for the machine, the cable robot, the extruder, all the subtractive elements, the building itself, the workshop where the machine is displayed/housed, and the factory. On top of this, there was electricity needed to run the machine and the concrete itself to print. Transport, as mentioned earlier, is included. Finally, the assembly of the pillar consuming reinforcing steel and some concrete to fill the pieces. Waste or disposals e.g., concrete dust from polishing or some loss during the casting, but also the machine itself at end-of-life, some parts will be recycled, and other parts might be sent to a landfill [99].

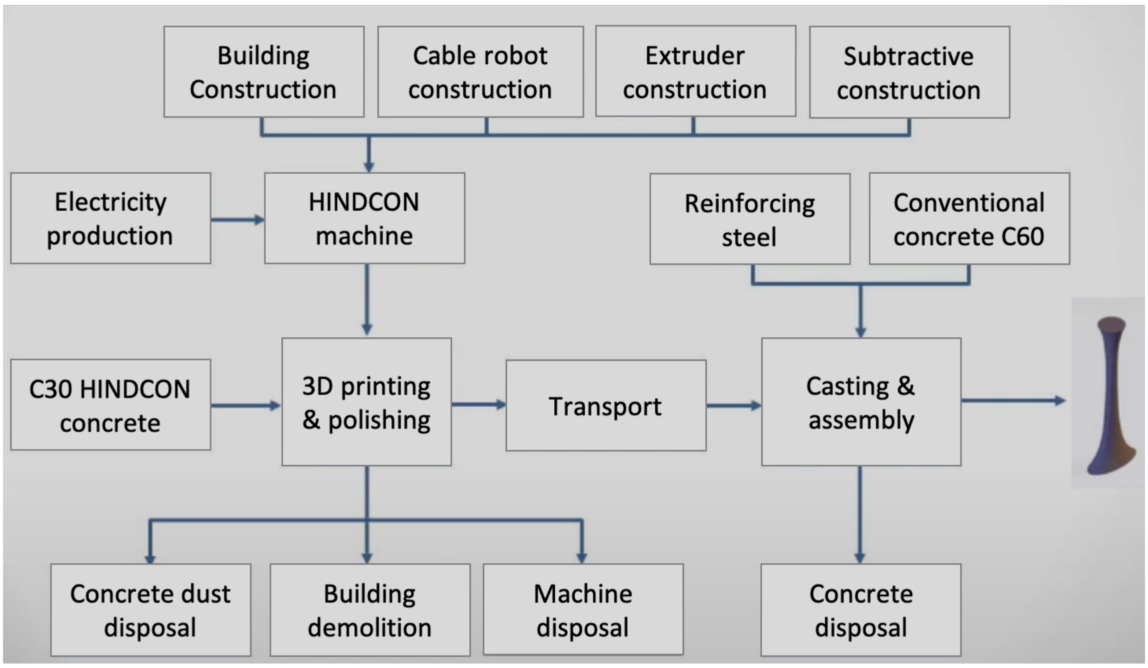

Figure 7.35 LCA of HINDCON [99].

The 3D printed pillar was compared with a traditionally produced pillar that is equivalent in shape and looks [99]. The same pillar was produced, with a tailormade disposable plastic mould, conventional reinforcing, and casting at the construction site, where the mould was discarded after use (becomes waste) [99]. The LCA components for a traditionally produced pillar are illustrated in Figure 7.36.

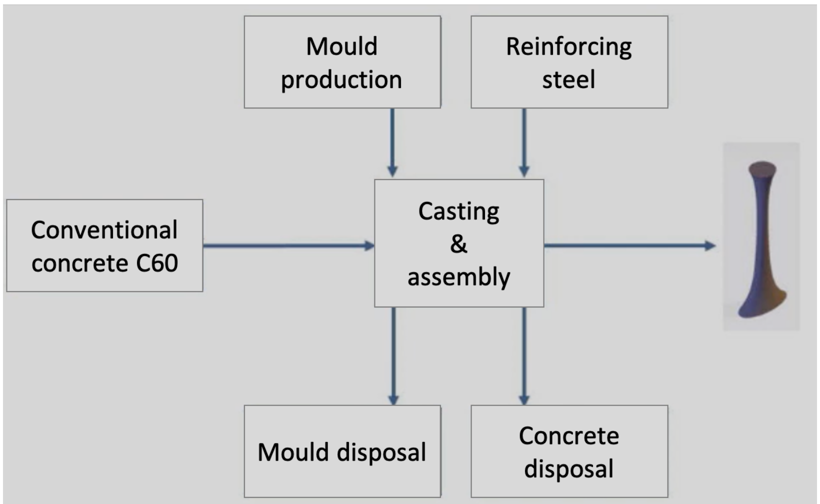

Figure 7.36 LCA Traditionally Produced Pillar [99].

The comparison is made with greenhouse-gas (GHG) emissions with a unit for analysis set as the production of one pillar (Figure 7.37). To produce one pillar, the quantified emissions quantified was 650 kilogram of carbon dioxide equivalent (kgCO_2eq) [99]. The diagram below shows how different activities in the production of the 3D printed pillar contribute to the 650kg. Firstly, it is interesting that the 3D printing activity, the part of the LCA that has to do with using the all-in-one machine has a tiny part of the impact. Only around 2kg of the 650kg of CO_2 are coming from operating the machine and the amortization of the machine. Most of the impact is related to the supply chain of producing concrete or producing reinforcing steel. It is essential to consider the transport of the printed pieces to the construction site to the customer is quite important, and it could vary, but it is not negligible [99].

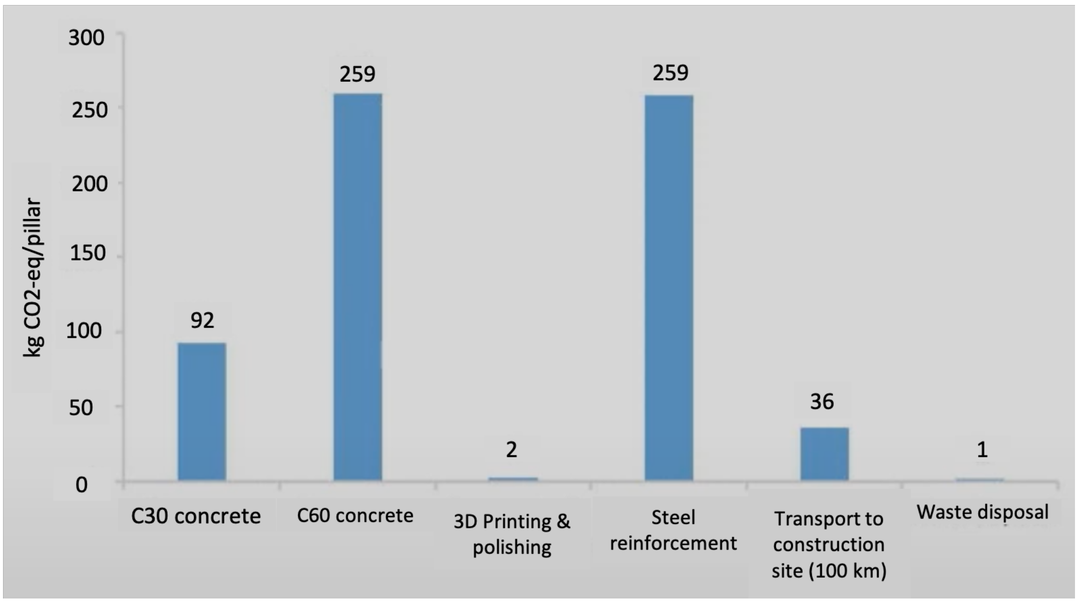

Figure 7.37 GHG emissions from 3D printed pillar = 650 kg CO_2-eq [99].

Comparing 3D printing with the traditional approach, HINDCON has between 20-25 percent reduction in GHG emissions (Figure 7.38). Both cases have the same impact coming from the production of concrete and reinforcing steel, but there is more impact on the traditional approach due to the production of the mould. For the 3D printed scenario, most of the impact is related to transport as the printing itself does not add much environmental impact [99].

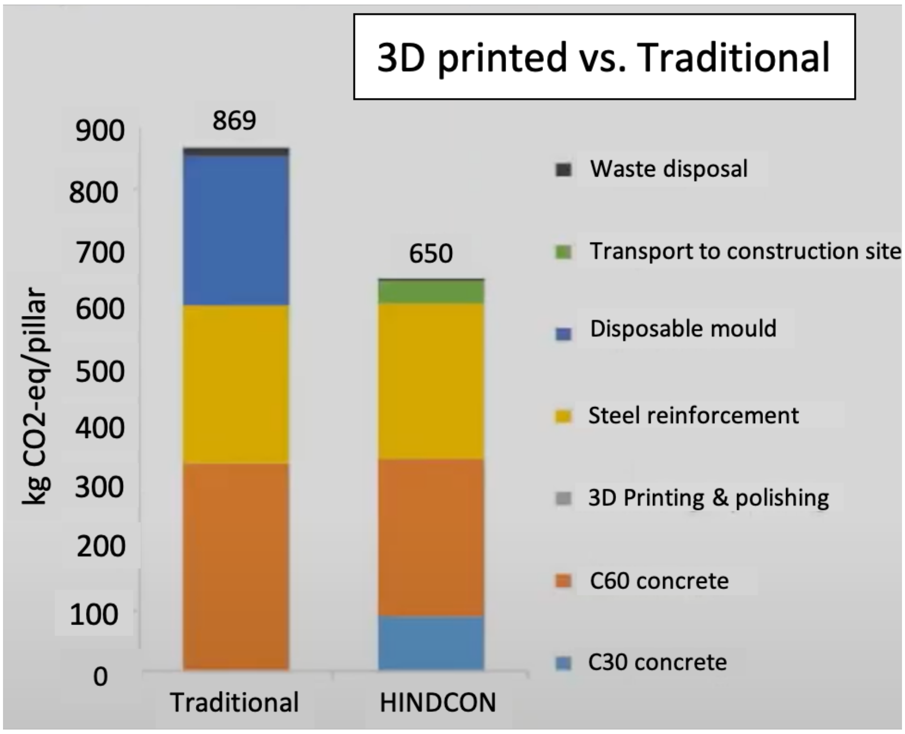

Figure 7.38 Approximately 25 percent Reduction in GHG Emissions [99].

An additional analysis was done for a hypothetical scenario on hollow pillars (Figure 7.39) [99]. 3D printed pillars need to be reinforced and cast to meet construction standards. One of the partners suggested that the printed hollow shell is structurally sound for most applications. The environmental benefits of this were looked closer into, with removing the casted concrete and reinforcement [99]. The results are showed in the third column in Figure 7.39. The environmental impact of such structures would be much lower because a lot of material is being saved. The conclusion is that most of the environmental benefit of the HINDCON technology will be in being able to make the type of hollow structures that save a lot of material and, therefore, the impact cause by producing all this material [99].

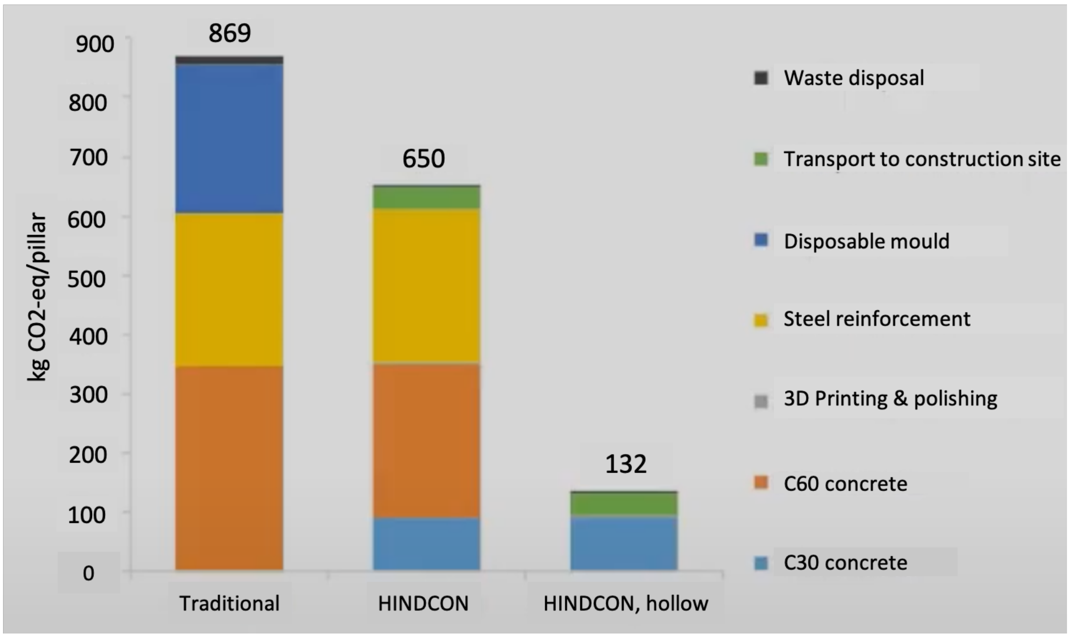

Figure 7.39 Traditional vs 3D Printed vs Hollow [99].

Printing an isolated activity has little impact. Most of the impact is in the materials (the supply chain, the production of the different materials of concrete and steel), but the transport of the finished piece is also essential [99]. Comparing HINDCON to the traditional construction, there is a velar benefit when compared with a disposable mould, but the most significant environmental potential lies in hollow structures whenever feasible [99].

7.5.4 Regulations and CE marking

The construction sector has been modernized in recent years to adapt to a changing competitive environment with e.g., BIM and now 3D printing. There are two types of innovation, production, and processes [100]. HINDCON covers innovative material, products, and operations. There are a lot of factors that are important for the result and they must be analysed. Standardization is always referring to existing products. In practice, there are some aspects that stakeholders see as a barrier [100].

Codes to test the structural properties of printed concrete is not available. The EN 206-1 is not suitable for material that cannot be vibrated. This challenge can be overcome by conducting material tests on the printed concrete [100]. The tested material properties can be used for the structural calculations that follow EN-1992-1-1. Using the codes for 3D printed structures has not yet been validated. To overcome the issue of lack of codes to follow, a scale model can be tested in a laboratory to demonstrate safety and compliance with the codes [100]. Tests can be done on the load-bearing capacity to exclude any failure during production. In addition to this, other tests can be conducted to find the best printing strategy and assembling.

CE marking is mandatory for construction products covered by harmonized European Standard but not in general for innovative products [100]. In Europe, the European Organization for Technical Assessment (EOTA) coordinates the application of the procedures set out for a request for a European Technical Assessment (ETA) and the procedure adopting a European Assessment Document (EAD) [101].

Developed products are in the market as printing is known, how to make additives is known, and the subtractive technology is known, which makes it possible to sell products in the market [100]. There are many standards on cement, additives, concrete, etc., but not about 3D printing. Therefore, the EOTA rules are possible, with using EAD to show all the requirement that the product fulfils, before it gets closer to ETA and CE marking [100].

HINDCON did not look at regulation as a real barrier to innovation and specified that regulations are not a problem for these types of products as the European commission establishes the minimum safety and suitability requirement in Europe for all kinds of structures and products [100]. Methods of verifications include; dimension and tolerances, dimension stability, compressive strength, flexural resistance, impact resistance, density, freeze/thaw resistance, chloride ingress, carbonation depth, reaction to fire, resistance to fire, water vapour permeability, thermal conductivity, thermal resistance, specific heat capacity, and airborne sound insulation [100]. All of these depend on the intended use. HINDCON project intended uses for elements for civil works. At the beginning elements for footbridge was considered as well as columns or bus shelters. The elements that were selected for intended uses were elements for building; facade elements, self-insulation walls, and technical wall elements. When the intended use is known, a list of essential characteristics and relevant assessment methods can be established [100]. When they have this, ETA can be used as a passport for all products [100].

8 Discussion

The interviews were carried out to strengthen and further investigate the key findings from the literature. The main findings from the interviews are presented in the results and are to be discussed in the following subchapters in light of the literature. First, chapter *8.1 3D Printing Market* elaborates on the construction industry's ability to adopt new technology, considering market reports and the participants' view. Second, chapter *8.2 Conditions, Challenges, and Opportunities for 3D Printing* consider the equipment being used, and what requirements must be given to the concrete for it to be printable, which challenges that occur and how to handle them, that again can lead to great opportunities.

8.1 3D Printing Market

This section addresses the first operational question *How is the market for 3D printing?* by looking at the construction industry's ability to adopt new technology, considering market reports and the participants' view from the interviews.

The industry knows that there is a need for change. The technology is available, but yet many hesitate. 3D printing technology responds to numerous concerns related to the industry. Digital technology has proven beneficial in many ways, e.g., optimization of construction, smoother operations, and better structure and collaboration between the design and project phases.

Several market reports have estimated a bright future for 3D printing and are expected to influence the concrete industry. SmaTech [67] predicted AM to grow considerably during the next years with an increased revenue reaching $40bn in 2027. The HINDCON project used a macro-economic study to analyse the market at the idea of synchronizing the market early in the development, where all parties were included in the development of a business plan. The market study used in HINDCON estimated AM to reach $27bn by 2022. Compared to the numbers in Figure 7.17, $3.3bn by 2022, it is a significant difference between the reports. The two market studies operate with different numbers, but bot predict a market for 3D printing. Considering these numbers over a relatively short period, there will be a market.

Nevertheless, growth is dependent on political, economic, and market demand factors. These factors play out somewhat differently globally and can be a reason for the geographical differences. North America is statistically proven to have the largest market, with Europa and Asia together at second. The Netherlands, Germany, UK, and France are highlighted as the leading countries in Europe. Other countries are not mentioned, which can indicate that there is probably no market for this type of technology. That is, to a certain degree, accurate as most of the participants in this study had not used such technology or knew little about it.

The report from WEF and BCG stated that 3D printing of components is likely to happen and will have an impact to a certain extent. They placed 3D printing of components almost on the middle of the scale for both likelihood and impact in the matrix (see Figure 7.16). What is interesting is that in the same report, prefabricated building components were stated to be likely and have a very high impact. Several factors make the two very different, but they have the same purpose, i.e., components.

Numerous participants considered 3D printing of elements to be most likely to happen at a factory, to some extent in the same way as prefabricated elements, but with a more elaborate design. The reason for the lower placement can be due to the challenges related to 3D printing, which is discussed in the next chapter, or that prefabricated elements are already highly used and are considered 'easier' in a sense.

The construction industry is facing several challenges that have been created over a longer period. If things continue at the same pace and direction, the results will be absent. The construction industry is ready for change, and it is time for a change. The actors that will grow and have success are those who can see options in sustainability, circular models, and who can orient themselves within a fast-growing development of technology. The reality is getting more complex, and it is challenging to think wide enough. Real competitiveness is, therefore, the ability to cooperate and share between people and environments, national and global, to see other opportunities and approaches than what our selves are capable of doing. Various transformation frameworks have been published by several organisations and associations, including steps and measurements. Transformation areas have been evaluated, and the most important factor is people, followed by adaption to new technologies, materials, and tools. Highly significant is the industry collaboration. Also, training of operators and operational management is vital to success.

There is no doubt that the construction industry is ready for new technology. That is confirmed by literature and the participants in this study. There is a growing demand for actors that have expertise in data-driven solutions. There is a common goal among leaders to be more data-driven, and there are actors who will challenge the traditional business and delivery models. Even though it is an interest, only one fifth is capable of fully utilizing and benefiting from such competence and driving the international industry forward, with regards to the enormous opportunities in technology and digitalization. There are several challenges with technology among different actors and within the organisation. There were various views amongst the participants about who is the driving force of technology in the construction industry. Some looked at the consultants as the bottleneck due to their ability to design. Some excluded contractors as a drive for development in Norway as none are willing to take a risk. Others thought quite the opposite, that the architects and consultant could design and engineer almost anything, or that contractors are the ones who are pushing the industry forward. Some contractors are recognising the inefficiency and slow productivity and are working with automated systems, modular construction, and other systems to enable them to have a competitive edge in the market. Some consultants live by the innovations of the past, while other consultants are more eager to innovate and come up with new solutions. There has been a shift where it used to be the universities that primarily worked with technology innovations but now it is the consultant firms that have grown larger and have more capacity to innovate. The suppliers were also mentioned as the most prominent innovators as they have the machine, software, chemicals, etc., and clients and contractors drive them. Several were missing requirements or demands from the client for the process to start. It is a thought that if there is no demand for it, it will not develop either. Therefore, we need some clients who dare to throw themselves out in the first projects.

There were many different opinions on whether the driving force of technology in the construction industry is the clients, consultants, architects, contractors, manufacturers, or suppliers. None of the parts of the value chain were standing out. Several of the participants could they could not point out a single actor and referred to the value chain as a whole to be essential as a driving force. The driving force is a collaboration where one has a unified understanding of risk in the project. The benefits are different in the different production stages. What many agreed on is that the client must be the one ordering the use of this type of technology, like what has been done with BIM. In Norway, there has traditionally been one big actor when it comes to bridges. They have been acting with a monopoly that decides what bridges should look like, which is a factor that makes the construction industry conservative.

A key driver is a technology development and new production methods, which provide other opportunities for production scale. Today, the industrial way of thinking is based mainly on the perception of the end product as systematically composed of components of different sizes and degrees of completion. The material development combined with new technologies can enable seamless products and completely different physical interfaces in buildings and facilities than there is today. There is a noted trend shift from industrialization being associated with end products having standardized appearance to having variations and a high degree of adaption. People see the benefits of transitioning to a more industrialized construction production process. The construction industry that traditionally has been regarded as a craft industry has substantial potential for industrial processes. It requires that the companies find the optimal degree of automation and involve the craftsmen in the development of the process.

The question of who benefits from technology can be challenging to answer, but at the same time, it is easy. It is society as a whole, and since technology is a wide term with different types of technologies, all actors benefit from technology in various ways. All the links in the value chain have significant advantages, but the one with the greatest benefit depends on the perspective that one chooses to look at it with. Some participants believed that access to technology or technology in general, is not a bottleneck for development. Once clear goals are set, technology is not the bottleneck. However, if no clear goals are set, then technology development spreads so much in every possible direction that nothing seems to be happening—for example, the Troll Platform in the North Sea or the Bjørnefjord floating bridge. When starting a new project, different solutions are considered and often rely on known technology and previous projects. Still, there is a willingness to challenge the known technology, e.g., the floating bridge in Bjørnefjorden. A structured and targeted approach to that problem then proves that those challenges are also possible to solve. Sometimes the technology can be developed along the way. These projects had high risks. Technology is not an obstacle when it has the right budget, and someone is willing to take the risks. Still, if they have not seen it used many times before and in that way been convinced, then not many will use it. Also, the challenge may not be so much that it lacks technology, but perhaps more to the lack of understanding in how it has to be used. Many technologies are waiting to be used in practice, but because they are talked about so much for so many years, people think it is already in use when it is not.

Today, technology is generally widely available. Therefore, it no longer becomes a factor that separates the actors from each other. In the future, advisors must compete with their ability to use technology, expertise, and new forms of work. There is no doubt that more of this 3D printing technology will be developed in the future. One can also imagine an even more innovative technology where robots can produce concrete and reinforcement elements. One must follow what is happening in these developments and possible synergies.

The criticism against the construction industry has taken many forms and expressions. It can be summarized as the industry is less productive, consumes too many resources, pollutes, and is behind in terms of digitalization and sustainability. Also, many actors are delivering their projects too late, with too many errors and shortcomings, which turns out to be overly expensive. As a consequence, conflicts arise, and it gets challenging to recruit the right talents into the companies. The complex problem is compounded, and no one can assume to sit with a full overview or the solutions to how to get out of it.

The technology is there, but it will not evolve without anyone using it. One can say that the construction industry is less efficient because it does not use available technology. Some participants believed that to get started with technology without talking about finances, a cultural change is needed. Not everyone is ready for it, and many are not prepared for it. It is not only economics, but the cultural change or restructuring required that is challenging for the organisations in the construction industry. Several participants pointed out the construction industry to be highly conservative. The construction industry is fragmented as there are many small businesses but few larger ones. The bigger businesses have more muscles to invest in technology while the smaller may not, but that does not mean it is less relevant for them. It illustrates an unbalanced picture of the construction industry. It can also be said that the construction industry is cut into many slices or parts with an interface between. There is an interface from builder to consultant, consultant to contractor, contractor and subcontractors, suppliers, etc. That is a big problem because everyone has their finances, each has a contract, and each has to produce optimally, so there will be no innovation. It is a contradiction to divide them because one part cannot change or innovate without the other parts are changing or innovating with them. It is easy to blame the lack of innovation and efficiency on the conservatism in the industry, but it is conservative for a good reason. The industry has to follow many requirements, standards, and legislation. The rules set by standards are quite conservative and might be due to safety, e.g. making sure that the bridge does not collapse. Those who are innovative and want to move forward with technology in the construction industry do not come from the construction industry. Typical start-ups that come from outside and have no background in construction but come up with new technology and will attack the construction industry market.

Several shared the opinion of the importance of collaborating. Everyone needs to be a part of a project for 3D printing to succeed. The most significant opportunity and probably one of the advantageous ways to make 3D printing of concrete bridges to work is to gather integrated teams and have integrative processes. If 3D printing should work, all representatives from the value chain must be gathered to create the innovation, with a clear target, and have financing. It requires a restructuring of significant dimensions to be able to see the possibilities with it, and there comes a big problem for everything that has to be financed So, there will be some significant private funds that go in and see some opportunities and prestige in contributing to development. The rational thing would be to say that all those who have influence should be together in a project office to agree, including the contractors and suppliers. This will optimize so that one always has a dialogue between all parts of the value chain making it a long flowing and much more complicated process. In the end, everyone can sign that it is the optimal technology used and all requirements set for technical, but also optimal for the environment, economy, traffic, durability, maintenance, appearance, etc. Then there will be no interfaces between the actors or different parts. This could be a great way to start e.g. a pilot project.

In a way, this is what HINDCON did in their project. A different option is to have all the various representatives from the value chain needed for 3D printing to create their own company. As there are different structural design methods, not every single architect, consultant or engineer will adapt and learn to design with 3D printing, and not all concrete technologist will be able to get the right concrete composition. Therefore, a company could specialize in this type of design and structures.

The construction industry should move from thinking about defining boundaries – by recognizing one company from another, a specialist group from another, an expert from another - to share and interact. The value created for the customer and the society must be defined - and new settlement models and mechanisms for distribution are needed. It is urgent to find ways to solve this. The industry needs both big and small actors who dare to try new ways to interact and to gain knowledge acquired in the industry. Sharing and interaction will be a prerequisite for survival. If using 3D printing on a daily basis for projects, it will not be realistic to have one participant from each company or each part of the value chain working all day long in the same office, as long as they belong to different companies. It has to be incorporated, to some extent, as we do with projects today, where much of the communication happen digitally. BIM is great for information flow across the actors. IoT, Big Data and cloud services can also contribute to enhanced communication.

There is still a prospect of good growth and access to projects. The winners of the future - those who will succeed in delivering good margins - are those who differentiate themselves on parameters other than price. The essential differentiators will be new technology, digitalization, and sustainable solutions. Traditionally, suppliers and service providers in the market have been viewed as individual actors, competitors, partners. Some have a wide monopoly, and others are very pointed and specialized. The Government, as a client, has a crucial role. Both because the Government are responsible for substantial value creation and employment, but also because it is critical in building the necessary infrastructure in an elongated country. A transition to sustainable solutions will come. The Government as legislator, client, and regulator must demand that sustainable solutions are chosen - in all competitions - even when the price is higher. If the Government wants and dares, these requirements can contribute to a strengthening of the Norwegian construction industry in competition with other countries.

The construction industry is not supposed to solve the same tasks in the future as it is doing today. The world is changing, and the problems are changing as well. Therefore, the solutions to the problems will change along with it. Some prominent examples are that technology is changing and new opportunities are continually emerging in the form of digital and technical solutions. The climate is changing, and with that, both the requirements for what is to be built and the framework conditions for the building itself are changing. The composition of the planet's population is changing, and with it, the needs, desires, and ideas of how the built environment should also change. The economy and access to resources are setting more definite boundaries.

Another aspect to consider is if the actors in the future will be the same as those we had yesterday. A question every actor has to ask themselves is the questions on which problem do they want to be a part of solving. The issues are the seeds of new opportunities. If the problem is not resolved, there are many opportunities to offer something that can contribute - knowledge, experience, resources. Not least, how one can help gather the resources needed, as no one can manage it alone, and make them work together.

8.2 Conditions, Challenges and Opportunities for 3D Printing

This section discusses the equipment, the requirement for the concrete to be printable, challenges with 3D printing concrete together with how they can be handled, opening up opportunities.

The three major AM processes targeted for construction (Contour Crafting, Concrete Printing, and D-shape) have some differences but are still possible for bridge construction and components. There is a lot of information in the literature, whereas the participants had various knowledge levels regarding 3D printers. A few of the participants knew some different types of 3D printers. Among the participants that did not know much about the 3D printing processes, the most frequent association was to extrude concrete, like toothpaste, out of a tube.

Several companies have developed their own solution and interpretations of 3D printers. Which one that is most suitable for 3D printing bridges can be difficult to say as it depends on the size and design. The size plays a massive part as 3D printing needs a comprehensive system to make it work. If elements or components are to be printed, then most technologies related to material extrusion can be used. In some cases, e.g., gantry or cable robot, the frame holding the robot and controlling the winches must be taller and wider than the construction or element that one wants to print. That causes a limitation in the size it can print, as it cannot print bigger than the printer itself; it might be easier to print elements. If the entire bridge it to be printed, it can be printed in a factory with mobile printers, but the size of the factory will be a limit on how big the bridge can be. When printing at a factory there will always be limitation on transportation, for both elements and the whole bridge. When printing on-site and there is a big machinery, there will be a lot of work with mounting, disassembling, and transportation if using a stationary printer, e.g., gantry. It will be time-consuming and costly. If a cable robot is used, the printer also has to be calibrated, and that can be almost impossible in the open, e.g., close to a river where the bridge is crossing. The weather is an unpredictable factor, and so is climate. It is a different climate around the globe where almost every country has to take precautions, which is also one of the reasons that the Eurocodes have a national annex. If the printer should stand outside and there are no storage opportunities, it must handle the weather, e.g., wind and temperature change. A mobile printer has better opportunities for storage as it can be stored in e.g. a large container. A mobile printer does not have to be assembled and disassembled to the same extent, but transportation can still be a challenge as it is heavy machinery. Also, Quality control will be particularly difficult if it is to be printed in the open, and it will be difficult no matter which printer that is used. Several projects have succeeded with 3D printers. In this study, no projects or literature have documented that there has been successfully 3D printed construction outdoors. Therefore, that could be a good argument for saying that 3D printing is most suitable to be done indoors.

The printing speed must be managed for the concrete and the equipment to be coordinated, so the machinery will not go too fast for the concrete to be placed. There should be a trade-off among the scale and the speed, as the size is a factor for printing quickly. Temperature and pressure are also essential factors with regards to printing speed. The pressure must be continuous, and the temperature affects the pressure. It can only be printed when those parameters are stable.

It is challenging to keep up with maintenance and cleaning, and this is also one of the crucial parts of 3D printing if some part of the printer gets clogged, or some materials go into the wrong part of the machinery, it might ruin the equipment. The open time window must be known so the equipment can be cleaned before it starts hardening.

The nozzle has different challenges. The size of the nozzle is one of the reasons why the aggregate must be on the smaller side, as it does not allow for coarse grain. With larger nozzles, the pulsating pumping will probably occur. That is also one factor why some printers do not take regular concrete. If a cable wire is integrated in the reinforcement when printing and is coming out from the same nozzle as the concrete, then the size of the cable must be taken into account. The nozzle that was used in the Netherlands was tailor made and a hybrid between the down- and back-flow nozzle.

One of the several challenges with 3D printing equipment is the high risk because if there are errors in the digital model, it can have severe consequences. Therefore, the digital model must be faultless. When having errors in the model, it is most likely to be visible when printing as it leads to, e.g., failure in layering the concrete as it might slide out and the printing are unsuccessful.

One significant challenge is that the printers today have been developed to construct a specific type of concrete. When the 3D printer and the concrete are designed together, it can be tricky to adjust the concrete afterward. The most commonly used approach is the 'trial and error', which means reaching for a concrete printing for certain tasks. The result is often a printer that can take a few concrete mixes, a material composition with less variation.

The biggest challenge for the concrete properties is to fulfil all the requirements. The requirements for a printable concrete given in the literature fortified the opinions of the participants. Three of the main requirements are printability, pumpability, buildability. The open time window has shown to be significant for the setting time and cycle-time, which again is crucial for the layer adhesion. The participants mentioned many factors to be important requirements for the concrete. For the aggregate that is used, it should be a proper sieve curve. The moisture content of the aggregate must also be under control. The sieve curve and moisture control could also be further used in research for standardised concrete with 3D printing. There should be some consideration of the mixing sequence as well. It will be imperative to have an even print, stability, no segregation and bleeding, compaction, and homogeneity. Consistency, viscosity, and cohesion are influential requirements. The concrete mix should have flowability and mobility and achieve a great ductility. It is crucial to have continuity between the layers, controlled curing method, and conditions to handle the setting and curing time. Due to the material setting time, the printing time has to be managed and planned. A material stiffness has to be achieved to avoid layer deformation, which can also happen due to self-weight. Durability is fundamental and essential for 3D printing.

The concrete needs to have robustness, reaching adequate strength and flexural resistance for the bearing capacity. Density, compressive and flexural strengths, tensile bond strength, and drying shrinkage are important hardening properties. Also, the 3D printed concrete should have a tolerance class. Quality assurance and control of production and product are challenging but needed. Rheology measurements and measurement of hardened material properties are vital for safety reasons.

For 3D printing to succeed, the requirements for the concrete to be printable must be achieved. Some of the participants did not see any problems with creating a printable concrete and had high thoughts and expectations for the concrete technologists. Several participants could see opportunities for the concrete to have stability, compaction, flowability, and mobility (curing and setting time), durability, and being environmentally friendly. Many of the participants looked at rheological properties to be the most extensive obstacle for 3D printing. Several of the participants did not know if they wanted to call it mortar or concrete. It can be challenging to get the desired quality of the concrete. It would be challenging to get the right material composition, based on the right raw material, being pumpable, having the capacity to handle loads, get even print, have the right consistency, durability, handle small vibrations, moldability, durability, and resistance.

Ultra-high-performance concrete (UHPC) was regarded as a good option for 3D printing by the participants. UHPC has also been successfully tested several times, e.g., during the HINDCON project. The results from both interviews and literature review indicates that UHPC is a possibility for concrete material.

Reinforcement is one of the most debated topics concerning 3D printing concrete structures. Participants mentioned several challenges like reinforcement handling, the amount of reinforcement, and complicated reinforcement. These difficulties were enhanced through literature. The reinforcement is a factor that influences the diameter of the concrete layer thickness, as it has to make room for the reinforcement. The direction of the reinforcement is crucial as it establishes how the structure will handle loads. Placing reinforcement perpendicular to the printing layer will be difficult. The more complicated a construction, the more complicated it is also to reinforce. Bridges normally need a lot of reinforcement. The participants mentioned possibilities with stirrups, pre-stressed reinforcement (pre- and post-tensioned reinforcement), steel wire, and fibres. It was suggested to use automated reinforcement processes, having a robot that makes the reinforcement in advance. Thus, having an automated reinforcement process doing its job before the 3D concrete printer starts working. 3D printing of steel reinforcement is studied and have shown satisfying results. Still, there are no projects that have tested them together as one operation.

Using a cable wire have successfully ben implemented by researchers in the 3D printed bridge project in the Netherlands. Using a wire reinforcement in the filaments provides longitudinal tensile strength and ductility. The wire must be strong enough but also flexible for it to follow the shapes of the 3D printer.

Fibre reinforced concrete is a good option for reinforcement and was often mentioned by participants. The participants imagined fibres combined with other types of reinforcement, particularly pre-stressed systems, to be the optimal solution. Fibre reinforcement with a free span is not enough, and therefore, it has to be combined with other types of reinforcement. Fibres can be challenging in relation to the equipment being used, as the fibres have to be a part of the blending process, increasing the possibility for the system being clogged or it can lead to segregation and increase porosity. Also, the fibres can have an uneven distribution in terms of the amount per volume. The fibres must have the right direction as well and ensure interface boundaries. Types of fibre were also up for discussion, and with good reason. Tsinghua University used polyethylene fibre concrete in the bridge they 3D printed in China. No sources have successfully been found on how Tsinghua University handled the challenges mentioned above, with polyethylene fibre reinforced concrete. Types of fibre were not investigated any further.

For each project, it should be considered if 3D printing is suitable as it should be adapted for a project where shapes and design are in focus, not for a bridge consisting of only straight lines. Dimension and shape are some of the most significant opportunities for 3D printing. The participants saw opportunities with the design, to have complex and free shapes, aesthetics, and geometry, as well as size. 3D printing opens up for individual solutions and the possibility of free design. That also means a new way of thinking, making constructions or bridges in this regard look differently to what they conventionally do. 3D printing offers great flexibility of geometric customisation, making it possible for giving the bridges different expressions. Small scale bridges and pedestrian bridges were mentioned as a possibility due to the accessibility for people, having it as a demo project showing that the technology is possible. The shape is essential for aesthetical reasons but also because the shape can affect the ability to handle loads. For that reason, some participants would rather see 3D printing be used for other structures than bridges, structures that do not have a large static and environmental load, and lower risk and smaller consequences. On the other hand, dimension and shape were also mentioned by the participants to be one of the significant challenges; aesthetics and geometry, complex shapes can make it challenging to print and changes the complete design on how to use and put together the different elements, geometric tolerances, loads, transportation and moving elements because of the weight of the concrete.

The construction industry is the number one consumer of raw material. It is also responsible for a significant percentage of global energy use and therefore, the GHG emissions. In general, concrete has a higher environmental impact compared to other materials. The concrete used for 3D printing consists of less aggregate and more fines, which increases the cement content compared to a regular concrete mix. That will again increase the total environmental impact, which is often mentioned as greenhouse gas emissions. Using fewer materials, i.e., being more material-efficient is therefore essential. Even though the concrete used for 3D printing is less environmentally friendly, it will be using much less material. Considering that, the total environmental impact will not be so much worse than ordinary concrete. Carbon capture and storage can be an alternative to reduce the impact of the concrete. Also, using a greener concrete can be a more environmentally friendly opportunity. Sustainability has been mentioned as an important factor due to material consumption. Also, if printed on-site, there will be no transportation of elements and, for that reason, be more environmentally friendly. On the other hand, if printed in a factory, then transportation can turn that picture around. The HINDON project evaluated if 3D printing is better than traditional construction by doing an LCA study on a pillar with a result showing 20-25 percent reduction of GHG emissions. The biggest difference was the impact on the traditional production of the mould. The biggest difference was for the hypothetical scenario on hollow pillars, working as a shell being structurally sound for most applications. The conclusion from the LCA is that 3D printing has environmental benefits with material savings.

The Circular economy was mentioned as a possible advantage for 3D printed concrete elements if it is achievable to print the elements (using reused materials if possible), mount them on-site, clamped together, and then tensioned. It can then be disassembled whenever to be reused or recycled.

There are some significant challenges regarding the economy. 3D printing gives the possibility of using the concrete more optimally with design, placing the concrete only where needed. That makes the process more material-efficient, which again, can increase productivity and reduce cost. Even though fewer materials are needed, the special concrete mixes and materials will most likely be more expensive. To build or buy a 3D printer involves enormous investments and development costs. Not all companies are willing to invest, and not many have the financial capacity. There is also a risk involved in this type of investment that the companies have to account for. To create an inclusive community and for companies to adopt the technology, the printer's cost must decrease for SMEs to utilize it and get financial benefits.

Regulations can be seen as an obstacle due to the lack of specific regulations and standardisation for 3D printing. Bridges have strict rules regarding safety. Looking at risk assessment, and the consequence for bridges are more significant. Regulations are an essential part of quality insurance. For 3D printing to be applied, it must be adapted to the regulations, in particular, because there are no regulations that concern 3D printing. Regulations are connected to knowledge, and many people are not sufficiently informed about the subject. Even though 3D printing has existed for over a decade, it is not widely adapted by the construction industry. It is the same for all new solutions introduced; it takes time for regulations to follow, e.g., fibre reinforced concrete. HINDCON did not consider regulation as a real barrier to innovation as it is possible to test your way to acceptable results.

There are great opportunities in the planning and production phase due to BIM. Quality issues are significantly lower compared to conventional construction. 3D printing construction has increased accuracy. A 3D printer can operate at any hour, which can avoid delays in project delivery.

3D printing can help the construction industry achieve a higher level of security. 3D printing can result in a decrease in the number of workers. Conventional manufacturing and plant leasing will not be needed to the same extent as today; there will be reduced use of other machines. There will be overall labour savings with 3D printing design, and a reduction in labour costs will reduce the total cost. Project risk is slightly lower as there are higher technological risks but fewer obstacles with workforce and coordination. By having fewer workers at the construction site and probably faster production, then the number of unwanted construction site events will be reduced, thus better security. One of the participants mentioned that even though someone is losing their jobs, we have to see what we are replacing them from. Many workers have tough jobs, which they cannot have throughout their lives because it is a burden on the body.

3D printing can lead to increased competition against other materials and production methods. For example, if someone manages to print the beam layer very cheaply, then the other actors need to sharpen themselves, introducing similar technology, or improving their technology.

It would probably open up a lot of opportunities for architects and designers. The majority of architects and designers face reality when they come out. All of their exciting designs cannot be realized because it is, either impossible to make or too expensive to produce. Architects, designers, and engineers need proper training to adapt the method and use the technology. Initial training is required for the installation of the printer for it to work with less needed supervision. For designers and architects, there is also the opportunity, an entrance into the market for smaller companies that do not have enough muscle to start the vast projects that large prefabricated concrete element companies have.

The construction industry is ready for change. Innovation related to production in the construction industry has extensive potential. 3D printing can affect the construction industry, but the right applications must be demonstrated to showcase the potential of rationalization. First, actors must adopt the technology, not only as niche or one-off projects. R&D was a subject that was mentioned as an important factor, so was pilot projects.

There are several opportunities for approaches with 3D printing. The group of participants did not agree on whether 3D printing was most suitable for customization or standardisation. The participants that mentioned standardisation thought about; a standardised element that is easy to replace, ready-to-print bridges that are smaller so one can lift them in place, and also standardised bridge details. Elements were frequently mentioned. It is clear that within more substantial buildings, bridges, a lot of work is done with finished elements, such a modularized mindset where one put things together. Looking at large buildings, one sees that they are the same elements that are repeated, to a considerable extent. And it is clear that, from an efficiency standpoint and an economic point of view, it is a somewhat superior way of doing it. Just as in mass production, 3D printing cannot compete. It will still be desirable to use modularized concrete elements for a large part, and thus characterizes the entire value chain. Because the design has to be adapted to the elements, it costs a lot to develop new elements. And it is an advantage for those who work with those concrete elements and because they want to sell volume. In many ways, it could also be a kind of threat for someone to introduce this technology. But it is clear that where 3D printing technology has its advantage, it is in the tailor-made part. So, for those who want a greater diversity, i.e., more significant opportunity to create similar specialized solutions that can also help in not making 'overkill' solutions in order not to have elements that are good enough in a way.

Many of the participants wanted a further development of the technology before they could see it be used in the construction industry. One of the ways was to borrow some of the techniques from other types of concrete works. Several subjects came up in the discussion of approaches: elements, equipment, software, extrusion and layer-by-layer, robotization, automation, industrialization, incremental launching bridge, segmental bridge building, shotcrete, and slip forming. Several of the participants could see opportunities for industrialization, by increasing use of automation. Segmental bridge building and incremental launching bridge were two bridge constructing methods that were seen as having the highest potential for industrializing. Some consider that both these building methods are industrialization, but they can still be further developed. The participants imagined that part of the process could be used with a 3D printer on-site, but that it would be more reasonable with an automated process instead of a 3D printer. Shotcrete and slip forming were also mentioned to be great opportunities for industrialization of bridges. Slip forming has further developed to Smart Dynamic Crafting (SDC) and has one of the same advantages as 3D printing, particularly the flexibility of shapes. It is mostly used for beams and columns with untraditional shapes, which is one of the benefits of 3D printing. SDC can only be used for prefabrication. SDG is a transition between traditional casting and a fully robotic 3D printing. The participant interview in this study mostly referred to elements printed at factories as the preferred solution for 3D printing. Further, the previous 3D printed concrete project and particularly bridges, have used elements. SDC can be seen as a competitor for 3D printing, even though 3D printing can have freer design compared to SDC.

8.3 Weaknesses of the survey

The survey method that was chosen was a small-N-study, as described in *chapter 6.2.2 Survey-set-up*. It is a method with few participants, and it can be difficult to generalize from the data. It was expected to have 5-10 participants as the engagement to 3D printing in the construction industry in Norway was mirrored to be very low. It turned out to be quite the opposite as many wanted to join and be a part of the survey. Having 19 transcribed interviews meant a lot of information to present in the result. Chapter *7.1 Main findings from the interviews* could possibly be presented in tables. Due to the anonymisation of the participants, it is difficult to emphasize the opinions that appear in the results. By emphasizing the opinions, it could also be easier to present the result in a different way, e.g., a table.

Since face-to-face and Skype interviews were conducted, these became time-consuming to analyse. It limited the number of interviews that could be conducted and the number of interviews that could be transcribed. Due to time, 19 of 25 interviews were transcribed and used in the survey. The last interviews were not transcribed, so there was no selection of which interviews were 'best' or more valuable.

From the start, it was wanted to have most of the interviews face-to-face at Multiconsult's premises in Oslo, if available, and the remaining respondents over Skype. Two interviews were completed in Oslo before Covid-19 came and it became lock-down. Thus, almost all interviews were completed over Skype. The experience during the Skype interviews was good, but it did cause some problems. It was not as easy to keep a good flow of conversation compared to the face-to-face interviews. When the interviewers and the respondent had not met before, so getting a holistic and correct impression of each other was difficult. On the other hand, there was a safe environment with the respondent when he or she sat in his own office or home.

Many of the respondents had no clear idea of what 3D was and mixed a lot of automation and robotization, which made it difficult to get their opinion on the topic. It made it difficult to categorize the interviews. Some of the views may have been mixed, both for 3D printing and industrialization. When the data was divided into categories, this was done by the author. In this way, information may have been unconsciously extracted that seemed essential to the task and overlooked opinions that the respondent believed were important. Something that was not done but which could have strengthened the validity of the results was to send the results to the respondents. In this way, the respondents could agree or disagree about whether what was extracted from the interviews was correct and that it represented their opinions. There was no time to do it.

The disadvantage of an open interview is that the respondent can easily track off. It happened during some of the interviews, where the respondents were very concerned about something other than the task. It could also be because they did not have a clear idea of 3D printing.

The investigations had to be started early to carry them out. It meant that the questions were shaped by how much information was collected so far. Through the survey, the interviewer got her views on the topics. It may have led to leading questions and influenced respondents to respond differently than they would otherwise.

9 Conclusion

The conclusion will summarize the discussion chapter and answer the operation questions more clearly.

How is the market for 3D printing?

To evaluate the future for 3D concrete bridges, the current 3D market was investigated. The market is moving very fast, and there will be a market on the 3D concrete printing, even if it is considered deficient today. The participants had many different opinions on who they thought would drive technology forward. Some believed it was the contractors while other meant it was the consultants, but several agreed that there has to be a claim from the client, and that probably no one will adopt the technology until someone asks for it. Many leaders are eager to adopt new technology, but not all construction industry leaders are capable of doing so. Risk is a significant factor in how willing the companies will be to invest and how capable they are. The industry is fragmented with a few large dominating companies and many small ones, making it difficult for smaller companies to grow. The links in the value chain will benefit from technology in various ways as there are different types of technology.

For 3D printing to be adopted by the construction industry, and not just to be used in a project or two, there has to be a cultural change. The construction industry has been known to be conservative, which is an obstacle for new technologies such as 3D printing. For 3D printing to be successfully implemented, collaboration is highly needed, and integrated teams can be an excellent way to start.

Which conditions must be met to 3D print concrete bridges?

This operational question was answered with two sub-questions.

What does the industry know about the equipment that can be used?

There are several approaches for 3D printing and the equipment, or robots, being used. Contour crafting, concrete printing, and D-shape are the most prominent processes targeted for construction. The type of printer depends on the size of the structure, and whether the bridge should be printed on-site, at a factory, or as components at a factory. The equipment is also affected by weather and climate conditions if printing outdoors. Printing speed, temperature and pressure are important factors that must be tested and decided before printing. Maintenance and cleaning are a crucial part. The nozzle and printing head should be adapted to the right size, so pulsating pumping is avoided, and if coarse aggregate, fibres or cable wires are used, then it has to be adjusted after that. The digital model must be faultless because if it is not, the printing will fail.

What kind of requirements must be given to the concrete for it to be printable?

- The main requirements for concrete properties are printability, pumpability, and buildability, within an open time window. That includes flowability, mobility, even print with stability, no bleeding and segregation, consistency, viscosity, cohesion, compaction, homogeneity, and great ductility. Durability is fundamental
- The open window time is essential for the setting time and cycle time, which again is crucial for the layer adhesion. It must provide continuity between layers and controlled curing

methods to manage setting and curing time. A specific material stiffness must be achieved to avoid layer deformation and to carry the next layer.

- Robustness, adequate strength, and flexural resistance are essential. Density, compressive and flexural strengths, tensile bond strength, and drying shrinkage are important hardening properties
- Rheology measurements and measurement of hardened material properties are vital for safety reasons. Quality assurance and control of production and products are necessary.

What challenges do we see with 3D printing of concrete bridges, and how can they be handled?
A complicating factor for the application of 3D printing in the construction area is that the requirements in this sector are tough concerning durability, safety, and strength.

Size is a challenging factor. Construction components of any significant size are heavy. Lifting and moving these parts is non-trivial. This suggests an in-situ deposition approach, printing parts on-site followed by the assembly, or ultimately printing large parts of a building or other infrastructure in-situ. A disadvantage is the sensitivity of the materials and processes to ambient conditions, which can hamper on-site applications. Alternatively, components can be fabricated off-site and transported to construction sites, as well as inevitable safety concerns for operatives. A factory-based approach to the manufacture of large components in a controlled environment is therefore attractive and well-aligned with movement within the construction industry away from on-site production to increase quality, speed of production, and health and safety. Size is also relative with regards to the printer that demands a large workspace (mobile or not), moving the printers around on-site or in the factory. If printed on-site, then transportation of the printers becomes an issue.

One of the biggest challenges is for the concrete properties to fulfil all the requirements. Ultra-high-performance concrete is a good option for 3D printing.

The integration of reinforcing steel to reach the required strength is a fundamental problem. Options are to use fibre reinforced concrete, steel wire cable, and prestressed, particularly post-tensioned reinforcement. All these possibilities of reinforcement have challenges. A combination of post-tensioned with either fibre reinforcement or a steel wire is to be regarded as the best option with today's technology.

Concrete has a generally high environmental impact, and in the material composition for 3D printed structures, more significant amount of cement and fines must be used to compensate for the lack of coarse aggregate. That results in an even higher environmental impact. 3D printing is more material-efficient i.e., uses less material by placing it only where it is needed. That can compensate for the high environmental impact, but per volume of material, the concrete used for 3D printing is not environmentally friendly. Carbon capture and storage can be an alternative to reduce the impact.

Knowledge and training will be a barrier to 3D printing as few people know the technology. It is necessary to educate and train skilled people who can run the 3D printer and have architects, consultants, and engineers that can design for it to be implemented. Conservatism can also be a part of this issue.

Regulations can be seen as an obstacle since there are no specific regulations and standardisation for 3D printing. The structures and components being printed can be tested for validation.

What opportunities does 3D printing of concrete bridges give?
One of the most significant opportunities with 3D printing is the shape. 3D printing offers great flexibility of geometric customization, making it possible for giving the bridges different expressions.

It can be an opportunity to use 3D printed elements circular economy as it is possible to print the elements, mount them on-site, clamped together and tensioned, and then it can be disassembled whenever to be reused or recycled.

3D printing can lead to a higher level of security (HSE) with fewer workers on the construction site, resulting in overall labour savings. It can lead to increased competition against other materials and production methods.

A few of the participants could see a future where the entire bridge could be built by a 3D printer but in a smaller size. When it came to more massive bridges, motorway bridges, nearly all of the participants hesitated. Most of the participants could see a future with 3D printing concrete elements used for bridges, having shapes that make the bridges extraordinary.

3D printing means that we can and must rethink tools, materials, and design. It does not hold that 3D printing is exciting; it must also be competitive. Most buildings are simple and will not pay off with 3D printing, but when the cost of using a printer is the same for a simple construction as for a complicated one, and you reach a certain level of complexity, it can become competitive.

One of the most exciting things about using 3D printing in the construction industry is to see how it is going to change the architecture and construction practice.

The focus area for the master's thesis was 3D printing of concrete bridges. Bridges were partially whispered out as research and documentation of 3D printed bridges was almost non-existent, which is not surprising as there are currently only four 3D printed concrete bridges. Only one of the bridges, the one located in the Netherlands, had published their solutions in articles. Thus, the study does not include bridges to the same extent and cannot fully answer the research question as much as assumed at the start-up.

10 Suggestions for further work

During the work on the thesis, some areas could be interesting to research further.

Reinforcement with 3D printed structures is one of the main problems, and there is still no perfect solution. Further research is needed for solutions on how to incorporate reinforcement in a better manner. Also, 3D printing of steel before 3D printing concrete would be interesting research.

Larger parts of the value chain could be included by focusing on the different actors. The designer has the key to the proper use of 3D printing. Thinking back to the Romans who built with stone, to solve long spans, they built arches because an arch has only pressure and not tension if it is properly dimensioned. One of the major problems with concrete 3D printing is the reinforcement that is primarily needed in the concrete where there is tension. It is an interesting discussion about how the design can facilitate increased use of 3D printing with concrete, which one obviously can.

There is uncertainty about how cost-efficient 3D printing is. Therefore, it would be interesting to compare 3D printing and traditional construction to see how beneficial it is. Also, include life cycle costs.

As there is a lack of regulations and standardisation for 3D printing, this could be further elaborated where the result could be suggestions for standardisation.

The terminology of 3D printing is varying. It seems like there are different perceptions among researchers on what 3D printing is, and that the term is used in different ways. It is perceived that there are shortcomings in theory.

One of the mentioned weaknesses is that the anonymisation of the participants makes it difficult to emphasize the opinions that appear in the results. Further work could be to emphasize who says what in the survey with less degree of anonymization, so it is possible to connect where in the value chain the statements belong.

It could be interesting to look further into only one part of the value chain to have a more centred target group, giving a less nuanced picture but maybe also a different view. In another way, it could be interesting to do a quantitative study to reach out to a larger group than in this study.

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12 Appendix

See separate file for appendices.

12.1 Interview guide

12.2 Interview questions

12.3 Categories form NVivo

12.4 Supervision meetings

12.5 A3 Poster