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Does 3D printing have a future in the construction industry and could it be a disruptive technology?

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Abstract

3D printing began to revolutionise the market in the late 1980s. Since, 3D printers have evolved and have progressively made their way to various disciplines such as aerospace, medicine or construction. However, it is only recently that entry-level models, more affordable and accurate, have made their appearance on the market. Their introduction has rapidly gained a lot of success and has emphasized the development of the Do-It-Yourself approaches.

In recent years, the need to automate the construction process for structures and buildings has been constantly propelled by the lack of innovation in the building processes, which has remained almost entirely based on manual labour for years. As a result, organisations around the world have demonstrated a keen interest in 3D printing projects in the construction industry. Compared to traditional methods, the use of 3D printers has revealed social, economic, technical and environmental benefits and opens the possibility of building structures layer by layer from digital data.

This master's thesis presents a holistic approach to 3D printing technology and its applications in the construction sector through extensive literature review. In recent years, the technology has shown potential in a wide range of fields: the building industry being a new exciting and growing area for 3D printing. This technique can create the opportunity for customisation of large-scale projects since it removes the restrictions of shape in the traditional ways of building.

However, there are still many unsolved issues related to the 3D technological innovation in this sector. One of them is its disruptive aspect on the market, the human being, the regulation and the environment. Therefore, the purpose of this thesis is to better understand whether 3D printing technologies will have a sustainable future in the construction industry. A content analysis on the state of the art of 3D technologies in construction and interviews with industry experts were conducted to identify their potentially disruptive impact on the market. A questionnaire survey was also adopted to complete the data collection and collect professional's and market's opinions on the use of the technology.

Keywords - Additive manufacturing; 3D printing; Construction sector; Sustainability; Disruptive technology.

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Florian Spitaels

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To my grandmother who supported me in every step of my life.

Table of Contents

1. Introduction 1

1.1 Motivation 1

1.2 Research Question 2

2. Literature review: 3D printing in the construction industry 3

2.1 General approach on disruptive innovation and emerging technologies 3

2.1.1 Evolution of innovation and convergence innovation (CI) 3

2.1.2 Disruptive innovation 4

2.1.3 Examples of disruptive technologies 6

2.1.4 Disruptive innovation in a crisis environment: the COVID-19 pandemic 7

2.2 Introduction to 3D printing 8

2.2.1 History 8

2.2.2 Definitions 8

2.2.3 AM and 3D printing 9

2.2.4 Opportunities 10

2.2.5 The 3D printing applications 11

2.3 The construction industry 12

2.3.1 Global environment 12

2.3.2 Belgium 14

2.3.3 Overview of the legal and regulatory framework 15

2.3.4 Current building methods - Specificities 15

2.4 Introduction to Construction 4.0 16

2.4.1 Industry 4.0 16

2.4.2 Construction 4.0: introduction and overview 16

2.4.3 The digital transition of the construction industry 18

2.4.4 Industrialisation and automation 19

2.5 3D printers launch in the construction sector 20

2.5.1 Digitally-native approach to building construction 20

2.5.2 A different approach to build 27

2.5.3 3D printing applications 28

2.5.4 Costs and time savings 29

2.5.5 Advantages and opportunities 30

2.5.6 Risks and challenges 31

2.5.7 Raw material supply chain and storage 32

2.6 Challenges of the launch environment 32

2.6.1 Technological adoption 32

2.6.2 Legal framework: 3D printing in the construction industry 33
2.6.3 Economic perspective: business model and value chain 34
2.6.4 Environmental and social issues in the construction industry 35
3. Theoretical conclusion 40
4. Methodology 41
4.1 Overall - Research questions 41
4.2 Research strategy and problematic 42
4.3 Data collection method 43
4.3.1 Semi-structured interviews 43
4.3.2 Online surveys 44
4.4 Method to analyze the information 45
4.4.1 Semi-structured interviews 45
4.4.2 Online surveys 46
4.5 Remarks and limitations of the methodology 46
5. Analysis of the results 47
5.1 Outcomes of the data collection 47
5.1.1 Interviewees presentation 47
5.1.2 Sample description 47
5.2 Market perception on 3D printing in the construction industry 48
5.2.1 Market perception overall - Demand 48
5.2.2 Technological maturity and innovation cycle 50
5.3 State-of-the-art on the 3D printing challenges in construction 51
5.3.1 Technological and regulatory challenges 52
5.3.2 The cost of a printer 56
5.4 The global environmental issue: does 3D printing have a role to play? 56
5.4.1 More durable materials - A new type of concrete? 57
5.4.2 Circular economy 59
5.4.3 Topology optimization 59
5.5 Best scenarios for 3D printing applications in construction 62
5.6 Socioeconomic impacts of AM in construction 66
5.6.1 From a social perspective 66
5.6.2 Cost-based approach 68
5.6.3 What does the market think? (Results of the survey) 69
6. Conclusion 71
Bibliography 74
Appendices 85

List of abbreviations

3D: Three-Dimensional

AM: Additive Manufacturing

AI: Artificial Intelligence

BBRI: Belgian Building Research Institute

BIM: Building Information Modeling

CA: Construction Automation

CAD: Computer-Aided Design

CC: Contour Crafting

CI: Convergence Innovation

DMC: Digitally Manufactured Concrete

GDP: Gross Domestic Product

ML: Machine Learning

ROI: Return On Investment

SLI: Stereolithography

STL: Standard Triangle Language

WAAM: Wire Arc Additive Manufacturing

WHO: World Health Organization

WYSIWYB: What You See Is What You Build

List of Figures

Figure 1	Innovation life cycle S-curve	4
Figure 2	The three point disruptive technology criteria	6
Figure 3	3D printing process flow diagram	9
Figure 4	Additive manufacturing categories with materials used	10
Figure 5	The different players of the construction industry	13
Figure 6	The three major challenges of Construction 4.0	17
Figure 7	Construction techniques	20
Figure 8	Foster's (1986) S-curves applied to construction	21
Figure 9	Steel Bridge 3D-Printed by MX3D in Amsterdam	23
Figure 10	Examples of 3D printed concrete walls	23
Figure 11	Similarities between the 3D printing processes	24
Figure 12	Main steps to produce a physical object through AM in construction	25
Figure 13	Schematic of the 3D printing setup	26
Figure 14	3D printed house made by Kamp C	28
Figure 15	Process stages in large-scale, on-site digital construction	32
Figure 16	Roadmap to climate neutrality in the cement industry by 2050	38
Figure 17	Graph of the level of satisfaction concerning the benefit of 3D printing in the activities of the company today and tomorrow (between 1 and 10).	50
Figure 18	3D-printed concrete bridge made by Ghent University	60
Figure 19	Most optimal bridge shape that requires the smallest amount of concrete	60
Figure 20	3D-printed construction project around the world	63

1. Introduction

"*World's first 3D-printed school tackles classroom shortages in Africa*"
- New Atlas, July 2021

"First 3D printed house in Germany inaugurated by Construction Minister"
- 3D Printing Media Network, July 2021

"World's first 3D printed steel bridge weighing 4.9 tons opens to public in Amsterdam"
- USA Today, July 2021

1.1 Motivation

Construction is a sector of great strategic importance for both emerging and mature economies. According to the World Economic Forum and European Commission, the sector contributes to about 6% of global Gross Domestic Product (GDP) and 9% of EU GDP. With an annual turnover of nearly USD 10 trillion (García de Soto et al. 2018), the construction industry creates jobs and builds the industrial and civil infrastructure that enables other businesses to thrive (World Economic Forum, 2017; European Commission, 2018).

For many years, the construction industry has been characterized by its high resistance to change and low incorporation of technology compared to other industries such as aerospace and the automotive industry (Boton & Forgues, 2017). The industry has been slow to innovate and has failed to put in place integrated and efficient practices (Bock, 2015).

Nevertheless, it was not until the end of the 20th century that new digital technologies such as Building Information Modelling (BIM) and 3D printing began to change the way the industry operates (World Economic Forum, 2017). These developments had a major impact on the general way of working, the organisation of construction projects and the roles of stakeholders (Liu et al., 2017). It must be said that the BIM approach has drastically changed the way projects are managed in architecture, engineering and construction (Eastman et al., 2011). By providing a three-dimensional model of the construction projects, BIM gives the construction industry the necessary tools to better manage the processes and final products (Boton & Forgues, 2017).

A report published by Roland Berger (2016) further explains that the industry had no choice but to adapt to such a change, including on construction sites. This digital transformation, usually described as "Industry 4.0", has been called "Construction 4.0" by analogy to the construction sector (Craveiro et al., 2019). The adoption of Construction 4.0 and the introduction of collaboration tools like BIM in the industry have highlighted the potential for new innovations in digital manufacturing technologies that will dramatically modernize the construction sites such as 3D printing (Wangler et al., 2019).

3D printing is the process of producing 3D objects from a digital design by layering material in multiple layers. As interest in 3D printing grows, research into large-scale processes begins to reveal potential applications in construction (Ghaffar et al., 2018; Labonnote et al., 2016). Since building structures are often large and made outside of a controlled environment, AM systems have been adapted. This development has led to several different solutions and pilot projects such as 3D printed houses in China, 3D printed offices in Dubai or a 3D printed pedestrian concrete bridge in the Netherlands (Paolini et al., 2019; Allouzi et al., 2020).

"*For 3D-printed construction to be considered a viable construction method in the long term, it must be competitive with conventional methods and both useful to and usable by its end users*" (Schuldt et al., 2021). However, the large-scale implementation of 3D printing in the sector remains unclear. Some uncertainties still remain about whether the technology will penetrate the sector on a large scale and will be accepted by both the society and the industry.

1.2 Research Question

The purpose of this thesis is therefore to determine, in a theoretical and practical way, whether 3D printing could have a sustainable future in the construction industry. A first goal is to conduct an in-depth research in the literature to find elements of answers to this question. The information provided in the literature will then be compared with the opinions of specialists in the construction industry. A secondary objective of this study is to assess, thanks to the data collected, if 3D printing in construction could have an impact on consumers, industries or businesses and should thus be considered a disruptive technology. For this reason, the fundamental question driving this research is: **"Does 3D printing have a future in the construction industry and could it be a disruptive technology?"** In order to approach this question, further sub-questions need first to be answered. They will be presented in the methodology section of this report.

2. Literature review: 3D printing in the construction industry

The literature review provides the theoretical framework for this thesis and is structured as follows. Chapter one provides an introduction to the general approach towards disruptive innovation. In chapter two, an introduction to 3D printing and its main features is given. Chapter three then presents the construction industry and its characteristics both globally and in Belgium. In chapter 4, different characteristics of construction 4.0 are discussed. Next, an overview of the introduction of 3D printing in the construction industry is provided in Chapter 5, including an overview of the technical aspects, the materials used, examples of use cases, the opportunities and challenges in implementing the technology, and its cost structure. Finally, the literature review concludes with Chapter 6, which provides a summary of the challenges associated with the 3D printing technology adoption environment. In order to provide the reader with a clear and comprehensible study, a list of definitions of some of the concepts mentioned in the following chapters is provided in Appendix 1.

2.1 General approach on disruptive innovation and emerging technologies

2.1.1 Evolution of innovation and convergence innovation (CI)

The concept of "**innovation**" has changed throughout history, going through several phases. Each successive innovation phase is based on the knowledge accumulated in the preceding phases, which in turn accelerates the speed and scope of the innovation in the next phase. (Lee & Trimi, 2021).

Ettlie (2006) wrote about her vision of "**innovation**" and explained that it usually involves a life cycle. Usually, the first-mover advantage, based on new technologies or business models, lasts until new entrants with new innovative products or services disrupt the market. Lee and Trimi (2018) support the idea that the innovation life cycle has become much shorter, as core competencies of organisations are based on fast-developing technologies.

Typically, the **innovation life cycle**, as shown in Figure 1, looks like an **S-curve** (Christensen, 1992; Ettlie, 2006). At the beginning of the curve, a new idea appears and creates value. Then the marginal revenue increases exponentially until it reaches the inflection point, where the marginal revenue starts to decrease until it reaches the peak of the curve. At this point, the company may exit the innovation S-curve and start a new cycle to avoid negative returns (Lee & Trimi, 2021).

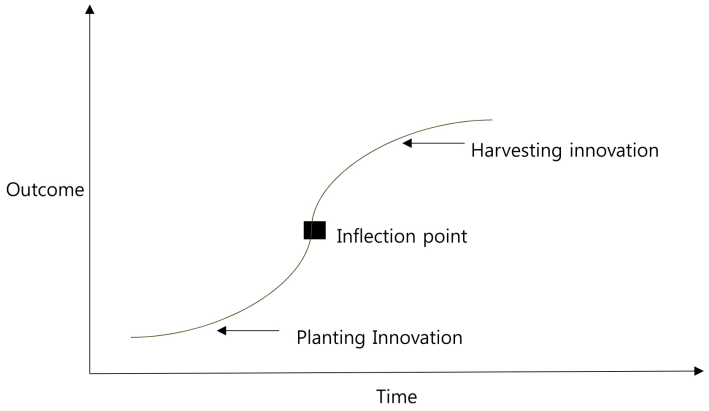

Figure 1 - Innovation life cycle S-curve. (Lee & Trimi, 2021)

2.1.2 Disruptive innovation

Definition and characteristics

In recent years, the concept of **disruptive innovation** has had considerable influence in the corporate world. It has proved to be a valuable tool in predicting which new industry entrants will be successful. Unfortunately, this theory has also been vastly misinterpreted by being applied in too many cases whenever a newcomer in the market disrupts established incumbents (Christensen et al., 2015).

Clayton Christensen is the researcher that initially introduced the term "**disruptive innovation**" in 1995. Disruptive innovation was defined by Bower and Christensen (1995) as "*a process by which a product or service takes root initially in simple applications at the bottom of a market and then relentlessly moves up market, eventually displacing established competitors"*. A decade on, the theory of disruptive innovation has received much attention in both the management research literature and management practice. However, criticism has also increased in the literature, and various authors have discussed the lack of an ex-ante perspective. That is the reason why Tellis (2006) argued that Christensen's definition is not future-proof and has little predictive value. Hardman et al. (2013) and Danneels (2004) also said that it would be necessary for technology developers and current market leaders to assess in advance to what extent an emerging technology can become a disruptive technology.

Recent studies carried out by Dijk et al. (2016) suggest that **disruptive innovations** bring a very **different value proposition** to the market and thus have the power to cause the failure of incumbents. Initially, their performance is generally inferior to that of mass-market products, but lower or non-standard features compensate for this. Disruptive innovation can give companies significant **competitive advantages**. According to Dijk et al. (2016), the "first-

moving" has the potential to enter a whole new market sector. Generally, the reasons for its position may be either technical leadership for the "first entrant" or its control over resources that the "followers" may not be able to compete with.

On the other hand, **emerging technologies** are associated with great uncertainty. The increasing pace of technological change increases the degree of uncertainty (Bouncken & Kraus, 2013), mainly because many of these technologies do affect not only individual companies (Eggers et al., 2014) but also drive economic and societal change (Jiang et al., 2017). Therefore, there is an increasing need for all stakeholders to manage technological change. Consequently, business strategies, policies and future research must be based on predictions of the most plausible developments in emerging technologies (Gartner & Maresch, 2020).

Historical disruptive technologies and evolution

In their research, Hardman et al. (2013) introduced different examples of successful disruptive technologies. Some of them are presented in this chapter to understand better how disruptive technologies enter markets:

1. The introduction of digital cameras in the 1990s overtook film cameras and the market leader in photography, Kodak. Early digital cameras struggled with poor image quality and resolution. However, economies of scale and research and development efforts have resulted in cheaper and better products, which enabled them to reach a large audience. Non-digital cameras then became a niche product (Dijk et al., 2016).
2. The introduction of mp3 players, in particular the iPod in 2001, replaced the personal CD and cassette players.
3. The introduction of tablets and eReaders had an impact on book and newspaper sales.

By looking at the results of previous studies, Dijk et al. (2016) suggested a model in which six hypotheses for market disruption are presented. It says that market disruption is significantly more probable when:

1. The consumer perspectives change: it happens when the beneficial attributes of the new technology become more important.
2. The social value of product technologies changes: it occurs when the emotional value of the niche product is considerably higher than that of the mature technology.
3. Companies earn or expect a higher economic return from the new technology than from the incumbent technology. It could eventually be through new business models.

4. Technology spillovers from other sectors compensate for the scale and learning gap of the niche concerning the regime.
5. There is a shortage of resources, which increases costs and lowers the price and performance advantage of the existing technology.
6. Regulation confers relative advantages on the niche technology over the established technology.

Dijk et al. (2016) took a case study relating to the automotive industry and tested the six hypotheses. Their study highlighted the interaction of these factors in a market and suggested that each element can become the potential trigger of a chain reaction for the growth of a disruptive niche. In their research, they also argue that the six factors are not independent. Instead, they are somewhat like a chain of cause-and-effect relationships: when one aspect changes, it starts to affect the others, and because of the interconnected nature of the factors, the change can be both rapid and non-linear.

More recently, Llopis-Albert et al. (2021) have developed an improved understanding of disruptive technologies that have allowed them in turn to define **criteria to identify when a technology is disruptive**. In this model, shown in Figure 2, Llopis-Albert et al. (2021) support the idea that if the potential disruptor meets at least two criteria, it is a candidate disruptive technology.

Table 3 – The three point disruptive technology criteria.

1. Disruptive to Market Leaders: The manufactures of the disruptive technology are different companies than those producing the incumbent technologies.
2. Disruptive to End Users: Disruptive technologies provide greater than equivalence of service over incumbent technologies meaning they are disruptive to the end user, changing the way in which technologies are used.
3. Disruptive to Infrastructure: The disruptive technology requires different infrastructure than the incumbent technology and/or negatively effects existing infrastructure.

Figure 2 - The three-point disruptive technology criteria. (Llopis-Albert et al., 2021)

2.1.3 Examples of disruptive technologies

Artificial Intelligence (AI) and Machine Learning (ML)

At one point, AI was a concept that was divided into broad application areas. Some of these areas were automatic programming, robotics, etc. Today, AI is better described as a group of

core ideas that involves many of these applications (Nilsson, 2014). Whereas Machine Learning (ML) is used to teach machines how to handle data more efficiently (Ribeiro et al., 2021).

The fundamental principle of smart factories and Industry 4.0 (introduced in another chapter) is the use of AI by machines to perform complex operations, reduce costs and enhance the quality of goods and services. The manufacturing industry is able to address modern challenges such as customisable requirements, shorter time to reach the market and an increasing number of sensors used in devices (Ribeiro et al., 2021). The use of flexible robots in combination with AI allows a more manageable process when manufacturing products. In addition, AI methods can analyse large amounts of real-time data collected from various sensors (Ustundag & Cevikcan, 2017).

In the last few years, AI algorithms and ML approaches have been successfully applied in real-world scenarios, such as commerce, industry and digital services (Ribeiro et al., 2021).

Electric vehicles

Another example of disruptive technology is the electric car. The automotive sector has shown increasing attention to alternative propulsion systems over the past 20 years, mainly through all-electric vehicles (introduced in the mid-90s) and hybrid electric vehicles (launched in 1997) (Dijk et al., 2016). Over time, technological innovations and their social context unfolded in two directions: the established combustion engine and the emerging electric drive (Dijk et al., 2016).

According to Llopis-Albert et al. (2021), many candidate disruptive technologies in the automotive sector, such as all-electric cars, are attempting to take market share from established internal combustion engine vehicles. Indeed, both technologies are competing for market share within the same industry. Therefore, the all-electric cars fit the three-point criteria model proposed in Figure 2 when compared to the incumbent vehicles.

2.1.4 Disruptive innovation in a crisis environment: the COVID-19 pandemic

The World Health Organization (WHO) (2020) has announced a **COVID-19 pandemic** on March 12, 2020. Looking at the literature published since the start of the outbreak of the COVID-19, several researchers such as Bratianu & Bejinaru (2020), van Looy (2021) and Lee & Trimi (2021) have conducted a comparative analysis to analyse the effect of such this crisis on organisations, knowledge strategies and the environment.

In their analysis, they have come to the same results as a group of medical students from the United Kingdom, that support the idea that: despite the recent challenges caused by the COVID-19 pandemic, this period has acted as a **catalyst for new opportunities** both for professional development and innovation (McMaster et al., 2020). They concluded that disruptive events, such as economic recessions and pandemics, can **push innovation** forward.

2.2 Introduction to 3D printing

The following chapter provides an introductory overview of 3D printing technology and its characteristics, starting with a brief historical background.

2.2.1 History

The idea of 3D printing has been developed since the early 1970s. Pierre A. I. Ciraud (1972) described the method as an application of powder where each layer solidifies through the action of a high-energy beam (Kihm & Trommer, 2014). Two decades later, Emanuel Sachs (1993), an MIT scientist, patented with co-workers the "*Three-dimensional printing techniques*". The idea was no longer to link the different layers employing a high-energy beam but binding material (Jamróz et al., 2018). After nearly 40 years of development, many industries are using the **additive manufacturing technology (AM), also known as 3D printing**. Indeed, a long list of conceptual AM techniques has emerged over the last few decades, many of which have gradually reached the industrial and commercial market, sometimes driven by highly dynamic open source communities (Sawhney et al., 2020). Since then, several improvements in the materials used in the process have been made: either plastic, metal or concrete.

2.2.2 Definitions

The concepts mentioned above ("3D printing", "additive manufacturing" and "construction") will be used extensively throughout this thesis; here are their definitions proposed by Labonnote et al. (2016):

- "**Additive manufacturing (AM)**" is defined as the process of assembling materials to produce objects from 3D model data, generally layer by layer, as opposed to subtractive manufacturing approaches.
- "**3D printing**" describes the various methods used to generate a 3D object.

- "**Construction**" refers to the process of creating large-scale structures where the purpose is related to structural engineering. These structures may involve large-scale engineering products such as houses, bridges and other types of buildings.

2.2.3 AM and 3D printing

According to Ghaffar et al. (2018), AM is a process that forms **layers** to create 3D solid **objects from digital models** with different types of materials. According to other researchers, Gibson et al. (2020), AM is a range of technologies that can translate these data into tangible models in an automated process. In fact, the concept of AM covers a range of technologies that allow similar products to be produced in a short time, such as rapid prototyping (RP), direct digital manufacturing (DDM), layered manufacturing (LM) and 3D printing (Saleh Abd Elfatah, 2019).

Commonly used AM technologies include the use of a computer, a 3D modelling software, a machine equipment and layering materials. In his study, Gopalakrishnan Deivanai (2020) described each step of the **AM process** in practice: the process begins with a 3D Computer-Aided Design (CAD) model of the desired part. The geometry is then optimised according to the printer specifications (Jamróz, 2018). After the design has been created, the file is converted to a Standard Triangle Language (STL) file format that contains the coordinate information of the object or part boundaries. Next, the tessellated object is broken down into layers with the same layer height (Gopalakrishnan Deivanai, 2020). The model is finally uploaded to the AM equipment, and the machine reads the data from the design file and proceeds to lay down the material in superimposed layers to create a 3D object (Chang, 2016). The different stages of preparation of 3D printed objects are shown in Figure 3 and Appendix 2 provides more detailed information about the 3D printing process.

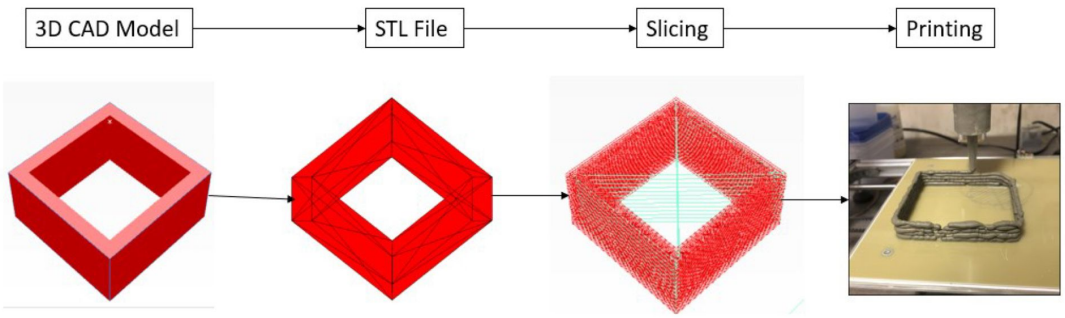

Figure 3 - 3D printing process flow diagram. (Gopalakrishnan Deivanai, 2020)

The **materials** used to create these objects are diverse; they can be solid, viscous, powders, or liquids (Labonnote et al., 2016). The possible applications of each AM process will be introduced in another chapter. With the increase in research on the development of 3D printing, there was an expansion in the range of materials that could be used to manufacture 3D objects, which led to the materialisation of distinct AM categories.

Currently, according to ISO/ASTM 52900-15 (ISO/ASTM 52900-15, 2015), AM can be divided into **seven process categories** that are presented in Figure 4, namely binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photopolymerization (Pessoa et al., 2021). For a more comprehensive understanding of the differences between these process categories, an organisational chart is provided in Appendix 3 to explain each process.

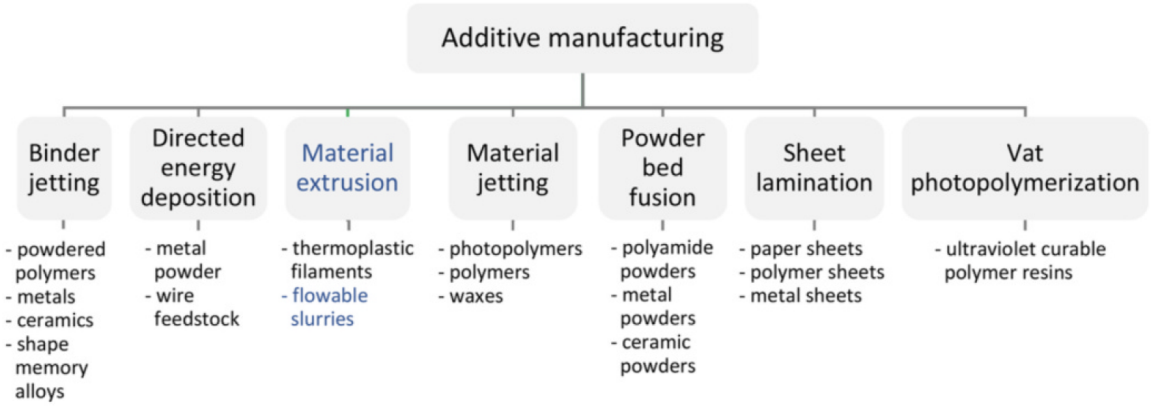

Figure 4 - AM categories with materials used. (Pessoa et al., 2021)

2.2.4 Opportunities

In the article from Gibson et al. (2020), it can be read: "*We can therefore say that the **AM** machine is a What You See Is What You Build (WYSIWYB) process that is particularly **valuable the more complex the geometry***.". This is further highlighted by the study of Langelaar (2016) where he says: "*Compared to conventional subtractive fabrication techniques, AM offers a much larger design freedom, and a completely different cost structure: for AM, geometrical complexity of a component is no longer a main indicator of manufacturing costs.*".

According to the articles cited by Ghaffar et al. (2018), AM allows creatives, architects, engineers and designers to make **customised designs** in a one-step process. The emergence of new technologies, coupled with demands for more sustainable and resource-efficient practices and trends for futuristic structures, are causing changes in the scale and distribution of

construction. Approaches such as AM offer a big step back from traditional construction methods. These new robotic processes offer solutions to **improve productivity, quality, labour conditions** and the lack of skilled workers.

2.2.5 The 3D printing applications

Back in 2003, Hague (2003) argued that AM has become an integral part of modern product development, having been commercialised over the last three decades, notably in aerospace, automotive manufacturing and medical applications (Lim et al., 2016).

Back in 2012, Ratto and Ree (2012) considered the medical industry as a niche market for the AM industry. The same applies to the pharmaceutical industry where Jamróz et al. (2018) wrote in one of their papers that "*Within many discoveries introduced into pharmaceutical and biomedical market, three-dimensional printing (3DP) is believed to be the most revolutionary and powerful.*". We can also read: "*Nowadays, three-dimensional printing is one of the fastest developing branch of technology, art and science, and still broadens the applications.*". According to them, 3D printing processes are gaining importance in pharmaceutical and medical applications due to the possibility of rapidly producing customised objects that can be used in therapy or personalised medicine.

Today, AM technology is regarded as **one of the most studied emerging technologies**, as 3D printing has impacted a variety of industries and is now an integral part of contemporary product development (Truong, 2019).

The technology has been commercialised to the point that the machines are now **accessible and affordable** for private use. Like in the medical field, industrial applications are apparent in aerospace and automotive manufacturing (Lim et al., 2012). Additive techniques are generally used to make small components, although AM, coupled with automation and robotics, have also the potential to disrupt the way in which structures are built in the construction industry (Sawhney et al., 2020).

As Lin et al. (2020) explained, AM, along with its many benefits, has the potential to be one of the **main driving forces for the construction industry's advancement**, particularly with how together with off-site manufacture, it could change construction methodology paradigms at a large scale. In the interest of further exploring 3D printing in this sector, an overview of the industry will be provided in the following chapter.

What to remember from Chapters 2.1 & 2.2[1]

- The concept of innovation usually involves a life cycle, called the "innovation life cycle", which looks like an S-curve (Figure 1).
- The concept of "disruptive innovation" was introduced by Bower and Christensen (1995). A disruptive innovation gives firms a significant competitive advantage by enabling them to bring a different value proposition to the market. Llopis-Albert et al. (2021) developed a model to determine when a technology is disruptive.
- Additive Manufacturing (AM)/3D printing emerged in the 1970s and is now used in many industries. It is a process in which layers are formed to create 3D objects from digital models using different types of materials.
- There are many 3D printing processes for a variety of applications. Each has its own advantages and challenges.

2.3 The construction industry

2.3.1 Global environment

The construction industry has made an essential contribution to countries' economies across the world. In Europe, for instance, the sector of activity is the **leading employer**, representing 7.5% of total European employment in 2020 according to Pessoa et al. (2021). The construction sector is also **vital for the EU economy**. In 2016, the industry directly impacted 18 million jobs in the European Union, accounting for approximately 9% of the EU's gross domestic product (European Commission, 2016). The sector of activity is also responsible for building infrastructures that drive progress, thereby promoting economic growth. It also provides solutions for climate, social and energy challenges (Pessoa et al., 2021).

Stakeholders and value chain

The value chain is the business model that describes the set of activities required to create a product or service. In other words, it is a step-by-step business model for transforming a product or service from idea to reality (Tardi, 2020).

[1] References to the points listed in the summary boxes of this work are found in the chapters preceding them.

In the construction sector, the different players (engineers, architects, contractors, subcontractors, consultants and material suppliers) are present at each stage of the process. Therefore, each stakeholder has a crucial role in the **value chain procedure of the industry** (see Figure 5) (Eriksson, 2007).

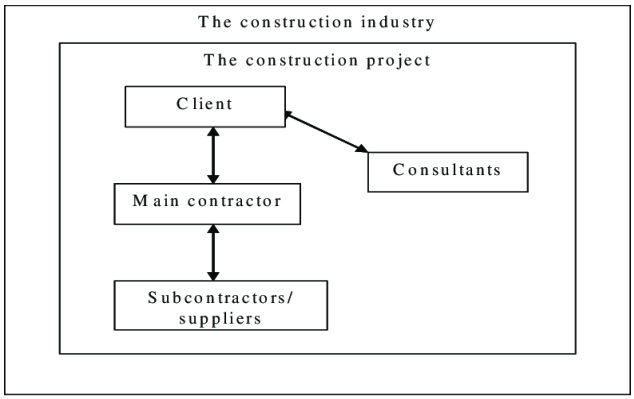

Figure 5 - The different players of the construction industry. (Eriksson, 2007)

Challenges and evolution of the construction industry

The construction industry has proven to be **very conservative** in recent decades. The fundamental principles of construction have not changed for hundreds of years; the Romans invented concrete around 100 BC, and today, we are still using it as a primary build material (Buswell et al., 2007). In terms of technological development, construction is far behind other industries such as automotive and aerospace. Some well-known problems in the construction sector have not yet been successfully solved. These issues become more complicated the greater the number of processes and participants and the more complex the projects become in their various phases. Muñoz-La Rivera et al. (2020) listed a couple of them in Appendix 4.

As a result, the sector faces serious problems and **productivity issues** due to poor project management and execution and insufficient investment in skills development, R&D and innovation (García de Soto et al., 2018). Over 20 years, the global construction productivity grew only about 1% a year in comparison with the manufacturing industry that grew 3,6% a year over (Barbosa et al., 2020). Another study by Bock (2015) suggests the same idea: productivity in the construction industry has declined globally in recent decades. It has one of the lowest capital investments and low capital intensity compared to other sectors.

In a report from the European Economic and Social Committee (2015) on "*Living tomorrow. 3D printing — a tool to empower the European economy*", one can read that: "*Manufacturing*

makes a significant contribution to the economy, particularly in terms of innovation, productivity and high quality jobs. However, Europe's industry has lost ground in the past two decades resulting in a decline in industrial employment and added value". In response to this statement, the Committee is interested in the future of the manufacturing industry: "*Using the right advanced manufacturing technology, Europe could re-shore production from lower-wage regions to spur on innovation and create sustainable growth at home*" (European Economic and Social Committee, 2015).

According to the Industry Digitization Index provided by the McKinsey Global Institute (Barbosa et al., 2020), construction is one of the least digitised sectors across the world, ranking second in the US, ahead only of agriculture, and last in Europe (Blanco et al., 2020). However, to increase the efficiency and overall productivity of the industry, the construction industry **must embrace the digital age** (Pessoa et al., 2021). The article "Digitization in the construction industry" by Roland Berger (2016) also supports that argument. We can read: "*There is no alternative to digitization. Even on the building site. Construction needs to catch up.*".

2.3.2 Belgium

Productivity of the construction industry in the Belgian market

Part of this study will be dedicated to the Belgian market and the evolution of the construction industry in Belgium. According to Statbel (2021), Belgium occupies a significant position in the construction sector in Europe. Despite the overall low productivity of the industry globally, Belgium benefits from one of the highest private property ownership rates in the European Union. Since Belgium is located in the heart of the EU, many multinational companies and other international organisations are interested in the Belgian market to set up their offices and production facilities. As a result, it has led to a boost in industrial and public construction and infrastructure in recent years (Open to export, 2017). Not surprisingly, the employment rate registered an increase of 12.6% in 2019, from 2010, accounting for more than 500.000 persons employed. (European Commission, 2020)

The construction market in Belgium is vast and is divided into three main sectors: Residential Construction, Non-Residential Construction, and Civil Engineering. Belgium is also a highly **competitive, growing market with opportunities** for international trade, especially for small and medium-sized enterprises. The Belgian market places great importance on factors such as design, quality, delivery and after-sales service (European Commission, 2020).

Total turnover in the Belgian construction sector rose to 111.4 billion euros in 2017 and will increase to 139 billion euros in 2019. This represents an increase of 67.6% since 2010. In addition, the gross operating rate in 2017, an indicator of the sector's profitability, remained at the same level of 2010, 14.6% (European Commission, 2020).

Challenges on the Belgian market

While there are plenty of initiatives launched on the Belgian market to contribute to the industry's growth, the latter also faces **several challenges**. The sector faces an issue concerning a shortage of skilled workers and a skills mismatch for existing jobs. In addition, the construction industry suffers from late payments that worsened due to the onset of COVID-19. Nevertheless, despite the exceptional circumstances of the pandemic, the Belgian construction sector is **expected to grow** from 2021 onwards. Investments in the industry are expected to increase in the coming months, driven by increased federal government support for developing new social housing and the renovation of the existing building stock (European Commission, 2020).

2.3.3 Overview of the legal and regulatory framework

In a recent blog article, Alizadeh (2017) claims that the responsibilities associated with the design and construction of infrastructures are so high that all stakeholders, from contractors to engineers, must be extremely cautious when making new decisions that involve some form of risk. For this reason, there are building codes and standard practices that must be followed during the design, construction and maintenance phases.

With current and upcoming new technologies, testing methods, materials, and practices related to the construction industry and developed by researchers in universities and research centres, we see a **greater range of standards** emerging every year on the market. In recent years, we have seen such examples with self-healing concrete and 3D printed structures. However, it takes a lot of time and effort to standardise these methods, which explains the slow process of introducing new technologies in the construction sector (Sawhney et al., 2020).

2.3.4 Current building methods - Specificities

In construction, there are **several methods of building construction**. Each requires specific materials and has properties that distinguish it from the alternatives. Sometimes, a material is selected for its visual qualities. Still, it may also be chosen for functional reasons, as when a

highly durable or water-resistant concrete is chosen instead of wood. The choice may also be based on technical specifications, such as selecting a non-combustible material. Finally, one system may be preferred over another because of its cost, energy consumption, maintenance or useful lifetime (Allen & Iano, 2013).

More than that, the **right materials** should properly be analysed according to the site, client's requirements and other factors like weather conditions. The most common building materials include concrete, wood, steel, cement, bricks, clay, etc. However, as mentioned earlier, the construction industry has been slow to innovate and has not been able to increase productivity. Currently, the construction sector is shifting from working with 2D Computer-Aided Design (CAD) processes to 3D modelling with BIM, an alternative way of working and managing information presented in the next chapter (Pessoa et al., 2021).

2.4 Introduction to Construction 4.0

The construction industry is responsible for the infrastructural and physical development of countries. It plays a pivotal role in determining the economic balance of the nations of the world. Hence, there is a need to continuously develop advanced methods for the execution of construction operations. The concept has led to the development of Construction 4.0, which involves the harmonisation of interruptions in technological applications to increase productivity in construction (Lekan et al., 2020). This chapter examines the impact of Industry 4.0 on technological development for the construction industry and explores the relevance of Construction 4.0 and other technologies (Appendix 5) provides an overview of these technologies).

2.4.1 Industry 4.0

Industry 4.0 relates to the fourth industrial revolution. It is a new level of organisation, control and development of processes and products over their entire life cycle. It applies technologies to succeeding generations of advanced tools and methods for optimising processes in a coordinated and efficient manner (Sanghavi et al., 2019).

2.4.2 Construction 4.0: introduction and overview

With the advent of new technologies, the construction industry had to modernise. In the last decade, the construction industry has accelerated the implementation of important innovations

for its management and design processes and is undergoing a significant transformation (Muñoz-La Rivera et al., 2020). There have been many developments that have had an impact on the usual way of working and collaborating, including the organisation of construction projects and the roles of the different stakeholders, especially the trend towards more openness between project stakeholders and the introduction of technologies such as **Building Information Modeling (BIM)** (Liu et al., 2017).

Construction 4.0 is a new evolving state of construction practice that entails a revolution that incorporates digitalisation in construction (Sawhney et al., 2020). In the article "*Innovation and Industry 4.0*" by Pascall (2019), Construction 4.0 relates to digitalisation in different phases of the construction process, such as the use of construction and design informatics, AI, data analytics, BIM and robotics. Other references, from Rüßmann et al. (2015) for instance, describes construction 4.0 as the one that involves the application of technologies such as social media, mobility, analytics, cloud, AI, robotics, in expressing construction phenomena and new areas of practice.

Despite the many existing definitions, we will consider in this study "**Construction 4.0**" as the construction sector's response to the adoption and use of Industry 4.0 on the construction site. The goal is to optimise time and cost, quality control and work safety (Muñoz-La Rivera et al., 2020). According to a study, Construction 4.0 should be located at the intersection of three major issues: **digital shift**, **industrialisation of construction**, and **sustainable building** (see Figure 6). The sustainable aspect of construction is linked to the three pillars of sustainable development: economic, ecological, and social challenges that will be presented in Chapter 6 of the Literature Review (Boton & Forgues, 2017).

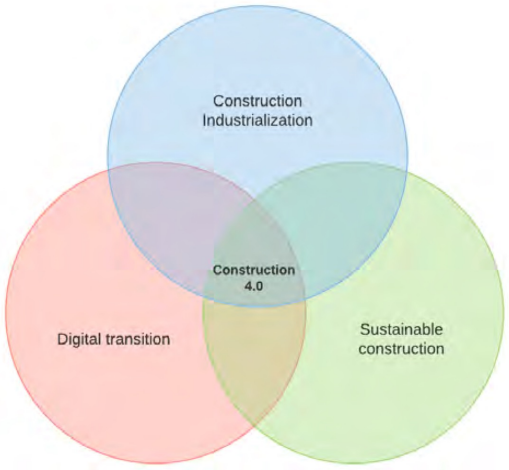

Figure 6 - The three major challenges of Construction 4.0. (Boton, Forgues, 2017)

In their paper, Muñoz-La Rivera et al. (2020) provide a methodological framework (see Appendix 6) for Construction 4.0. The model synthesises the life cycle stages of the construction industry: from the conceptualisation of the project to the demolition or renovation of the structure. It also incorporates the principles of Industry 4.0.

2.4.3 The digital transition of the construction industry

Overall

Digitisation is about companies encountering connected systems at every point in the value chain. It is about working with tools and practices based on information and communication technology (Roland, 2016). Digital technologies are fundamentally changing the way business is done. Digitisation has brought significant changes to most industries, transforming the business environment while maximising profits. For example, in the music industry, digital offerings already account for 46% of total global sales (Roland, 2016).

Construction increasingly relies on digitised processes and buildings, and infrastructures are becoming data sources in their operational phase (FIEC, 2017). Many players in the construction industry today recognise how digitisation is impacting every part of their business. According to a study by the Association of German Chambers of Commerce and Industry (DIHK), 93% of companies agree that digitisation will influence every part of their processes (Roland, 2016).

BIM and the digital shift

The development of the BIM approach has been central to the digitalisation of the construction industry and the paradigm shift of the construction industry towards better productivity and sustainability. Moreover, it has been crucial in raising awareness and progressive paradigm shifts in the construction industry (Boton & Forgues, 2017).

In a nutshell, BIM is a unifying concept that generates multi-dimensional parametric models. Digital designing allows problems to be solved before the start of the construction. It also eliminates the need for numerous copies of blueprints, which cannot always be guaranteed to be the latest versions. Instead, a BIM model can be updated in real-time by all partners concerned and the data collected is then available throughout the life of the building (FIEC, 2017).

Together with the integration of all stakeholders in the design, construction and operation process, **BIM** improves the industry and brings in line with its counterparts in the automotive or aerospace sectors (Muñoz-La Rivera et al., 2020). While BIM is only one tool, it makes the **difference between standard construction and digital construction**. However, the digital transition in the construction sector does not only relate to the use of BIM technologies. It also relates to complementary technologies: the Internet of Things (IoT), Cloud Computing, Big Data, 3D printing, etc. (Boton & Forgues, 2017).

2.4.4 Industrialisation and automation

Industrialisation and automation are characterised by a number of features. One of these is the shift from on-site construction to off-site production of parts of structures and components, using more automated production processes such as robots. By this, we introduce the notion of "pre-fabricated" construction. In short, the components of the infrastructure or building are produced off-site and are then assembled on-site (FIEC, 2017).

On the one hand, **industrialisation** of construction aims to find ways to reduce waste in the construction supply chain and improve efficiency on construction sites to increase the industry's productivity (Boton & Forgues, 2017). On the other hand, **automation** is closely related to the use of 3D printing, which will be presented and discussed in the course of this thesis.

What to remember from Chapters 2.3 & 2.4

- The construction industry is a very active sector worldwide: it creates thousands of jobs and is vital for the EU economy.
- The sector, which is very conservative, has been one of the least digitised industries in recent years. As a result, the industry, which is also characterised by many standards, has faced significant productivity issues.
- Today, the sector offers new solutions to climatic and social challenges thanks to new practices and materials with lower environmental impact.
- Construction 4.0 is a new stage of development in construction that incorporates digitalisation and increases productivity in construction. It provides the opportunity to automate and digitise the design and construction processes thanks to new technologies such as Building Information Modeling (BIM).

2.5 3D printers launch in the construction sector

2.5.1 Digitally-native approach to building construction

History and evolution

As indicated above, the construction industry has relatively been **slow to adopt many innovations** that have revolutionised other industries. Since Pegna (1997) first introduced "*freeform construction*", several AM processes have been explored for large-scale application, and recent trends have indicated that the industry is trying to move towards a digital-based design system (Wangler et al., 2019). One good example is the introduction of **BIM**, presented in the last chapter. Given the impact of AM in numerous industrial applications, architects, engineers, and builders have become interested in their use in construction (Naboni et al., 2019).

García de Soto et al. (2018) stated that **digital fabrication** allows for greater productivity than the established building methods. To illustrate, Figure 7 shows the contrast between the traditional construction methods with blocks or bricks and the 3D printing method.

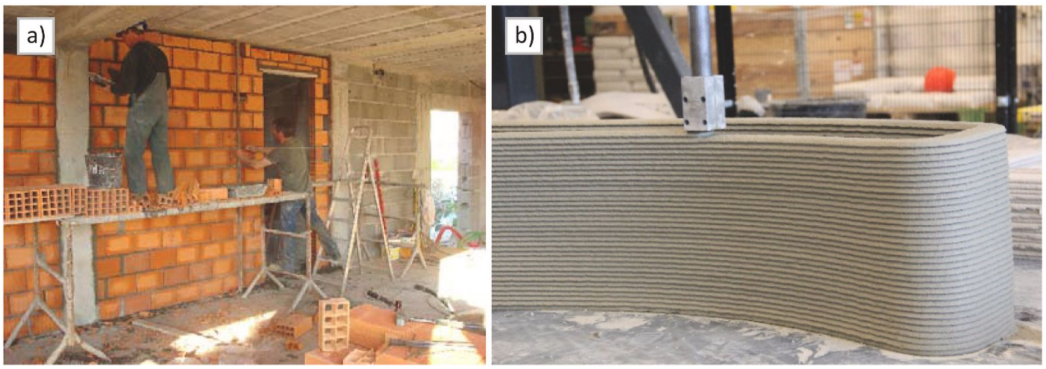

Figure 7 - Construction techniques: a) Traditional construction with bricks and b) Construction 3D printing. (Wofs et al., 2019)

Recent papers like "*3D Printing in Architecture, Engineering and Construction (Concrete 3D printing)*" by Saleh Abd Elfatah (2019) give an excellent introduction to 3D printing in construction by stating that 3D printing architecture models have become an interesting alternative to typical 3D printers used to 3D print random objects. According to Saleh Abd

Elfatah (2019), "*3D printing at a construction scale will have a wide variety of applications within the private, commercial, industrial and public sectors.*".

Collaboration efforts across the building industry have led to the approval of 3D printing as a safe, affordable, and artistic advancement in the field of construction and engineering (Truong, 2019).

In a study from Bock (2015), an analysis was conducted to understand where construction automation stands in the **Foster's S-curves model** (introduced in chapter 1). The overlaying curve illustrated in Figure 8 describes the relationship between the stagnation and technical limits of the traditional way of building and the initiation, development and growth of the future of construction automation (CA). As shown on the graph and interpreted by Bock (2015), after a certain period of time, the construction automation's performance and adoption rate exceed those of conventional construction.

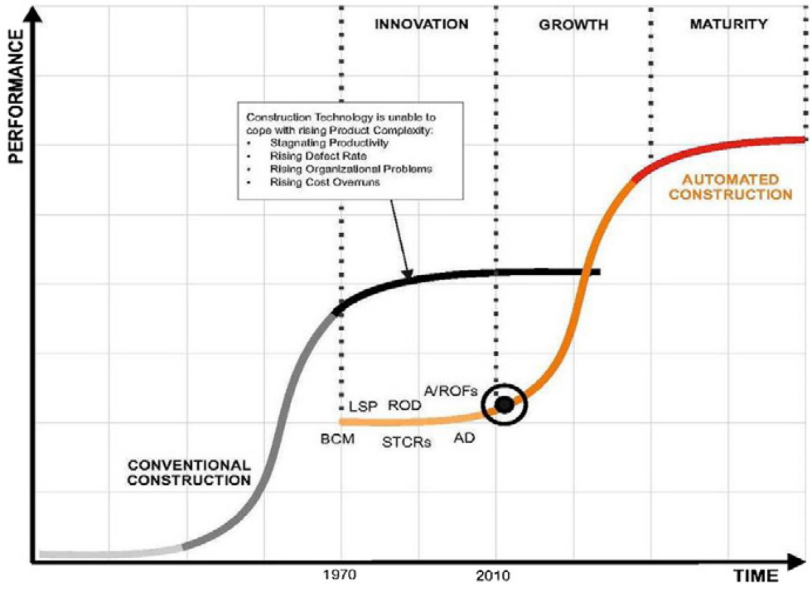

Figure 8 - Foster's (1986) S-curves applied to construction: the black mark on the graph corresponds to the position of the new construction technologies[2] (Bock, 2015).

Materials used for 3D printing construction

The use of AM allows the use of both natural and recycled materials, thus contributing to a more **sustainable approach** to construction, which is an aim of Construction 4.0. (Craveiro et

[2] BCM = building component manufacturing; LSP = large-scale prefabrication; STCRs = single-task construction robots; ROD = robot-oriented design; A/ROFs = automated robotic on-site factories; AD = automated deconstruction

al., 2019). Currently, the most commonly used materials in digital fabrication for construction projects are wood, steel, polymers and concrete (Oyster, 2018). Of these, polymers are the least common and their use in building components is limited due to high manufacturing costs and low rigidity (Paolini, 2019).

Except for wood and steel, **concrete and cement-based materials** have been increasingly used for digital fabrication techniques in the last 5-10 years. To put into perspective, a recent study conducted by Tay et al. (2017) showed that research on concrete printing techniques almost doubled worldwide in 2013-2016 compared to the previous 16 years.

Concrete is the most commonly used construction material in the world. This is due to concrete's intrinsically functional properties: easily available raw material all over the world, ease of processing and handling, and its ability to move from the liquid state in which it can fill a mould, to the solid-state in which it can subsequently support a structural load (Wangler et al., 2019).

Types of 3D printing processes in construction

3D printing processes are closely related to the materials being handled. To print **metal** parts, bed fusion and direct energy deposition processes can be used. During the printing process, a heat source such as a laser or electron beam fuses the metal raw material into the form of powder or wire (Paolini et al., 2019).

Large-scale applications using the Wire Arc Additive Manufacturing (WAAM) technique have recently gained much notoriety through the MX3D bridge project in Amsterdam (see Figure 9). The MX3D project is a 12-meter stainless steel 3D-printed bridge that was unveiled in 2015. Six years later, in July 2021, the 3D-printed pedestrian bridge designed by Joris Laarman was completed and opened in the centre of Amsterdam (Demaitre, 2021).

Figure 9 - Steel Bridge 3D-Printed by MX3D in Amsterdam. (Demaitre, 2021)

The first attempt to use **cement-based materials** by the 3D printing procedure was suggested by Joseph Pegna (1997). As concrete dominates 3D printing design to a great extent, this subchapter will mainly focus on the types of 3D printing technologies used in building with concrete. Figure 10 shows an example of a 3D printed concrete multifunctional wall produced by Gosselin (on the left) and CyBe (on the right) (Gosselin et al., 2016; Cybe, 2016).

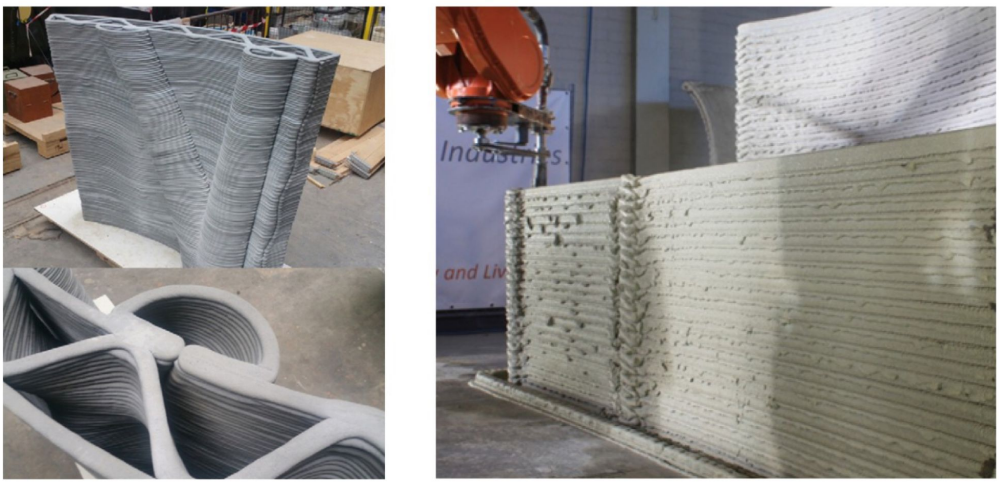

Figure 10 - Examples of 3D printed concrete walls. (Gosselin et al., 2016; Cybe, 2016)

Recent work by Mechtcherine et al. (2019) underpins that concrete will continue to be the focus of interest in the coming decades. A recent review paper by Austern et al. (2017) classifies the occurrence of digital fabrication projects in the available literature and notes the implementation of approximately 15 different automated processes using more than ten different materials. All these fabrication techniques inevitably lead to feasibility and

affordability issues that often force engineers and architects to adapt the design itself according to the constraints imposed by the new processes.

Looking at the literature examining existing approaches to AM targeted at construction, Allouzi et al. (2020) explain that it exists three different processes (see Figure 11) that are suitable for construction applications:

1. **Contour Crafting (CC)**: also known as *deposition modelling* or *material extrusion*, is a technique in which concrete is automatically placed layer-by-layer through one or more moving nozzles mounted on a robot arm, gantry (type of printer), or crane, following a predefined digital path (Menna et al., 2020) (see Appendix 7);
2. **D-shape**: also known as *selective binding* or *binder jetting*. In this technique, a selective and automated laser or liquid is applied to a layer of particles, fusing the material and creating a solid body such as sandstone or steel. During the chemical or thermal reaction, each new layer of material hardens on top of the previous layer (Menna et al., 2020);
3. **Concrete printing**: this is the extrusion of mortar. The process has been developed to retain 3D freedom (Allouzi et al., 2020);

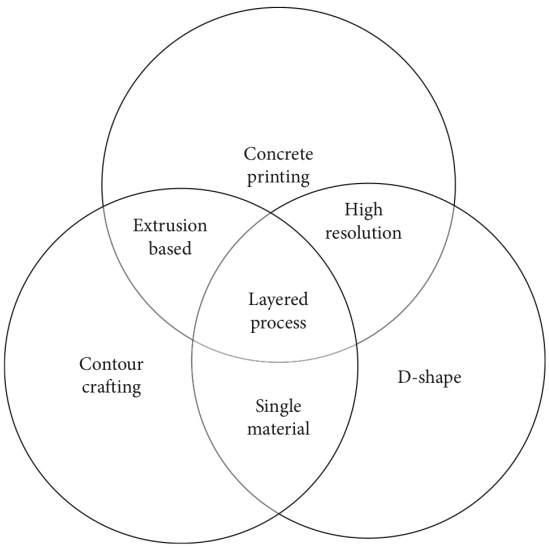

Figure 11 - Similarities between the 3D printing processes. (Allouzi et al., 2020)

The three procedures are the same in terms of the slayer-based approach. On the contrary, each of these procedures was developed for different applications and materials (Allouzi et al., 2020).

While the listed approaches are highly interesting, the following chapters will only provide an overview of the most commonly used approach in large-scale 3D printing - CC (or selective deposition by extrusion) - for the sake of simplicity. This method seems to be the most used due to its economic viability and overall technology readiness (Mechtcherine et al., 2019).

Process for 3D concrete printing with concrete

The **functioning of a 3D printer in construction** is similar to that of a conventional 3D printer, except it is on a larger scale (Truong, 2019). As presented in a previous chapter, a computer-aided design (CAD) model is first generated, tessellated (STL) and converted into the standard STL format that specifies spatial coordinates of the structure. Then, the model is sliced into multiple cross-sections that are sent to the 3D printer (Craveiro et al., 2019). Figure 12 shows the typical information flow of a 3D printing process.

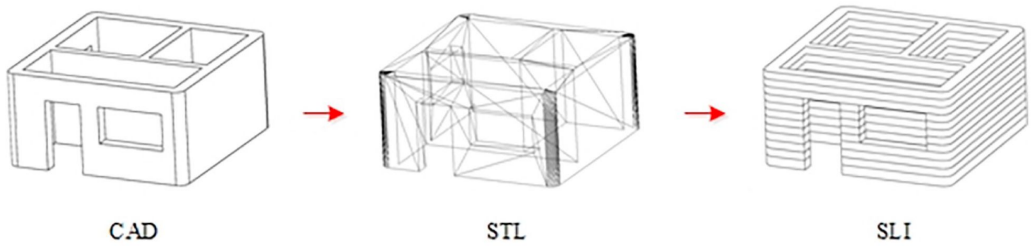

Figure 12 - Steps to produce a physical object through AM in construction. (Craveiro et al., 2019)

The **components of a 3D printing machine** used in the construction industry are presented in Figure 13 and Appendix 8. The large scale printer has a printhead (nozzle) with the 3D printing material attached to the end effector that discharges the print material (Truong, 2019). It also has a positioning system (manipulator), that carries the print head and moves it precisely along the print paths. The type and size of the manipulator significantly determine the possible print object dimensions. In addition to its primary function of printhead movement, the manipulator also has the task of ensuring the supply of concrete to the printhead via pipes (Mechtcherine et al., 2019). As Mechtcherine et al. (2019) explain, the movement of the manipulator should be fast enough so that economical printing speeds can be realised.

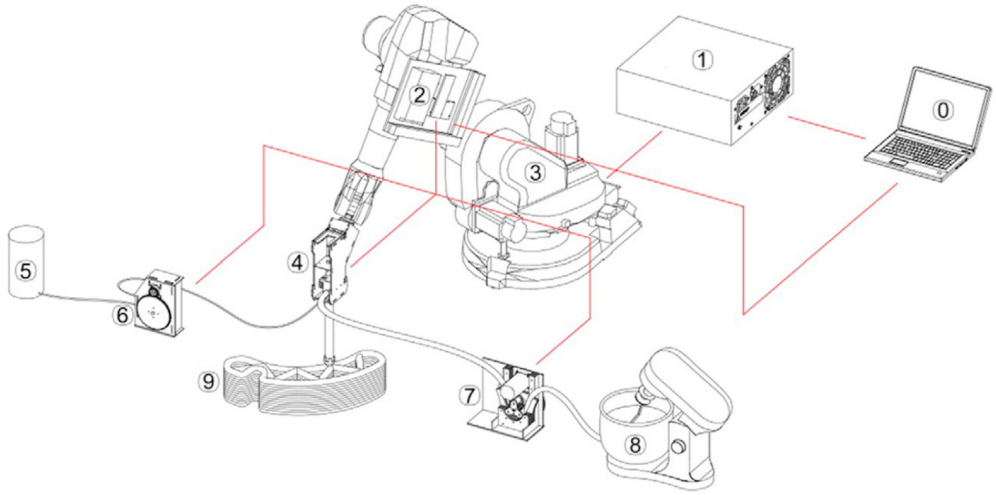

Figure 13 - Schematic of the 3D printing setup: 0. System command; 1. Robot controller; 2. Printing controller; 3.Robotic-arm; 4. Printhead; 5. Accelerating agent; 6. Peristaltic pump for accelerating agent; 7. Peristaltic pump for premix; 8. Premier; 9. 3D printed object. (Gosselin et al., 2016)

Concerning the pump used for conveying the concrete, it is generally located outside the printing area. Once ready to operate, the concrete is pumped through a hose over a relatively great distance to the printhead. Then, the computerised 3D printer moves the end nozzle to the coordinate points indicated by the computer. Finally, the concrete is discharged through the nozzle at the end of the printhead (see Appendix 9) in layers with a relatively small cross-section, about 30 to 50 mm in width and 10 to 30 mm in height (Mechtcherine et al., 2019). As illustrated in Appendix 10, the computer model has been sliced into various layers, and the 3D objects or structures are printed layer by layer by creating a nozzle path (Truong, 2019).

Generally, existing concrete printing projects used conventional industrial robots to move the printhead. The choice of these robots as manipulators for the printhead seems evident at first because industrial robots are available everywhere, relatively inexpensive, and very versatile. They also feature high precision and dynamics and are easy to control due to significant advances in software development (Mechtcherine et al., 2019). To increase efficiency and avoid insufficient or excessive concrete delivery rates, several nozzles can be used simultaneously. Khoshnevis et al. (2004), for instance, use such a “multi-nozzle system” in his CC process.

2.5.2 A different approach to build

On-site construction

When 3D printing a structure, the first option is to produce it entirely in an open environment employing machinery usually larger than the structure being fabricated (Craveiro et al., 2019).

As stated in the literature (Wangler et al., 2019), Dr. Berock Khoshnevis was the pioneer of CC. Looking at the literature published a few years ago, papers explain that he envisioned CC as an **on-site construction method**. In such a system, the printer would be constructed, produce the structure, and disassembled afterwards.

In their study, Buchli et al. (2018) refer to the technological advantages offered by on-site manufacturing with a fixed printer in a well-defined environment. According to the authors, this simplifies and sometimes eliminates many technical issues, which in turn simplifies design, programming, and deployment:

- If someone can ensure that the printer supplies the workpiece in an accurate and repeatable manner, the printer does not need to localize it.
- If the machine is in a fixed location, workers on site do not have to deal with unexpected circumstances, such as people or other machines breaking into the workspace.
- If the machine is tied to the ground, it does not need to locate itself in the area.

Buchli et al. (2018) go on to state that concrete structures are a perfect example of a product that fundamentally needs to be assembled at the point of final use. It is of course possible to partially prefabricate concrete structures off-site, but this presents some logistical challenges, which are presented in the next section.

Off-Site 3D Printing: prefabricated constructions

The second option refers to a more robust fabrication process, an **off-site construction method** enclosed in a controlled environment that produces components/subassemblies at the structural scales (but note entire structures) with a higher quality level.

For Wolfs et al. (2018), while on-site construction is an attractive prospect, it seems most apparent that prefabrication is where most digital fabrication technologies have the current highest potential. The overview presented in their study gives several advantages of building off-site, such as:

- A controlled environment can limit the impact of humidity and temperature sensitivity on mineral binders (materials).
- Prefabrication allows introducing a bit more flexibility in the construction process by expanding the options for the design and planning of the assembly process.
- Some processes such as particle bed fusion can only be expected to be viable in the prefabrication context.
- Prefabrication also increases the possibility of incorporating functionalities into concrete elements (Buswell et al., 2007).

2.5.3 3D printing applications

3D printed buildings and houses

3D printing can now be used to create **entire buildings** (Saleh Abd Elfatah, 2019). Until now, companies have generally limited themselves to smaller buildings, particularly compact single-storey houses. However, companies such as Kamp C have 3D printed a two-story house of 90m² using a stationary 3D printer system (see Figure 14). The model house is intended to demonstrate the benefits that 3D printing can bring to the construction sector (Sertoglu, 2021). Several other use cases will be presented in the practical part of this thesis.

Figure 14 - 3D printed house made by Kamp C. (Reversez, 2021)

3D printed bridges

3D printing can take advantage of the topology and properties of metals and concrete - ideal properties for creating pedestrian **bridges**. In this context, no moulds are required and we can adapt the structure to any shape thanks to the properties of 3D printing (Allouzi et al., 2020). The first 3D printed concrete pedestrian bridge was made in the city of Alcobendas in Spain. It has a length of 12 meters and a width of 1.75 meters (Valencia, 2017).

3D printed building components and architectural models

Architects and designers were early beneficiaries of 3D printing. Thanks to 3D printers, it is possible to create **components** such as facades, joints and architectural models. Some companies have started to print unique objects with particular aesthetic or functional properties. Some of the most famous 3D printed models are those of the Sagrada Família church in Barcelona (Gerbert et al., 2016). These models are based on Gaudí's visionary and sophisticated designs. Thanks to these new printed patterns, construction progress has been accelerated (de Laubier et al., 2018).

2.5.4 Costs and time savings

This chapter is devoted to the **cost and time aspects** of the project. Saleh Abd Elfatah (2019) forecasted that the labour cost of an architectural project could be reduced by up to 80% if most of the construction is done with 3D printers. García de Soto et al. (2018) conducted a cost analysis of the DFAB HOUSE, a three-story building module in Switzerland, to stimulate the debate on the impact of digital manufacturing on architecture, industry and society. As stated by the researchers in their study, it is important to note that the results from their research are only illustrative and should not be extrapolated to every digital manufacturing use case.

The results of the simulations, based on the collected data, were used to calculate the overall productivity and to perform a quantitative comparison between the construction of two types of walls using two different methods: a traditional manufacturing method and a robotized method (García de Soto et al., 2018). All data relative to the costs used in the case are given in Appendix 11.

First, the results demonstrated **no real economic advantage** in using the **3D printing** process **to build a straight wall**. However, the case study also shows no additional cost derived from the robotic fabrication method if the complexity of the wall geometry increases.

In their observations, they support the idea that, **as the level of complexity increases**, the use of robotic fabrication provides **significant savings**. The authors observed, for example, an increase in the relative cost of materials, which more than tripled when the complex wall was built in a conventional way (García de Soto et al., 2018). This observation has been confirmed by other studies, such as those of Pessoa et al. (2021), where we can read: "*Compared to traditional construction methods, construction 3DP has revealed technical, social, economic and environmental benefits, opens the possibility of producing more complex shapes with lower*

associated costs". However, this needs to be nuanced as the same study also states that there are still many aspects related to building performance that need to be further explored.

In terms of **time savings**, García de Soto et al. (2018) observed that the use of robotic manufacturing showed high reductions in hours per installed unit compared to conventional construction options. Consequently, the use of automated manufacturing also has significant benefits when the level of complexity increases.

2.5.5 Advantages and opportunities

Several drivers are pushing construction towards automation. Recent work introduces 3D printing and its potential advantages over traditional construction methods. According to Panda and Tan (2018) and Bos et al. (2016), the potential advantages of this method include the ability to build complex geometric shapes without the need for a framework, to use multi-materials depending on strength requirements, to optimise material distribution depending on application needs, to print on demand, and to reduce material waste. Abd Elfatah (2019) also defends that 3D printing could also enable building in harsh or hazardous environments unsuitable for human workers, such as locations with special conditions.

Looking at the literature, the consulting firm BCG shared a chart showing many of the benefits associated with 3D printing in construction (Appendix 12). Some of them are briefly presented below.

Customization: design flexibility

Design flexibility is usually presented as the main interest for 3D printing in high volume manufacturing applications. Ma et al. (2017) support that this technique allows more **liberty in architectural design** and offers versatility in building structures with different architectural geometries that are complicated or impossible to build using traditional methods. This argument is further emphasized by Lin et al. (2020) who claim that concrete elements with special cellular shapes can be 3D printed to produce lightweight elements with the potential for improved thermal insulation performance.

Speed of process, design, and production - reduced construction time

By operating 24/7 and reducing site disruptions and thus delays, 3D printers can drastically **reduce construction times**. Indeed, delivery of construction materials and interactions

between different trades are likely to be reduced, leading to a shorter supply chain (de Laubier et al., 2018). Printing speed is also likely to increase if we use multiple nozzles at the same time, as presented in the subsection "Cost and Time Savings" (Mechtcherine, 2019).

Sustainability and eco-friendly structures

According to Wofs et al. (2018), using 3D-printed design for architectural projects is more **environmentally friendly**. 3D printed design generates about **30% of the amount of waste of a regular construction project** because little energy is used. This is also the opinion of Truong (2019), who states that 3D-printed concrete is **waste-free** and can achieve similar results as traditionally built concrete structures in a more environmentally efficient manner.

2.5.6 Risks and challenges

The 3D printing technology also has its unique limitations. Some of its drawbacks are addressed in this section.

Regulation and potential legal issues

According to Ghaffar et al. (2018), one of the main barriers for the 3D printing industry is the **regulation and procurement rules**. This is particularly the case in Europe, where the construction sector relies mainly on existing standards for processes and material selection to ensure consistency and quality. The lack of certifications and the slow integration of standards may hamper the use of AM for the mass production of components in the coming years. As a result, many potential customers and tenants are not sufficiently informed or convinced of the safety and sustainability of 3D printed buildings (Ghaffar et al., 2018; de Laubier et al., 2018).

Structural strength and durability

As Lin et al. (2020) explain in their study, another issue is the **structural strength**. The interfacial strength between layers extruded from a 3D printer tends to be a problem due to the yield stress of each layer. Thus, over time, weaker concrete interfaces between layers can occur, leading to an overall loss of strength in the 3D printed structure.

Limited workspace

Mechtcherine et al. (2019) argue that it is important to consider the **limitation of the workspace**. Indeed, conventional stationary industrial robots used for 3D printing usually have a limited workspace, which makes them more suitable for printing objects with a size of a few

meters and a limited height. However, a few companies like XtreeE and TU Brunswick's DBFL have found alternatives to increase workspace. They suggest using multiple robots at specific distances, mounting the robot on a larger support system, or making it mobile itself.

2.5.7 Raw material supply chain and storage

According to Ghaffar et al. (2018), additive manufacturing of construction materials has been one of the emerging advanced technologies that aim to **minimise the supply chain** in the construction industry through autonomous production of building components directly from digital models without human intervention and complicated formworks. Craveiro et al. (2019) also confirm that the industrial use of AM processes involves a potential for a simpler supply chain, shorter lead times and lower inventories.

In analyzing the digital building process based on large-scale extrusion, Mechtcherine et al. (2019) identified several process steps shown in Figure 15. Each of these processes is further presented and described in detail by Buchli et al. (2018).

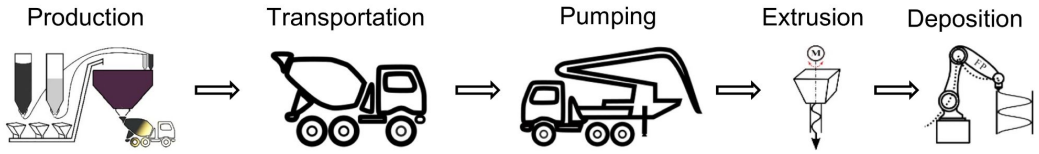

Figure 15 - Process stages in large-scale, on-site digital construction. (Mechtcherine, 2019)

2.6 Challenges of the launch environment

The following section will address the various external factors that positively or negatively impact the implementation of AM in the construction industry. This section is intended to provide an overview of the overall deployment environment of the technology and its complexity in terms of integration. It is composed of five main paradigms, which are respectively: technological, legal, economic, social and environmental.

2.6.1 Technological adoption

When looking at the technical aspect of 3D printing, the technology adoption appears to have a **secure place in the future of construction,** according to Ghaffar et al. (2018). The construction industry has traditionally been very conservative and unsuccessful at boosting

productivity. However, the construction industry's adoption of 3D printing has been hitting the headlines recently (de Laubier et al., 2018).

Recent papers, such as an article published by the consulting firm BCG, present the reasons why 3D printing is a natural fit for the construction sector (see Appendix 13). They also present several reasons for the sudden upswing for 3D printing by the construction industry:

1. **Technological advancement**: 3D printers and the materials used in construction processes are constantly improving, and their costs are decreasing. New types of machines are becoming available and are making more sophisticated use of robotics, enabling new applications.
2. **New entrants**: According to Statista (2021), the number of companies active in 3D printing in construction has recently soared (see Appendix 14). According to de Laubier et al. (2018), there were only about 20 startups in the field at the start of 2013. Five years later, in 2018, there were 65 organisations involved. As a result, 3D Hubs (2021), an online manufacturing platform, also shared an AM trend report in which it reveals that the AM global market grew by 21% in 2020, to a total of $12.6B, and is expected to continue to grow by 17% annually over the next three years.
3. **Strategic moves by established construction companies**: Well-known construction companies that have not yet made the switch to 3D printing technologies are in the process of adapting to these new trends (de Laubier et al., 2018). Most are looking to become early adopters of the latest technology, such as France's leading construction company Vinci which invested in the French startup XtreeE, specialised in printing concrete elements (de Laubier et al., 2018). Several construction material suppliers have also started to explore this technology. For example, the cement manufacturer LafargeHolcim has also teamed up with XtreeE to develop a range of experimental concrete mixes specifically for 3D printing (Gosselin et al., 2016).

2.6.2 Legal framework: 3D printing in the construction industry

One of the challenges previously outlined in the diffusion of 3D printing in construction is related to the **standards** and **regulation** of the technology. Hossain et al. (2020) recently published a study on the challenges of 3D printing. The development of standards, specifications and safety regulations for these non-traditional buildings is an essential aspect of the development of technology in the future. Strauss (2013) has also pointed out that the lack

of legislation to regulate 3D printed structures is problematic for the 3D printed houses, as any construction activity would adhere to such a code of conduct in case of injury or death.

The European Economic and Social Committee analysed different future perspectives for 3D printing in a first study. On 10 July 2014, the Committee decided to draw up an own-initiative opinion on "*Living tomorrow. 3D printing - a tool to empower the European economy*". Their report refers to AM, its disruptive and technological impact on employment, training, and education. Among other things, it is claimed that "*The European and national regulatory framework was unable to keep up with the fast pace of change in additive manufacturing, which is why a specific regulation is needed to deal primarily with standards and certification, intellectual property, consumer protection, health and safety at work, and the environment;*" (European Economic and Social Committee, 2015).
The Committee acknowledged that a **lack of standards** had limited the uptake of 3D printing in key industry sectors such as aerospace, medical and dental. In addition, professional markets often require certification, making the adoption of new technologies very challenging. The European Economic and Social Committee believes that the availability of standards will help increase the adoption of technologies and open up extensive research and development opportunities. It will also enable faster and more cost-effective certification of all materials, processes and products (European Economic and Social Committee, 2015).

2.6.3 Economic perspective: business model and value chain

The European Economic and Social Committee (2015) have commented on the future of AM and its disruptive impact on industry and business. In their publications, they claim that AM will shape new approaches to manufacturing. This implies that 3D printing will significantly impact the supply chain by making it more dynamic and centralised. To support this argument, they argue that digital designs and new technical solutions will form the basis for local personalisation and production, replacing the shipping of products from centralised factories. Consequently, this will lead to disruptive, digitally-driven business models with a high degree of customisation.

Jiang et al. (2017) also support this statement. They conducted a study to develop a scenario for the future outcomes of 3D printing to prepare for future developments. A core question guided their research, "*How will additive manufacturing influence the business ecosystem of firms, consumers, and society by 2030?*" (Jiang et al., 2017). In their final results, it appears

that the most likely scenario for 2030 will most likely **influence all elements of the value chain**: product development, product attributes, distribution channel and intellectual property. AM will dramatically change the way products are designed, distributed, and purchased. On the one hand, this means that the scope of products that can be printed via AM will be much larger, as multi-material AM and embedded electronics will be possible on a large scale. On the other hand, spare parts production will take place locally, which will completely change the role of suppliers in production chains, according to Jiang et al. (2017).

According to the European Economic and Social Committee (2015), rethinking the way companies produce and move products along their supply chains will lead to **new types of supply chains and business models**. Their papers suggest that a more straightforward and shorter value chain could replace the current value chain.

2.6.4 Environmental and social issues in the construction industry

In the architecture, engineering and construction sector, sustainability initiatives have profoundly changed the game rules in the industry and have been integrated into project planning and operational processes (Lu & Zhang, 2016).

In their research, Zhao et al. (2012) developed a CSR framework for construction companies (see Appendix 15). The framework is essentially used to list the main evaluation systems related to CSR and their respective performance issues. Some of the CSR issues from the organisational approach suggested that the construction industry has some similarities with other industry sectors.

In fact, the principle of CSR emerged in the late 1950s as proposed by Bowen and Johnson (1953). Since then, CSR has been more and more appreciated as a factor that contributes to the sustainable development of companies. To understand and measure the economic impact of CSR for business cases, Shreck (2009) structures CSR into four perspectives: **environmental, social**, **governance**, and **corporate engagement**. Of those four dimensions, two are addressed in the following sub-chapters: the social and environmental.

Social impact: education and training

According to The European Economic and Social Committee (2015), the deployment of AM technologies will directly impact the traditional production models and, more specifically, the internal work organisation, mainly through creating new jobs. As AM will facilitate the

construction of new plants, it will generate more consumer demand, which will, in turn, trigger more jobs. Consequently, **training** and **educational programs** will be needed to maintain and develop workers' readiness to master this new technology, which can also develop new learning programs from an early age.

However, as industrial deployment is still in its infancy, it is currently hard to certify its real impact due to the lack of studies on the subject. Furthermore, the likelihood that existing jobs will be substituted for AM operators must also be considered (European Economic and Social Committee, 2015).

Impact on the environment

This section aims to present the environmental opportunities of 3D printing through a review of related scientific studies.

In 2020, the UNEP (2020) published a report stating that the construction sector was a **highly active industry** responsible for 40% of global energy consumption in 2019. The overview presented in the report gives a insight into the current environmental trends of the sector:

- The CO_2 emissions for the building construction industry peaked at 38% of global greenhouse gas emissions in 2019.
- Due to the highly fragmented nature of the construction process, waste from construction and demolition accounts for around 25-30% of all waste produced annually in the EU.

Although it is a significant contributor to environmental impacts, the buildings sector also has a **high potential to reduce emissions**, according to Agustí-Juan and Habert (2017). Increasing concerns about sustainability issues in the building sector lead to the development of innovative technologies such as 3D printing, innovative building processes and materials to solve environmental improvements and overcome inefficiencies (De Schutter et al., 2018).

Ford and Despeisse (2016) refer to AM as a solution to **lower energy use**, resource demands and CO_2 emissions over the product life cycle. According to Labonotte et al., 3D printing demonstrates a significant potential to reduce material through **topology optimization**, produce complex geometries without supporting structures and integrate multi-functionality in building elements, which is impossible with conventional construction techniques.

In their research, Agustí-Juan and Habert (2017) conducted comparisons between large-scale 3D printing processes and conventional manufacturing in their life cycle assessment. The study concluded that the energy consumption of AM in construction is relatively low compared to the impact of building material production. Indeed, the manufacture of the robotic arm, the production and recycling of the lithium batteries used to power the robots, and the electricity used during the manufacturing processes contribute only slightly to the overall environmental impact of a digitally manufactured structure. This argument is also underlined by the study of Ma et al. (2017), which points out that concrete 3D printing could result in near-zero material waste. However, they also advise the reader to take this argument with a grain of salt as 3D printing is still in its early stages in the construction industry. Therefore, progressive innovations and developments of 3D printing in construction are required to realise the technology's environmental benefits fully.

As a consequence, the analysis of Agustí-Juan and Habert (2017) confirms that most of the **impact comes from the amount** and **type of building materials used**.

Pessoa et al. (2021) highlighted that AM **requires fewer materials** compared to conventional manufacturing processes. This is because the material only has to be placed where it is needed, thus reducing material consumption, which leads to an **optimization** of the construction components and reduces the industry's environmental impact. In short, less waste produced will result in a significant reduction in CO_2 emissions.

Material optimization: the challenge of the cement industry

Nowadays, **concrete** is the most commonly used construction material globally (Panda & Tan, 2018). But these aggregate-based materials are also the most common in the field of AM (Lin et al., 2020). A review of the literature (Agustí-Juan et al., 2017) shows that the process of concrete production has a relative impact of more than 75% on climate change due to the energy-intensive conversion process of clinker for cement production. The impact of concrete is mainly caused by burning fossil fuels during clinker production and the water consumed during gravel production.

The European Cement Industry (Cembureau, 2020) is ready to change. In 2013, the Cembureau developed the first **roadmap towards carbon neutrality** throughout the cement value chain. The goal was to reduce CO_2 emissions in the cement industry by 80% by 2050. In 2018, the roadmap (see Figure 16) was enhanced by the "**5C approach**", which promotes a collaborative approach along the Clinker-Cement-Concrete-Construction-Carbonation value chain, engaging

all stakeholders to turn the vision of low carbon emissions into reality. For each of the 5C, they identified areas where progress could be made to significantly reduce emissions and achieve the goal of carbon neutrality across the cement value chain.

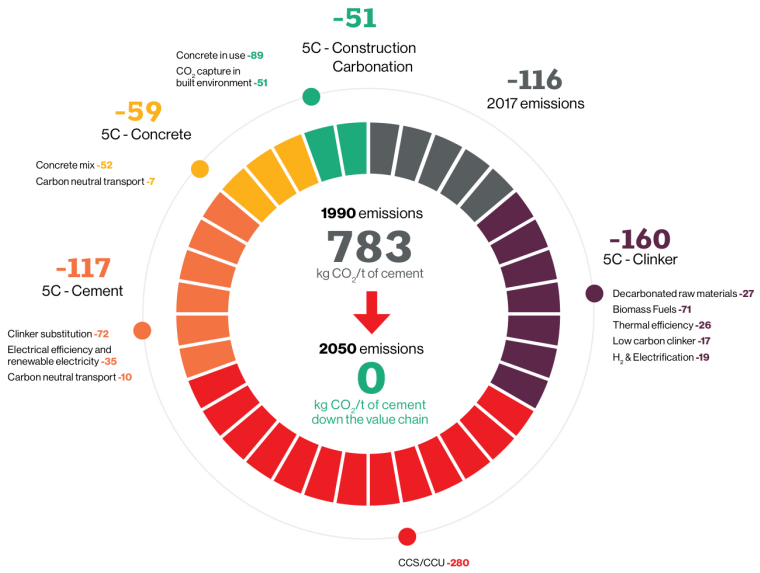

Figure 16 - Roadmap to climate neutrality in the cement industry by 2050. (Cembureau, 2020)

Circular economy

The modern construction industry has transformed from a profit-oriented environment to a constantly adapting socio-economic and environmentally driven entity in recent years. In light of this, and with the help of AM and proper circular models, the reuse and recycling of construction and demolition waste could guide the successful implementation of the circular environmental economy in the construction industry (Ghaffar et al., 2018).

According to the Cembureau (2020), "*the circular economy goes hand in hand with carbon neutrality*". The European Green Deal also recognises it: the **circular economy is crucial** for reducing emissions from clinker (the backbone of cement production) and managing waste from construction processes. The European Parliament (2020), on its side, believes that resource efficiency based on a circular economy strategy will enable the construction sector to seek to reduce CO_2 emissions and save energy actively.

What to remember from Chapters 2.5 & 2.6

- Digital fabrication in the construction industry, called "Additive Manufacturing" (AM) or "3D printing" in construction, was first introduced by Pegna (1997).
- It allows for better productivity than conventional construction for various applications.
- The use of AM allows the use of natural and recycled materials. The most commonly used materials are steel, polymers, and cement-based materials.
- There are several processes that are suitable for 3D printing: Contour crafting (CC), D-shape, concrete printing. The most widely used is CC. The functioning of the 3D printer in construction is similar to that of a conventional 3D printer.
- The 3D printer in construction can be used on-site or off-site (prefabrication). Depending on the type of application (house, bridge, or architectural components), each approach offers some opportunities and challenges.
- 3D printing in construction offers several advantages:
    - High degree of customization;
    - Simpler supply chain (fewer actors);
    - Less cost and time when the complexity of the structure is high.
- However, the technology also has its own limitations in terms of:
    - Lack of regulation;
    - Issues with structural strength;
    - Limited workspace.
- 3D printing seems to have a secure place in the future of construction, but the market environment also poses some challenges in terms of various aspects: technological adoption, regulatory framework, business model disruption, social impact on workers and organisations, and environmental impact.

3. Theoretical conclusion

The literature review presented in this paper highlights the essential theoretical foundations necessary to conduct research on 3D printers in the construction industry. By presenting the academic literature on disruptive technologies, 3D printers, the construction industry, Construction 4.0 and the current challenges related to the construction industry, the reader is able to make connections between the theoretical knowledge and the practical findings.

In their study, Seyed et al. (2018) mention that: "*The adoption of AM as an advanced technology appears to have a secure place in the future of construction, one that will most likely be unbeatable when it comes to, amongst others: shorten localised value chains and production expenses, increase resource efficiency and environmental sustainability by the inclusion of recycled materials and cutting on transportation costs.*".

While Seyed et al. (2018) have a positive view about the future of 3D printing, Pessoa et al. (2021) argue that there are still major problems to overcome for 3D printing to be accepted by the construction industry. According to the authors, one of these is the lack of specific legislation, which can make compliance a barrier to full adoption of the technology. The authors also support the idea that the building industry will not tolerate solutions that raise concerns about technical issues, such as acoustic insulation or energy efficiency (Pessoa et al., 2021). Similarly, García de Soto et al. (2018) also noted that clear guidelines on the social impact of 3D printing in construction were lacking.

This literature review does not provide detailed information about the legislation on 3D printing in the construction industry. However, it takes a first step by considering it and other issues when reflecting on the future of 3D printing in construction and the technology's potential impact on the market. The study looks at 3D printing from different angles to determine whether 3D printing could be considered a disruptive technology tomorrow.

4. Methodology

4.1 Overall - Research questions

This section is dedicated to the description and discussion of the research method and methodology adopted for this thesis. This report follows an academic structure: the content about 3D printing in the construction industry is introduced, and a literature review of related works is presented. A set of keywords was selected within the scope of the analysis to collect the data necessary to support the literature review: “Additive manufacturing”, “3D printing”, “Material extrusion”, “Construction sector”, “Sustainability”, “Disruptive technology”, etc.

However, what is not yet known are the practical answers as to what the future of 3D printing will be. It remains to be seen whether 3D printing could be considered a disruptive innovation in the construction sector.

In order to properly answer the research question posed at the outset of the thesis, **"Does 3D printing have a future in the construction industry and could it be a disruptive technology?"**, a number of sub-questions needs to be answered.

AM is an emerging technology that has the potential to be "*one of the next major technological revolutions*", according to Rayna and Striukova (2016). Although the technology has been around for over thirty years and has developed from its initial use for prototyping to a manufacturing technology that can be used with various materials in different applications, it has not yet reached its full potential (Ford et al., 2016).

The first step is to understand the uncertainties and speculations about the future of 3D printing in construction and therefore determine the market perception of 3D printing in the construction sector through its innovation journey.

Then, the second step is to understand why 3D printing has not yet established itself on a large scale in the construction industry. An analysis will be carried out to clarify the remaining technological challenges related to 3D printing in construction.

The literature review supports the idea that 3D printing is used for a variety of applications and offers some opportunities in each situation (Menna et al., 2020). To illustrate this, Schuldt et al. (2021) recently published a paper demonstrating the viability of 3D printing in the areas of structural design, process efficiency, labour, and environmental impact through the

construction of two 3D-printed homes in 2019 by ICON, an American company based in Austin (Schuldt et al., 2021). However, research is still lacking to identify the most favourable situations and priority niche applications for 3D printing in construction.

Finally, despite the rapid development of 3D printing technology in the construction sector, there are still several unsolved issues regarding its potential disruptive impact on the market. Therefore, this topic will be approached through a discussion in order to identify and measure the impact on the business models

As is the case for any other new potential disruptive technology, the success of 3D printing in construction depends on both technological progress and commercial relevance. The following research questions, that will be addressed in the practical part of this paper, are thus of major interest:

Research questions

1. What is the market perception towards 3D printing in the construction sector?
2. Why 3D printing, which has been around for over thirty years, is still struggling to make a substantial impact in the construction sector?
3. What are the most favourable situations and the priority niche applications where 3D printing technology could be used in the construction industry?
4. To what degree 3D printing could disrupt the business models in the construction industry from a socio-economic perspective?

4.2 Research strategy and problematic

When starting a data analysis, there are usually two methods of data collection to choose from: a qualitative and a quantitative data method. Both have a similar structure in terms of presentation: they usually begin with research questions, then analyze the data collected to answer those questions, then produce results based on the questions answered, and draw conclusions from those results (Chigbu, 2019). In order to answer the four research questions, only the **qualitative method** was used.

Qualitative approach

The objective of this study is to generate primary data on 3D printing in the construction sector. As 3D printing is a relatively new topic in the industry, the amount of existing data is very limited. Therefore, **qualitative research** was conducted to collect and analyze the missing data. The methodology used is based on a comparative analysis of existing literature and emerging knowledge based on a series of interviews and surveys.

4.3 Data collection method

4.3.1 Semi-structured interviews

In the first place, the objective was to gather in-depth insights on the main research question and provide new ideas for research. The majority of data that will be presented in the following section was collected through 10 semi-structured interviews with players of the construction industry in Europe. Among them, insights were provided by:

- Benoit Parmentier, Strategy and innovation manager at BBRI;
- Prof. Dr. Henke, Chair of Enterprise Logistics at TU Dortmund University and Director of this section at Fraunhofer IML;
- Mathias Rotgeri, Research assistant in material flow and logistics at Fraunhofer Institute;
- Marijke Aerts, Project manager at Kamp C Westerlo;
- Noël Naert, Engineering consultant at FEBELCEM;
- Xavier Köttgen, Architect and manager at Section A-A;
- Gieljan Vantyghem, PhD researcher at UGent;
- Vytautas Naslenas, Global sales coordinator at COBOD International;
- Jarett Gross, Construction tech correspondent;
- Dr Fabian Meyer-Broetz, Head of 3D construction printing at PERI AG.

The ten interviews were conducted with different players that were concerned, from a distance or close up, to 3D printing in construction. It included, for instance, the point of view of a PhD student of MIT/UGent and the opinion of the project manager of the first company to have printed a full concrete two-story house in Belgium. The different profiles have provided an opportunity to gather views from all areas of the sector.

Interview guide

The use of an interview guide (available in Appendix 28) with clear and well-defined themes had several advantages. It ensured consistency between interviewees and resulted in a structured process, while allowing the interviewer to adapt the questions to the interviewee's situation and position in their organization. It also ensured that all applicants had the same experience.

Interview process

The structure of the semi-structured interview followed the funnel principle, generally starting with an introduction to the topic of the paper and a presentation of the interviewee. The next step was a general discussion about 3D printing, the construction industry and current projects related to this technology. The interview then continued with a more specific discussion of the issues surrounding 3D printing technology in the construction industry: its benefits, challenges, and its impact on society, the business model, the regulatory framework, and the environment. Finally, the discussion focused on the future of the technology, the potential barriers to its large-scale integration into the building sector, and the most favourable areas of application. After all topics were covered, respondents were able to make some comments on topics not covered in the discussion if desired.

4.3.2 Online surveys

Secondly, two surveys were created to complete the data collection on 3D printing in construction. The purpose of the questionnaires was twofold:

- To gather the perceptions of actors in the construction sector, especially companies that are likely to invest in 3D printers (Appendix 29).
- To collect the opinions of Belgian individuals with different backgrounds to assess what elements might impact the broad acceptance and adoption of the technology in other sectors of activity (Appendix 31).

Context of the research and sample description

In Belgium, in the case of public contracts, construction companies are subject to accreditations authorising them to respond to contracts. These approvals are issued by the SPF Economy and are intended to demonstrate financial reliability, technical capacity and professional integrity (references) in order to access contracts. Companies are classified into "classes" (between 1 and 8). Only companies of "class 8" are authorised to respond to contracts with a value of 5.335.000€

Speaking of prices, de Laubier et al. (2021) provided an overview on 3D printing in the construction industry and gave an approximation of the **price** of an onsite concrete 3D printer: **500.000$ to 2.000.000$**.

Taking both arguments into consideration, the following hypothesis is suggested: *Construction companies likely to invest in 3D printers are large construction companies of class 8. The companies of class 8 are allowed to carry out heavy construction work that may exceed 5.330.000€.* (Arrêté royal fixant certaines mesures d'application de la loi du 20 mars 1991 organisant l'agréation d'entrepreneurs de travaux, 1991).

Most of these companies of class 8 are members of the "Association Des Entrepreneurs Belges de grands travaux" (ADEB). The ADEB is the representative of the large construction companies in Belgium. The association consists of 65 companies with a total turnover exceeding 10 billion euros.

Qualitative surveys

In the context of this study, the target segment of the survey intended to the construction actors is relatively small. In contrast, the technical expertise required to understand the survey is quite high, especially among the target group of the second survey. It was therefore to be expected that only a limited number of responses would be received.

Although the (online) survey is generally considered to be a **quantitative method** of data collection, it was decided to work in a more qualitative way in the context of this thesis.

Braun et al. (2020) support the idea that surveys also contain a variable amount of **qualitative data**, and the rich potential that qualitative data can deliver is often not realised through the collection or analysis of data. In one of their recent publications, it was asserted that: *"Fully qualitative surveys, which prioritise qualitative research values, and harness the rich potential of qualitative data, have much to offer qualitative researchers, especially given online delivery options"*.

4.4 Method to analyze the information

4.4.1 Semi-structured interviews

The data gathered during the interviews were recorded and carefully transcribed (in the language of the interview) with consent of each interviewee (transcripts are available in the

Appendices 23 to 32). The data obtained from the interviews were analysed and organised by themes. After classification, the collected data were linked with the theoretical data from the literature review to prepare the discussion of the recommendations.

4.4.2 Online surveys

Both surveys were shared through social networks and emails in French and English in order to reach the largest possible audience. The questionnaires contained both open and closed questions and generally introduced some notions (e.g. “Additive Manufacturing (AM)”) necessary for the understanding of the questions.

Then, the data were exported in an Excel spreadsheet and several types of graphs were used to display the results obtained in the two surveys. Among these, pie charts, single and multiple bar charts, column charts and likert plots were used to identify trends (Appendices 35 and 37). The choice of graphs was made in accordance with the type of data collected from the survey in order to convey the appropriate implicit message to the reader.

4.5 Remarks and limitations of the methodology

While this thesis attempts to identify elements of answers to the research questions, it is also necessary to address some of the limitations of the methodology used.

The research question of this paper relates to the application of 3D printing technology in the construction sector. Currently, the applications of 3D printing in construction are limited due to the small number of organisations designing and building infrastructures on a large scale (Schuldt et al., 2021). Given the state of implementation of the technology in the construction industry, the maturity of the technology in this sector does not yet allow access to a wide range of numerical data such as detailed costs and reliable construction times. Indeed, most of the known data is usually extracted from conceptual projects.

As Ma et al. (2017) explained in one of their reports, “*3D printing in the construction industry is still in the start-up stage*". To some extent, this affects the results of the interviews and surveys, and the collected data should therefore be treated with caution.

5. Analysis of the results

The next section presents the results and analysis of the practical part. The first part of this chapter introduces the interviewees and the population samples targeted by the two surveys. Then, an in-depth analysis of the collected data will be carried out in order to answer the four research questions stated in the methodology.

5.1 Outcomes of the data collection

5.1.1 Interviewees presentation

Ten interviews were conducted as part of this research, including one semi-structured interview on site, six semi-structured interviews that took place remotely and three written interviews. Ensuring the good representation of all stakeholders in the construction and 3D printing industries was a priority to capture as much data as possible. A short presentation of each interviewee and their position in their company is provided in Appendix 17.

5.1.2 Sample description

The survey, which was directed exclusively at players of the construction industry, ultimately yielded **47 responses**. The second one, addressed to the whole Belgian market (regardless of the field of activity), reached an almost equivalent **number of responses**, **56**.

According to the survey presented in Appendix 29 (Q24), among the construction professionals that took part in the survey (47), 10 of them are large construction companies of class 8 located in Belgium. The other respondents cover the different areas of the construction industry: most are architects, building engineering offices, real estate agencies or professional federations.

Concerning the second survey, the graph provided in Appendix 31 (Q15) shows the diversity of the sectors of activity represented. However, the relatively low number of responses in regard to the target population (the entire belgian population) makes it impossible to draw any general conclusions but rather trends in one direction or another. By soliciting the opinion of the entire population on a subject as technical as 3D printing, we are in fact asking for people's opinions on a subject that is barely known. As a consequence, it discourages some people from responding to the survey.

5.2 Market perception on 3D printing in the construction industry

To set the stage and understand the perception of the market inside and outside the construction industry, diverse questions on their interest and knowledge about the technology were asked to the main players of the sector. Among them, architects, general contracting construction companies, building engineering offices, real estate agencies but also 3D printing industry stakeholders, raw material suppliers and researchers, gave their opinion through interviews or surveys.

5.2.1 Market perception overall - Demand

According to the survey presented in Appendix 29, among the construction professionals in Belgium, **only 4% of respondents are unaware** of the implementation of 3D printing in the construction industry, while **17%** are closely or remotely **involved or interested** in the 3D printing processes in construction.

By reviewing the open-ended questions of the survey; the different projects related to 3D printing in construction, known to these companies, are generally located in Belgium, in the Netherlands and in the United States. All are conceptual projects, such as the two-storey pilot house built by the company Kamp C in Westerlo, Belgium. Some companies are also familiar with other types of 3D printed constructions, for instance the very first steel bridge installed in Amsterdam by the company MX3D.

Given that AM is already routinely used in a great number of industrial applications, architects, engineers and builders have developed an interest in its use in construction (Naboni et al., 2019). However, despite the acknowledged potential of using 3D printers in the construction industry, there are still **remaining doubts** about whether AM large-scale constructions are feasible (Pessoa et al., 2021).

One question regularly raised in interviews was whether we can really benefit from the advantages offered by 3D printing in construction. This sentiment was clearly expressed by Xavier Köttgen from the architect's office Section A-A who works in close contact with his clients on a daily basis. Mr Köttgen is very **optimistic about the future** of 3D printing in construction but remains **sceptical about the large-scale implementation** of this technology in the sector :

> *"We are not reinventing the principle of construction with 3D printing. We still have rooms with straight walls. Of course, we can envisage making a curved wall with this process. But here, we are already touching a segment of the population that will have a sensitivity ready to accept having a work of art in its interior. They will also suffer from the consequences (e.g. where to put the furniture) and we have to see if they don't get tired of the result in the end."* (Xavier Köttgen, translated from Appendix 23)

Regarding the immutable principles of construction, he added:

> *"When I say that we don't reinvent the way we build, there are still certain unchangeable rules. We also want to build in a reliable way. We are not here to build, as if we had a formula 1 team. We don't push the buildings to the extreme. We can't afford to do that. The budgets are such that the investment in a building household is "such that we look twice at what we are doing". So, we have a whole series of constraints which, when transposed to a construction of this type, will really reduce the potential that 3D printing can offer with all its freedoms and creative aspects. Or you have to limit yourself to very limited parts, such as small parts or subtleties."* (Xavier Köttgen, translated from Appendix 23)

When asked about the future of 3D printing in the construction industry, the **overall opinion** of the construction professionals is quite **promising**. Indeed, after the respondents were provided with a list of realised projects and opportunities related to 3D printing in construction, their point of view was rather optimistic. The survey in Appendix 30 (Q20) shows that the percentage of respondents interested in adopting 3D printing technology in their business in the next 5 to 10 years ranges **from 43% to 75%**, while another 11% have already adopted the technology in their operations. The remaining 15% of respondents did not foresee the added value that 3D printing could bring to their operations.

The graph below (Figure 17) provides a clear comparative overview of the degree of satisfaction of the respondents from the construction sector regarding the potential benefits of 3D printing on their activities today and tomorrow.

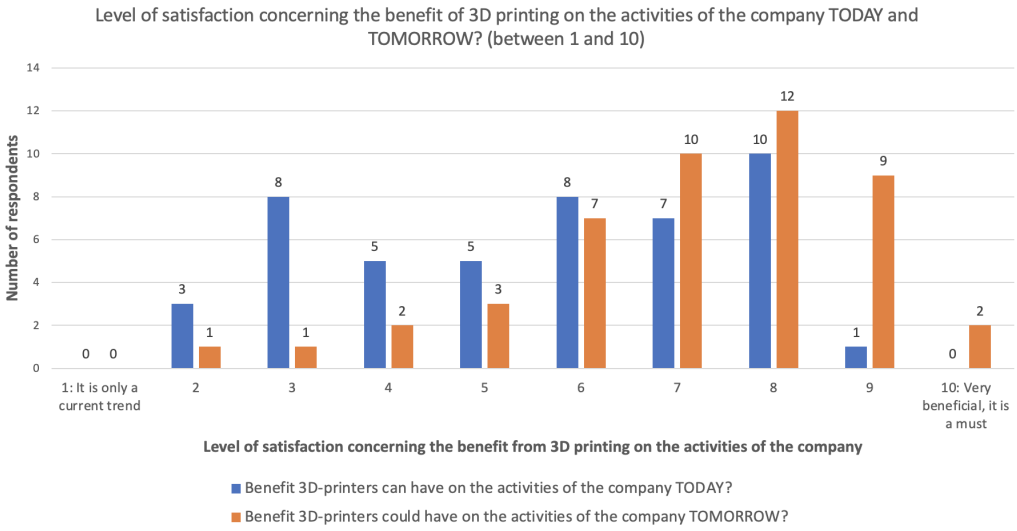

Figure 17 - Satisfaction level chart regarding the benefits of 3D printing for the company's activities today and in the future (between 1 and 10).

Overall, the degree of satisfaction concerning the benefits that 3D printing technology can bring to the company's activities today is mixed. However, an interesting observation is the **steady increase in interest** when it comes to satisfaction in the **future**. Approximately 70% of respondents selected a satisfaction level between 7 and 10 regarding the benefits of the company's activities in the future, while only 38% had the same satisfaction level regarding the benefits that 3D printing can bring to today's company activities.

> *"If you see the time evolution of 3D concrete printing, you also see that we have an **exponential growth** at the moment. This is already from 2019, when we had only a couple of projects. Now, if you follow the right groups on LinkedIn and Facebook every day, you see new projects which are mind-blowing. You can see how many new companies are coming and new spin-offs. So, it's a very fast evolving field. And I think we can expect a lot of it in the coming years and all the problems will be solved."* (Gieljan Vantyghem, Appendix 24)

5.2.2 Technological maturity and innovation cycle

Thanks to the results of the survey (Appendix 30 - Q3), it was also possible to determine where stakeholders placed 3D printing in the **innovation cycle**. More than half of the respondents, 29 out of 47, stated that 3D printing was in the **pilot stage** currently. In other words, respondents believe that 3D printing is at a stage in the cycle where feasibility, duration, cost, and adverse events are being evaluated prior to full-scale adoption. The results are in line with the propositions advanced by the literature which defends that onsite applications of digitally

manufactured concrete (DFC) with 3D printers are in the pilot stage currently (de Schutter et al., 2018). That's also the opinion from Benoit Parmentier from the BBRI. After asking him on the future of 3D printing in construction, he commented:

> *"In construction, this technology is currently at a stage where it is **being tested** for industrialisation."* (Benoit Parmentier, translated from Appendix 18)

> *"There is a **real potential**. We will have to see how mature the technology is on the one hand, and there are still some technical issues that need to be resolved. There is a market that is currently being tested. There are industrialists who are very interested in it."* (Benoit Parmentier, translated from Appendix 18)

To be considered mature in the market, a technology usually requires complementary and disruptive change throughout the industry. To understand this point, an additional piece of theory was shared by Bock (2015) who claims that changes of such complexity take a lot of time, sometimes decades. However, after nearly 40 years of technical development and experimentation in this area, 3D printing has recently seen an increase in activity across the sector.

As a result, the applicability of 3D printing for any construction process will depend on both **technological performance** and **economic viability** (de Schutter et al., 2018). According to Benoit Parmentier, these two factors, which will be discussed in the next chapter, are important for the development of 3D printing on a large scale.

5.3 State-of-the-art on the 3D printing challenges in construction

With a growing number of 3D printed projects worldwide and an equal number of companies interested in the subject, it is necessary to consider why 3D printing, which has been around for over thirty years, is still struggling to make a substantial impact in the construction sector (Gartner & Maresch, 2020).

The different issues related to 3D printers in construction have been discussed with 10 researchers and experts of the construction industry. The discussions led to an in-depth analysis carried out on the application of 3D printing in this sector to identify the **current problems and challenges** associated with the large-scale introduction of this technology in this industry. This chapter presents an overview of the weaknesses and threats identified in the semi-structured interviews.

5.3.1 Technological and regulatory challenges

Process efficiency and technical issues

As reported in the literature review, studies strongly suggest that the productivity of the construction sector has been decreasing worldwide over the last decades (Bock, 2015). The massive consumption of raw materials and energy in construction processes presents several challenges for which the traditional construction industry currently has no solution (Bock, 2015). While all the points made in the literature indicate that conventional construction has reached its potential technological performance limit, this is exactly where 3D printing can help.

As stated by Benoit Parmentier from the BBRI, the state of the art of 3D printing is widely driven by concrete-based processes. Although the process faced significant technical challenges in its early stages, the systems currently in use can successfully correct for speed and load capacity parameters in the construction of real life structures (Labonnote, 2016). But, before being implemented on a large scale in construction industries, some remaining **technical obstacles** must be addressed (de Schutter, 2018).

Among those obstacles, an example published in an article from Labonnote (2016) explains that very little research has been conducted in essential qualities of additive construction building materials such as durability, water resistance, thermal properties, etc. The author suggests that researchers should develop new innovative materials that exhibit a good combination of all essential material properties.

Other kinds of technical issues were also assessed in the interviews conducted with professionals of the construction sector, concerning the materials used in 3D printing. One of these concerns has been raised by Vytautas Naslenas from the 3D printer provider COBOD who explained that the biggest technical issue for the company was the **control of the material** according to the location of the working site :

> *"The biggest technical issue (for us and all of the providers) is material control. As for each region/country/area a different mix may be used, due to weather conditions (temperature, humidity) also the mixture should be adjusted for local materials (as only using local aggregates makes sense)."* (Vytautas Naslenas, Appendix 25)

Another technical concern has been brought to the forefront by Gieljan Vantyghem about the **material flow** in the printer. In the interview, he supported the idea that:

> *"The main problem with the materials used in 3D printing, is that, at the moment we are printing using progressive cavity pumps. It's a pump that gives you a constant flow. For larger concrete grains, we use different pumps, but you get another constant flow, which is not a problem if you want to pour a slab. Then it does not matter how fast or what is the flow of the material. But if you are printing, you really need a constant flow."* (Gieljan Vantyghem, Appendix 24)

> *"...most of the limits you see in concrete printing is "the max size of your aggregate which is approximately two millimeters". The conventional pumps are still not yet adjusted to use large aggregates."* (Gieljan Vantyghem, Appendix 24)

Either way, according to Jarett Gross, it is clear that technological improvements are still needed and the **full potential benefits of 3D printing have not yet been realised**.

Material choice

The **variety of materials** available in AM was another topic discussed in the interviews and the literature. The limited material palette currently available in practice raises many questions across the literature.

> *"We personally have only worked with cementitious materials. Yet, there are companies exploring green (no/less cement) 3D printable material."* (Vytautas Naslenas, Appendix 25)

In their study, de Schutter et al. (2018) point out that **the real technical challenge** that needs further optimization is the **proper hardening** of 3D printed building parts when no formwork is available. To ensure that the structure is structurally durable over time, the material properties are studied to get the desired material performance.

Even though the current focus on material properties is still limited, a lot of progress has been made since the introduction of 3D printing in construction. Currently, aggregate-based materials such as **concrete** are the most widely used in additive construction (Paolini et al., 2019). Benoit Parmentier and Gieljan Vantyghem expressed in their interviews that the choice

of concrete for 3D printing was motivated by the fact that it is an **inexpensive material** with high rigidity properties, durable, and able to form almost any shape.

> *"Initially, classic cementitious materials were developed because this is the most widely used material. It is a material that is highly stressed at a young age and must harden very quickly to be very stable. This requires very important properties in terms of rigidity and large quantities of cement."* (Benoit Parmentier, translated from Appendix 18)

> *"That's the benefit of concrete. Concrete is a very cheap material."* (Gieljan Vantyghem, Appendix 24)

However, it is important to note that the material properties and requirements of 3D-printable concrete differ slightly from those of concrete used in conventional constructions (an example of concrete mix is provided in Appendix 16). The compositions are the same except for the proportions of binders and aggregates (Hossain et al., 2020).

In addition to concrete, there are also new **projects using other materials** such as **biobased materials**. According to Benoit Parmentier, attempts are currently being made to replace cement with recycled elements, sand, industry-specific materials, etc. Marijke aerts illustrated the points made by Benoit Parmentier with an example:

> *"There are different innovative thoughts about that already. In Italy, they are trying to print with a local clay material. So, they use sand and clay from the soil on-site and then they try to make a solution to print the house with the clay. They cover it with a wooden rooftop. So, when you use cleaner and more sustainable materials, it can be beneficial for the environment."* (Marijke Aerts, Appendix 21)

Yet none of the companies interviewed (involved in 3D printing in construction) have tried other materials than cement-based. Nevertheless, the project manager of Kamp C, Marijke Aerts presented a project in which they are looking to create a **new type of concrete** which is more sustainable. New types of concrete materials, suitable for 3D printing, will need to have the appropriate mechanical properties and capabilities to be continuously extruded and stacked by layers on top of each other (Allouzi et al., 2020).

> *"I'm also involved in another project where they are trying to find out a new kind of concrete that is made with other binders than the classical Portland cement binder, and*

also with the aggregates coming from other industries like waste from other industries. It's really a sustainable way of building." (Marijke Aerts, Appendix 21)

The company COBOD supports the idea that new material capabilities in 3D printing will allow companies to incorporate more sustainable materials into their mixes. The initiative could, in result, allow companies to build in a more **environmentally friendly** way by using recycled materials as aggregates, for example.

Regulatory framework

Currently, 3D printed buildings and structures are subject to the **same requirements as conventional constructions**. Indeed, the conventional construction policies/regulations have not yet adapted to the new technology. As a result, the lack of building codes and standards related to 3D printing in construction raises concerns about the large-scale adoption of the technology in the sector (Ghaffar et al., 2018). In the survey targeted at the Belgian construction sector, several stakeholders expressed their opinion on the standards that should or should not be implemented regarding 3D printing.

According to one of the construction actors, the regulatory framework **should be more dynamic** in order to integrate new innovations in a general way, and to be able to react more quickly to the major challenges the industry is facing (climate change, scarcity of resources, etc.). To illustrate his argument, he shared an experience his company often encounters: when their company has to renovate a building with new external insulation, facade alignment constraints and energy requirements regularly prevent the projects from being optimised. He supports the idea that the new technologies such as 3D printing must at least meet the same requirements as the conventional ways of building (safety, environmental impact, etc.) but the common framework should be more dynamic and evolving than it is now.

Overall, most respondents are aware of the new opportunities that 3D printing can offer, but **remain cautious** as their most important concern is that construction regulations are not changed by the introduction of these technologies. According to them, the construction sector is sufficiently regulated already. Other respondents, on the other hand, consider that the construction examples using 3D printing are still too marginal to come up with a legal framework.

5.3.2 The cost of a printer

The **cost of acquisition and operation** of a 3D printer in construction is a recurring issue. All the professionals who took part in the questionnaire either took the price of the printer into consideration or attached great importance to it (Appendix 30 - Q7).

Vytautas Naslenas works for one of the biggest suppliers of 3D printers today: COBOD. In the written interview undertaken with him, he provided some information regarding the operating costs of a concrete 3D printer in the construction industry:

> *"The cost will depend on the local cost of labor and concrete materials in your country. Denmark is a high cost country but for the BOD building of 50 sqm the cost of materials for printing the curved concrete inner and outer walls was approximately 2,000 USD. Coming to 40 USD per sqm house for the concrete".* (COBOD, 2020)

To find out the actual price of a 3D printer, it is necessary to ask the company for a price list of the different models available. These generally range from around **180.000€** for the smallest printer **to over 950.000€** for the largest.

When asked about the **price of printing a square meter**, the company explains that it is impossible to give a general price because there are too many variables involved in the cost calculation. These variables include: the design of the wall, the cost of materials on site, the cost of staff to oversee the printing, etc.

5.4 The global environmental issue: does 3D printing have a role to play?

The literature reported that the construction industry accounts for about 40% of the world's raw material consumption, 40% of the world's energy consumption, 38% of greenhouse gas emissions and 40% of solid waste generation (Schuldt et al., 2021). According to the professionals, the result is unanimous: **some improvements must be done** in the industry to comply with current environmental issues.

Looking at the responses to the survey shared with the construction industry (Appendix 30 - Q15), it can be seen that companies are quite positive about the impact that 3D printing can bring to the sector. However, they are not totally convinced either, as half of them selected a level of agreement with a positive impact (with a score between 4 and 5) from 3D printing on the environment , and the other half seemed to have a mixed opinion, or even disagree with it.

Interviews with construction experts made it possible to identify **three key aspects** of the environmental issues that 3D printing could be confronted with in the future: the **sustainability of materials** (with a focus on concrete), the **circular economy**, and the **topology optimization**.

5.4.1 More durable materials - A new type of concrete?

As concrete is the most used material in 3D printing in construction but is also part of **one of the most polluting** industries in the world. According to the newspapers The Guardian and different experts:

> *"After water, concrete is the most widely used substance on the planet."* (Watts, 2019)

> *"...concrete is said to be responsible for 4-8% of the world's CO2. Among materials, only coal, oil and gas are a greater source of greenhouse gases. Half of concrete's CO2 emissions are created during the manufacture of clinker, the most-energy intensive part of the cement-making process."* (Watts, 2019)

In recent publications, the difference in **environmental impact** between an ordinary concrete used in conventional construction and a high performance concrete mix was studied by Agustí-Juan et al. (2017) and showed that the difference between the contribution of the two mixes to climate change is significant. The custom mix contributes about 40% more CO2 emissions than the conventional concrete.

For Gieljan Vantyghem, it is definitely feasible to use **other types of materials** in 3D printing to reduce the environmental impact of concrete. But he also believes that this is not where the problem lies. The issue rather is in the composition of the concrete.

> *"Concerning durability, one of our colleagues working with universities is highly involved in making a 3D printable concrete more sustainable and durable. I think the type of cement can be changed."* (Gieljan Vantyghem, Appendix 24)

> *"In fact, now, we use twice as much cement as normal concrete for all the projects you see around the world. I think it's fair to say that the amount of cement that is used in the concrete mix is about two times as much. And if you know that cement is the main contributor to the CO2 emissions, then you know that we have about two times worse materials."* (Gieljan Vantyghem, Appendix 24)

According to Noël Naert and Arnaud Tandt from the FEBELCEM, the **framework** (presented in the literature review) suggested by the European Cement Association (Cembureau) proposes the most realistic options **to decrease the footprint across the sector**. As presented in the literature review, the change must be done across five levels, called the "**5 C**", respectively: the Clinker, Cement, Concrete, Construction and Carbonation.

> *"These 5 'C's show how important it is to act on different levels and not only on the construction technique or the materials."* (Noël Naert, translated from Appendix 22)

For each of the five C, Noël Naert outlined the various improvements that could be made throughout the concrete production and life cycle chain:

- **Clinker**: "*This is the raw material, which comes out of the cement furnace. It is the chemically active part of the cement and the most polluting because, to manufacture clinker, a lot of CO2 must be released.*" (Noël Naert, translated from Appendix 22)
- **Cement**: The idea of this second phase is to focus on using renewable energy for the process and transportation of the raw materials. Then, there is a need to conduct research in order to consider more sustainable cement compositions, with less clinker or with other constituents such as additives.
- **Concrete**: This is the most commonly used material on earth after water (Wangler et al., 2019). The direct CO2 emissions related to concrete come from cement production. Here we need to produce other types of concrete depending on the application.
- **Construction**: Here, the focus is on finding new construction methods that will help to dimension structures more efficiently in order to avoid material losses. Topology optimization (presented in the following sub-chapter) and 3D printing are two of the tools that can be used for this purpose.
- **Re-carbonation**: This is finally the process by which concrete reabsorbs some of the CO2 released during clinker production. Thanks to this process, cities effectively act as "carbon sinks" and allow further reduction of emissions throughout the cement and concrete value chain.

> *"As you may have noticed,* ***3D printing construction is located somewhere in this strategy****. It could, in some cases, bring some advantages compared to traditional ways of building."* (Noël Naert2, translated from Appendix 22)

The 3D printing technology would therefore fall somewhere within this model. According to the experts in the concrete sector, 3D printing is not the ultimate solution, but rather **part of a much wider range of solutions** to the environmental issue.

> *"It is also important to keep in mind that "sustainable construction" is not only about the environment (protecting nature and biodiversity). The three dimensions of sustainable development are still of primary importance. Besides the environment, there are also economic and societal aspects."* (Noël Naert, translated from Appendix 22)

5.4.2 Circular economy

There is also the **circular economy** aspect that is reflected in the 5C model. When it comes to reducing the impact on the depletion of raw materials, some choices have to be made.

Recycling and **reusing** are two important concepts that need to be taken seriously. According to Noël Naert, this is not only a matter of technology. The first step is to think about a circular economy process, which is much broader than the scope of the technology. The second step is to consider that 3D printing and other new technologies could very well be **tools** that contribute to more sustainable and environmentally friendly consumption and production patterns.

Looking at the literature published recently, it can be read: *"Unlike most conventional approaches, which are unsustainable, 3D printing will make construction more efficient while creating sustainable growth and stimulating circularity principles, for instance through the use of recycled and environmentally friendly materials."* (Pessoa et al., 2021)

5.4.3 Topology optimization

Another option available is **topology optimization**. This method avoids the excessive use of materials in different types of constructions. In practice, this method automatically generates the perfect layout of reinforced concrete structures by incorporating the different forces acting on the structure into a 2D topology optimization model. "*It is all about finding the most **optimal shape**"* according to Gieljan Vantyghem, specialist in that field. The latter has designed and 3D printed recently a bridge at laboratory scale with the smallest possible amount of concrete, in collaboration with the Dutch company Vertico (provider of 3D printers) (see Figure 18 and Figure 19).

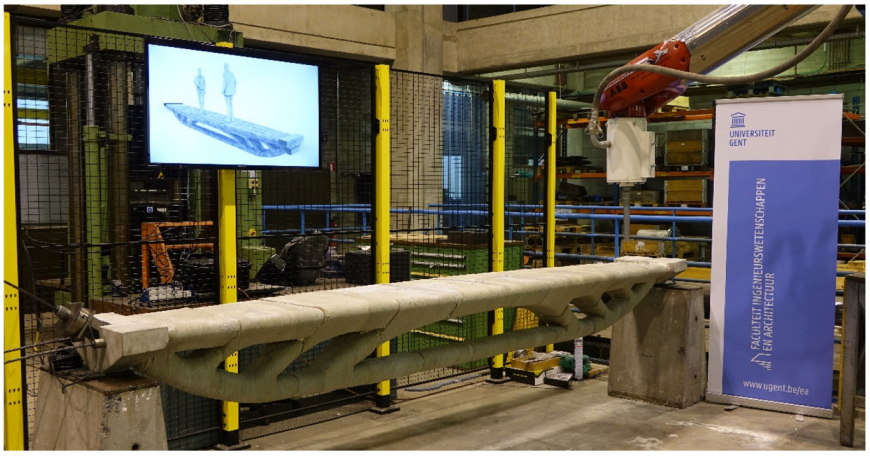

Figure 18 - 3D-printed concrete bridge made by researchers at the department of Structural Engineering (Ghent University) (Vantyghem, 2020).

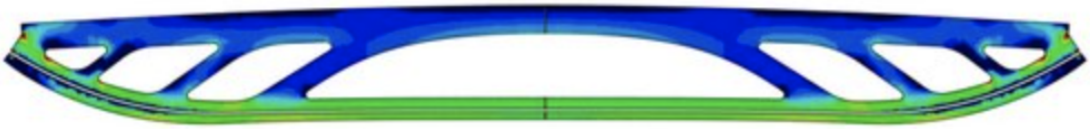

Figure 19 - Most optimal bridge shape that requires the smallest amount of concrete. Blue corresponds to the lowest level of stress on the bridge (Universiteit Gent, 2020).

> *"So, the result of the optimization is that most of the time you get very complex shapes (that are very hard to produce using traditional techniques) ... Another finding was the fact that we can achieve some large amount of* ***reduction of material*** *and without affecting structural properties. So, of course, it's a technology that has been around for quite some time, but it is not used often in the construction industry because of the limits, for example in the way of production, which is very traditional."* (Gieljan Vantyghem, Appendix 24)

3D printing coupled with topology optimization could therefore make it possible to **eliminate the need for formwork**. Benoit Parmentier also discussed this topic, explaining that it is possible to produce exactly the right shape to support the intended load if the structural elements are optimised according to the load. This in turn avoids the consumption of material.

What to remember from Chapters 5.2, 5.3 & 5.4

- Among the construction professionals who responded to the survey: only 4% have never heard of 3D printing in the construction industry and 17% are already involved in 3D printing processes.
- The overall opinion about the future of 3D printing in construction is positive; only 15% do not foresee the added value of the technology.
- But there are still remaining doubts: most respondents are more optimistic about the benefits 3D printing can bring to their businesses in the future than they are today.
- Respondents and interviewees consider that 3D printing in construction is in the pilot stage of the innovation cycle and is therefore not yet implemented on a large scale.
- The applicability of 3D printing will depend on both technological performance and economic viability. The challenges and weaknesses are as follows:

Technological and Regulatory aspects

- Process efficiency and technical issues: the material control and flow in the printer
- The limited variety of materials available for 3D printing (mostly concrete)
- The lack of building codes and norms and potential legal issues

Economic aspect

- The high cost related to the acquisition and operation of a 3D printer in construction

Environmental aspect

- The role that 3D printing can play in the environmental issue regarding the:
    - Sustainability of the materials: the impact of concrete on the environment: 3D printing is part of a wide range of solutions within the “5C framework”
    - Circular economy: 3D printing can be used as a tool for recycling/reusing
    - Topology optimization: to find the optimal shape of a structure and avoid material waste

5.5 Best scenarios for 3D printing applications in construction

The qualitative research of this thesis initially addressed the place of 3D printing in the construction sector. Through this first part, an attempt was made to understand the market's perception of this new construction technology. Secondly, it was important to identify and consider the main remaining barriers to the large-scale implementation of 3D printing. Having identified the obstacles, the topic will now be further developed to identify the **ideal conditions and circumstances** under which the benefits of 3D printing could be fully exploited. In this context, the various stakeholders shared their views on whether additive construction techniques were intended to replace existing construction techniques or were targeted at being used in specific applications.

> *"The BBRI is currently installing a 3D printing machine in their laboratory, which will be on permanent display in a building dedicated to new technologies from next year. We will soon be able to visit it. We will be testing a number of use cases and identified scenarios in which 3D printing could be useful. We really need to identify the best scenarios for applying the technology. From an economic point of view, is it worth it?"* (Benoit Parmentier, translated from Appendix 18)

> *"You need to find the appropriate use-cases: where it might be relevant from a technical and economic point of view."* (Benoit Parmentier, translated from Appendix 18)

The **three best-case scenarios** suggested in this chapter have been identified thanks to a multitude of pilot projects around the world (see Figure 20) and the opinions collected from the semi-structured interviews. It should be pointed out that these scenarios are part of a much larger set of ideal situations. However, for the purposes of this study, only three are presented in this practical part.

When manufacturing companies were asked what the optimal scenario would be to take advantage of 3D printing, opinions varied. Nevertheless, there was a **surprisingly high level of consensus** among interviewees about the **promising future** of 3D printing in construction even though the technology is still in the experimental stage.

Figure 20 - 3D-printed construction project around the world: **a**) Office building in Dubai, (UAE); **b**) Public restroom in China (2016); **c**) 12-feet done in California, USA (2017); **d**) MX3D bridge in Amsterdam, Netherlands; **e**) First 3D-printed in Minnesota, USA (2014); **f**) Hotel in Manila, Philippines (2015); **g**) Pedestrian bridge in Madrid, Spain (2017); **h**) TU Eindhoven Pavilion, Netherlands (2016); **i**) Home for vulnerable people in Tabasco, Mexico; **j**) 3D-printed house in Italy (2018). (Hossain et al., 2020)

Scenario 1 - Isolated environment

When large-scale 3D printing was first introduced, the first applications were aimed at presenting construction methods and technologies that may be adaptable for applications beyond our home planet.

> "*We want to increase the technology readiness level and test systems to prove it would be feasible to develop a large-scale 3D printer that could build infrastructure on the Moon or Mars*" said Corky Clinton (Mohon, 2020)

In recent years, there has been growing interest in the idea of using 3D printing for human colonization on other Planets (Koshnevis, 2004). According to Gieljan Vantyghem, we are not

far from being able to print on planets like the Moon or Mars as people think. This would allow for construction of viable habitats to take place before the arrival of humans.

In reality, the main reason to use 3D printing in space is the technology's ability to build structures in **harsh environments** that are sometimes inaccessible to humans. Similar conditions can be found on Earth: arid deserts, polar zones, mountainous areas, etc.

By increasing the degree of **automation**, 3D printing in construction can reduce physical workload and improve workplace safety (Paolini et al., 2019). The technology can be particularly valuable for the construction of buildings in difficult climatic zones, for example. This is what Xavier Köttgen and Vytautas Naslenas believe: for any situation where access to the construction site is problematic and working conditions are not sustainable for the labor force due to weather conditions, 3D printing provides a valuable alternative. For example, in places affected by natural disasters, war zones, or extraterrestrial locations.

> *"It is relevant for most cases where: Access to a skilled labour force is hard, which drives labour cost up."* (Vytautas Naslenas, Appendix 25)

> *"In some places other than Belgium with aggressive working environments and areas that are difficult to access, it is easier to use a machine than people."* (Benoit Parmentier, translated from Appendix 18)

Scenario 2 - Emergency situation

This scenario, which was recurrently raised by the construction stakeholders during the qualitative research, seems to be one of the most interesting for the use of 3D printers. To illustrate, Hossain et al. (2020) stated in their research that 3D printing has already been successfully used for the rapid construction of **disaster relief** shelters and military bunkers.

Accordingly, Noël Naert suggested that additive manufacturing could be particularly useful for the rapid construction of houses in areas with **housing shortages** for instance.

"We could therefore imagine that this type of industrialisation (3D printing) could be useful in order to quickly build basic cells (in concrete). Then it will be up to the people who live there to complete their homes with extensions. It is a repetitive job where the machine builds these different cells in a chain. These notions of 'repetitiveness' and 'industrialisation' are at the heart of 3D printing." (Noël Naert, translated from Appendix 22)

In addition, some countries have a real need to build houses in a fast and efficient way. **Speed** and **efficiency** are the most important factors. 3D printers have a real use here because they can carry on printing overnight and can reduce labour costs. According to Gieljan Vantyghem, the future of 3D printing lies beyond Belgium's borders.

Another recent example of an emergency situation is the outbreak of the COVID-19 pandemic, which cannot be ignored. In China, this out-of-control situation had required a large human capacity to complete the construction of two hospitals in less than two weeks (Miller, 2020). This is a typical situation where 3D printing could once again prove very useful according to Xavier Köttgen.

> *"If we experience a new **pandemic**, for example, there may be an interest in constructing modules very quickly in a production line to design buildings or hospitals as in China."* (Xavier Köttgen, translated from Appendix 23)

In practice, companies are eager to switch from traditional processes to 3D printing as they want to solve various issues, such as housing shortages or natural disasters, with the help of technology and automation. However, they usually don't take the leap because the technology itself is still quite young.

Scenario 3 - Building projects that differ from the norm

The **great degree of freedom** afforded by 3D printing offers unlimited possibilities in design. Therefore, tailor-made solutions are also to be taken into consideration. The market is becoming more and more interested in the **customization** of buildings and originality. Thanks to automation and robotization, a high degree of customization is possible.

> *"You can really manufacture things that wouldn't have ever been possible before with traditional procedures. And, I think that's the case for all new technologies."* (Michael Henke, Appendix 19)

> *"More complex geometries can be created for greater architectural diversity. You can design curved walls, you can design overhangs, you can design completely original shapes and structures. And it is no more complicated to do with printing machines. Whereas with a formwork, even if made in a factory, it would have cost much more."* (Benoit Parmentier, translated from Appendix 18)

There is an interest, according to most, in using 3D printing for structures that are **out of the ordinary**, such as the recent construction of pieces for the Sagrada Familia in Barcelona (introduced in the literature review). These are somewhat "unlimited cost" projects where the freedom to customise is really pushed to the limit. Xavier Köttgen further explained,

> *We have to see if this construction technique will not be more useful to develop rather exceptional projects: museums, impressive projects, stations, etc. We say: "The technique exists and we still do it the old way". But in this case, we don't really care about budgets.* (Xavier Köttgen, translated from Appendix 23)

The latter summed up the picture by saying,

> *The interest of this process is when there are things that are unpayable, and you want to realise them in a regular way.* (Xavier Köttgen, translated from Appendix 23)

5.6 Socioeconomic impacts of AM in construction

As far as 3D printing is concerned, it is becoming clear that this technology could very well **disrupt** the **business models**, the **value network** and the **organisations** (and their processes) of the construction industry. Previous studies have already highlighted the impact of AM on the business models and value network in other application areas of AM (e.g. medicine, aerospace) (Gartner & Maresch, 2020). In addition to exploring the economic implications of the potential disruptive technology, this chapter will also investigate the technology's societal consequences.

> *"It is not just a matter of technology. The materials have to be ready to be used. But there is also an **economic** aspect and a **social** aspect."* (Noël Naert and Arnaud Tandt, translated from Appendix 22)

5.6.1 From a social perspective

One of the interviewees, Marijke Aerts, was involved in one of the 3D printing construction projects. She was indeed the project manager for the construction of the first 3D printed house in Belgium. When asked about the **impact of this technology on workers** and stakeholders, she looked surprised. In fact, Kamp C's project, like most 3D printing projects in construction, is not in line with conventional large-scale projects. As most 3D printing projects are at the

experimental stage, it is **too early to identify the social impact** of 3D printing in the company's activities.

The increasing use of technologies, including 3D printing, would certainly **minimize the recourse to human resources** and have the potential to **increase productivity**. It could also improve worker safety and health by minimising high-risk work carried out with innovative technologies (Hossain et al., 2020). Therefore, the literature suggests that the broad adoption of 3D printing could have a significant negative impact on the labour market worldwide.

Marijke Aerts does not support that idea. According to the project manager, the social aspect will probably be at most limited to workers who will have to follow **trainings** adapted to the new technology. There is no discussion of eliminating jobs to replace the workers by "machines". Those most impacted by these changes could be the engineering staff, also called the "white collar", who will have to review the manufacturing processes, the site management and organisation. But this will not be a revolution as it is in line with the breakthrough of BIM on construction sites.

> *"First of all, of course, it's necessary to work with more people that are trained to use computers and technology. You cannot say that that is not happening with this kind of technology, because it's controlled by a computer, of course. But, at Kamp C, we are not technicians, we work together with students who are 20 years old. Of course, we had some companies on which we could lean on to hear about their expertise. But if you know that within less than a year, we could print a house like we did. Then, you also know that the technique is not that difficult, and I really believe that* ***you can train people to use it*** *and that you can retrain your constructor employees if you want. I think it's really not a difficult technique to use, but of course, you need some IT people who can support you on the whole process."* (Marijke Aerts, Appendix 21)

It is certain that 3D printing processes will always involve materials scientists and civil engineers. But they will not replace the on-site workforce. However, **workers will have to adapt** to the new processes. In short, the social impact will be limited and more likely to take the form of training and refresher courses in the smooth running of the construction process.

> *"I don't think so. To work with the printer, you don't need to be an engineer. It's not necessary to be an engineer. Of course, when you want to design the house and develop it in its most opportune way and print it, then you need to be an engineer. But, I don't think it works like that, you always need several people who work together and then you have the most interesting solution."* (Marijke Aerts, Appendix 21)

5.6.2 Cost-based approach

A number of studies have investigated whether 3D printed construction is cost-effective and efficient compared to conventional construction. But the studies are generally based on case studies carried out in laboratories or with conceptual projects. Most of **these situations do not reflect the economic reality**.

> *"To compare costs, as 3D printing is in an artificial context and disconnected from the economic reality with all kinds of subsidies: companies are testing and experimenting. It is very complicated to count all the actual costs."* (Noël Naert, translated from Appendix 22)

For the purpose of this thesis, the author has repeatedly tried to find out whether a 3D printed structure is more cost-effective than the same structure built in a conventional way. However, in order to calculate the final price of a 3D printed construction, **many variables** have to be taken into account. These data are very difficult to access today due to the young maturity of the technology.

> *"There isn't transparent cost data available from anyone. I've heard vague estimates of 20-40% more expensive than traditional construction. I would be fascinated to know if you find out."* (Jarett Gross, Appendix 26)

> *"Even us, we have tried many times to calculate the price of what we print. We know the method, we know the cost of the material ... but there are so many variables: What is the part? How much prowder do we need? It depends on the part orientation in the machine. There are a thousand things to calculate and, in the end, we just use some very basic numbers. That's very, very hard to calculate."* (Mathias Rotgeri, Appendix 20)

Trends in the literature seem to indicate that 3D-printed buildings are no more expensive than traditionally manufactured buildings, although Gieljan Vantyghem is not convinced of that. According to Marijke Aerts, the **price will be determined by the complexity of the construction**. Benoit Parmentier further explained that several costs can be avoided compared to traditional construction methods. This is generally due to the following:

- Lower use of raw materials compared to traditional methods: this results from the fact that the shape of the structure is optimised to exactly match what is needed in relation to the forces required.
- A higher speed of execution.
- The elimination of costs such as formwork costs.

5.6.3 What does the market think? (Results of the survey)

The 3D printing technology is still in an early stage of development and is therefore only available to professionals in the construction industry. There is no price list yet for private use. Currently, only professionals are allowed to get a quote but that may change in the future. (COBOD, 2020).

A survey was shared on the Belgian market to gather the opinion of the population regarding 3D printing in general and in the construction sector. When analyzing the results (Appendix 32 - Q2) of the questionnaire shared on the Belgian market, it was observed that, out of 56 respondents from different sectors of activity, only **7% of them own a conventional 3D printer** at home. It is of course not possible to draw any conclusions given the small number of respondents, but it does indicate a general trend that 3D printing is not yet widely implemented at the individual level.

Individuals and end consumers **are not opposed** to 3D printing technology and the possible advantages in terms of ecology, speed of execution and durability. But as the technology is in its infancy, they **do not perceive yet the potential benefits**. Most of them are familiar with the principles of 3D printing but adapted to other industries such as aerospace, medical or the classical extrusion of polymeric materials.

As pointed out in the various interviews, this is a technology that has not yet reached maturity and whose first achievements have been presented recently or are in the process of being realised. However, it is important to note that a degree of curiosity emerges from the responses received from the questionnaire.

The end consumer will probably adopt a 3D printed house one day. However, the day when individuals will have a 3D printer to build their own house is not in the near future.

What to remember from Chapters 5.5 & 5.6

- To fully benefit from the advantages offered by 3D printing in construction, three best-case scenarios were identified:

Scenario 1: Isolated environment

- 3D printing could be very helpful in harsh environments. The automation of the printer reduces the need for human presence.

Scenario 2: Emergency situation

- In situations of climatic or health disasters, for example, or in areas of housing shortage, the speed and efficiency of 3D printing are important assets.

Scenario 3: Building projects that differ from the norm

- The high degree of customisation offered by 3D printing makes it possible to create buildings and structures with unique designs that were previously unachievable using conventional methods.

- As most 3D construction projects are at the experimental stage, it is too early to identify the social impact of the technology on humans.
- According to Marijke Aerts, the use of 3D printing will not reduce the need for labour. Workers' functions will change and they will have to adapt through training.
- There are too many variables to consider when evaluating the cost effectiveness of 3D printing over traditional construction.
- Many costs can be avoided by 3D printing: less material needed, faster process, no need for formwork.
- The survey shared within the Belgian market showed that 3D printing is known by the public but not yet adopted on a large scale. They do not perceive the benefits yet.

6. Conclusion

This thesis aimed to clarify whether 3D printing has a future in the construction industry and whether it could be considered a disruptive innovation. In other words, this study attempts to illustrate how the implementation of a potentially disruptive technology in a new environment could impact the industry, the stakeholders and the processes.

To approach this question, the study made a comprehensive review on the current progress and future prospects of 3D printing in construction. Two branches of literature were consulted: one on the principles of 3D printing and the other on the construction industry and the challenges associated with this industry.

Then, to complement the literature and try to understand in more detail what factors might influence the large-scale implementation of 3D printing in construction and thus its future, 10 interviews were conducted with construction professionals. The interviews provided clear insights into the use of this technology in the industry and the challenges and opportunities it faces today and will probably in the future.

In the last part, future customers and end users were interviewed in order to collect their perceptions on the technology. This study finally suggested scenarios in which 3D printing could be used to the fullest extent and what could be the socio-economic effects associated with these situations.

One of the motivations for undertaking this research is the interest in the development of these new projects around the world. Recently, many pilot projects have highlighted that the development of these projects has been of great interest to the society and the environment.

The following question can therefore be answered: "Does 3D printing have a future in the construction industry and could it be a disruptive technology? The answer tends to be positive. However, its disruptive impact will depend on many factors. It will have to be disruptive to market leaders, end users and infrastructure, as suggested by the three point disruptive technology criteria presented in the literature review.
In conclusion, the findings from this thesis suggest that 3D printing is a fast evolving field that can make a substantial disruptive impact on the construction environment. What is clear is that current projects show that 3D printing has a long way to go as it is still in the early stages of incredible potential.

Limitations of the study

Following this study, it was observed that **professionals** had a lack of perspective on the technology and its current and future applications. The technology is not sufficiently mature yet and most of the construction stakeholders remain cautious about the future of the technology in the industry. This comes also from the fact that the sector is very competitive and the margins are low. Investing in an early stage technology is risky, especially for young companies.

As far as **end users** are concerned, the public is not yet aware that 3D printing technology is being used in the construction industry. In practice, these are essentially pilot projects that are still largely unknown to the general public. In addition, the construction industry is a rather conservative sector that is traditionally not very open to technological developments. As a result, technological advances are not widely communicated to end users.

This was reflected in the responses to the survey intended for the Belgian market, where it was found that no tangible results could be derived from it, certainly due to the lack of knowledge of these new technologies. Some of the respondents' opinions were therefore guided by the limited information they had received on the subject and the limited number of existing projects known to the public.

Suggestions for further researches

Following the realization of this thesis on the future of 3D printing in construction, **three new study tracks** are suggested to further develop the findings of the author's research.

From a **technical point of view**, this study focuses mainly on 3D printing using concrete-based materials. However, the production of concrete still has a considerable impact on the environment. Further research and validations are necessary to determine if this is truly the most economically and environmentally suitable material for 3D printing. 3D printing projects involving materials other than concrete already exist: the TECLA project in Italy (Chiusoli, 2021) is an innovative house model that is made only of natural and local materials. According to the architects, it is a **nearly zero-emission** project that took less than 200 hours to print. It would be interesting, in future research, to carry out a comparative study from an environmental and economic point of view between a similar project (which is made of raw and natural materials such as clay or wood) and a more traditional 3D printing project made of concrete, in

order to determine which one is the most cost-effective and the least impactful for the environment.

A lot of research into the **social impact** of 3D printing has been carried out in this work. However, the study has only taken a global view of it. Because current 3D printing projects in construction are almost exclusively conceptual, they **do not reflect social reality**. The workers are usually researchers, and the social impact cannot be analysed. The issue of the impact of the technology on the labour market and the people involved in the construction of such projects is not currently relevant. Further research would then be necessary once the technology is no longer in the experimental phase.

Finally, further study would be necessary to identify the situations in which 3D printing is more **economically** profitable than traditional construction methods. In this study, only hypotheses have been presented. As most of the current projects are intended to demonstrate the technical feasibility rather than the economic viability, the costs associated with them **do not reflect the economic reality**. In addition, the large number of variables involved in the calculation of the total cost did not make it possible to establish whether 3D printing was economically interesting or not. Once the technology will be implemented on a large scale, the cost element will be the deciding factor. Then it will be possible to determine the return on investment of such a technology for a company

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Appendices

Appendix 1: Methodological-Technological Framework for Construction 4.0.

Source: (Muñoz-La Rivera and al., 2020)

Additive manufacturing (AM) Additive manufacturing refers to the construction of 3D objects by adding and superimposing ultra-thin layers of material, achieving high levels of precision and reducing construction times. It can be used to automatically build at the same construction site as well as to make exact scale building models or components.

Artificial intelligence (AI) Artificial intelligence refers to the ability of machines to solve complex problems using algorithms that mimic and are inspired by human intelligence. AI optimises the processes of design, monitoring, and prediction of the behaviour of structures and their elements, in the areas of structural engineering, energy, safety, among others. AI also enhances prediction models for water resources and natural phenomena which can affect structure of the building.

Building information modelling (BIM) Building Information Modelling is a collaborative working methodology for the design, construction, and operation of construction projects. From a technological point of view, BIM can be seen as an evolution of traditional CAD tools towards a parametric digital modelling, based on 3D models, and incorporating variables of time, cost, sustainability, occupational safety and management, through the integration of the project stakeholders. It is also contributing significantly to the digitalisation of construction data, providing multidisciplinary information to be processed and used throughout many project purposes, allowing interconnection with many other technologies in the industry.

Internet of things (IoT) The Internet of Things is the networking of objects and physical devices to capture data and interact with the environment. IoT is applied in the construction industry to connect digital BIM models with physical devices for on-site control and monitoring (workers, materials, equipment, health and safety, work progress), optimising communication, and construction logistics in general. IoT is also used for energy and disaster monitoring and facilities management during the operations phase.

Machine learning (ML) Machine Learning is an Artificial Intelligence discipline for making systems evolve as if they were learning, using algorithms based on existing data to predict future behaviour. ML automates many parts of the designs, based on data from previous works and the study of their behaviour over time, from structural and architectural aspects to installations, as examples. It also supports the automation of decision making in safety, logistics, and processes during the construction phase.

Mass customisation (MCu) Mass Customisation is the creation of goods and services tailored to the specific require-ments of each client. Paradoxically, for the construction industry, characterised by the fact that each building or infrastructure is a unique product, it is not easy to implement high levels of customisation due to current rigid workflows. However, the upcoming flexibility and automation of design processes, the 3D visualisation, modularisation and additive manufacturing, could help to promote MCu, which is being increasingly required by developers and users.

Off-site construction (OSC) Prefabrication, modular or Off-site Construction is a construction procedure based on components and subsystems built-in series outside the final location, and then placed and assembled there. OSC brings to the construction site structural 2D or 3D elements (complete spaces, such as bathrooms or kitchens, for example) manufactured in controlled industries, requiring only assembly and installation on-site, optimising time, logistics and quality of finishes. Therefore, the technical aspects of the prefabricated elements are controlled in a factory, applying rigorous management and quality control principles, systematising the construction processes and without exposure to uncertain weather conditions at the building construction site. A greater adoption of BIM facilitates OSC, providing the component breakdown from the digital models and all the details of the facilities.

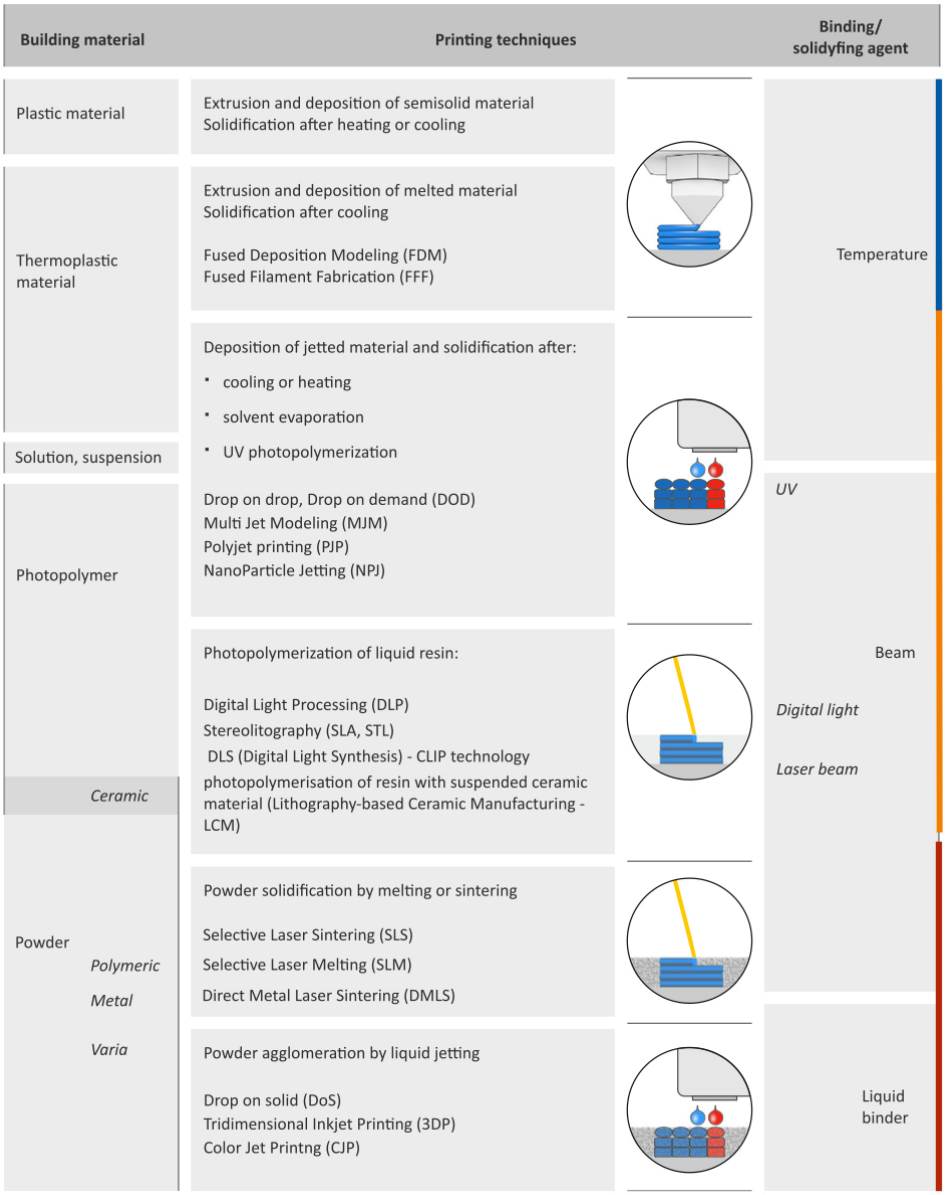
Sensors (S) Sensors are electronic devices to determine the variation of a physical or chemical mag-nitude, by transforming them into electrical variables. Sensors are used in construction to monitor the structural health of buildings and infrastructures, to check the correct operation of machinery, workers, equipment, systems, thermal comfort, and many others.

Supply chain management (SCM) Supply Chain Management is the process of planning, executing, and controlling an efficient supply network. It is applied to systems and procedures to link the knowledge, procedures, and learning of the supply logistics of the different projects,

optimising the purchase and distribution of materials (quality and specific requirements). SCM brings together and improves relationships between all stakeholders in the construction sector, by clarifying processes and distribution of roles and risks. BIM contributes to the SCM by connecting digital models of materials and inputs.

Appendix 2: Development of 3D printed objects.

Source: (Jamróz, 2018)



Appendix 3: The seven categories of additive manufacturing process.

Source: (ISO/ASTM 52900-15, 2015)

1. ***Binder jetting***: selective deposition of a liquid bonding agent onto thin layers of powdered material to join the powdered materials and generate an object layer by layer. The typical materials used are powdered polymers, metals, ceramics and shape-memory alloys;
2. ***Directed energy deposition***: fusion of materials using concentrated thermal energy (a laser, electron beam or plasma arc) to melt the material as it is being deposited. It is usually used with metal powder and wire feedstock;
3. ***Material extrusion***: selective deposition of a material through a nozzle or orifice to produce an object layer by layer. It is typically used with thermoplastic filaments and flowable slurries;
4. ***Material jetting***: selective deposition of droplets of the building material layer by layer to produce an object. Usually, the typical materials applied are photopolymers, polymers and waxes;
5. ***Powder bed fusion***: selective fusion of regions of a powder bed with thermal energy (a laser or electron beam), where the surrounding powder acts as support material. The common materials used are polyamide, metal and ceramic powders;
6. ***Sheet lamination***: the bonding of sheets of material to produce an object. Depending on the material, the layers can be bonded by glue or adhesive coating (paper and polymer sheets) or ultrasonic welding (metal sheets) can be used;
7. ***Vat photopolymerization***: the selective cure of a vat of liquid photopolymer by light-activated photopolymerization, via a laser or projector. The typical material used is ultraviolet curable polymer resins.

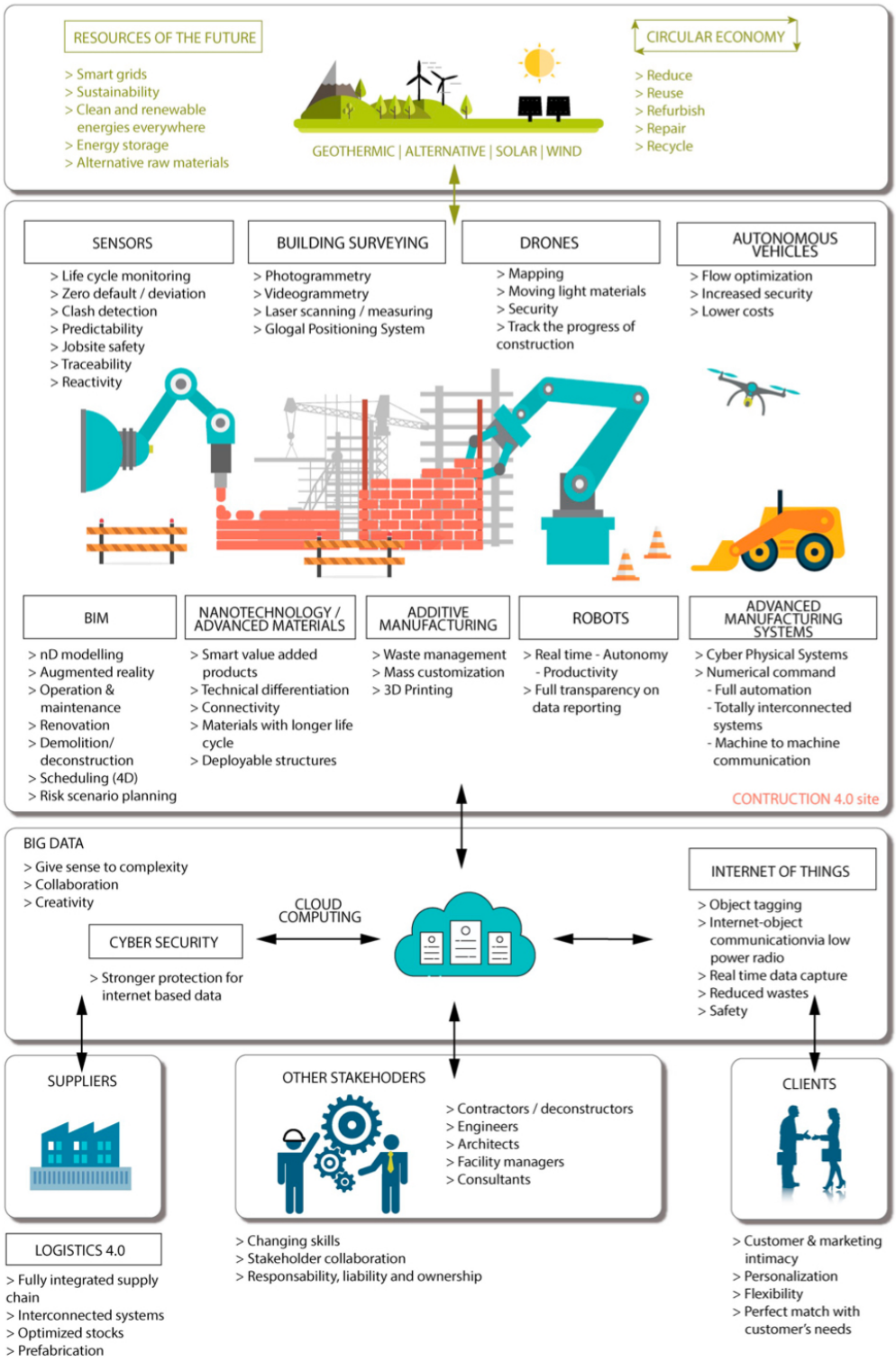
Appendix 4: Some problems of the Construction Industry.

Source: (Muñoz-La Rivera and al., 2020)

Problem	Description
Cost overruns and delays	Delays and cost overruns are one of the most serious problems in the construction industry, with causes ranging from inherent technical difficulties to administrative and legal difficulties in carrying out tendering procedures. These over costs and delays distort the natural mechanisms of competitiveness as they make it significantly more difficult for different construction agents to foresee the proper fulfilment of the contract on time and in form [1]
High dependency and low interaction with suppliers	There is a high dependency of construction companies on their external suppliers (60–70% of total activities depending on them), a situation that can also be seen in other industries, such as manufacturing. However, in the AECO industry this dependence is not accompanied by systematic and methodological agreements of interaction or co-development. As a result, construction companies are conditioning their growth on te acquisition or incorporation of external innovation and learning [2]
Ineffective knowledge management	In construction companies, there are limited internal networks which does not allow for efficient access to information from previous projects and sometimes not even from the current project. Lessons learned from projects generally remain in individual teams and do not reach the entire organisation, especially technical information, actual budget and execution times, deviations, incident handling and on-site problem solving specific to the sector [2]
Focus on classic routine activities	Focus on repetitive processes without or with little innovation and no use of the learning of the different teams in the company due to a lack of collection and limited dissemination of information [1, 2]. There is not systematic treatment of global information both for each work and among the company's set of jobs over time
Extensive regulation limiting innovation	Construction projects operate in public and private regulated contexts, related to consumer protection, safety, and technical and environmental standards. Some regulations may be an obstacle to innovation when their original intention is distorted, specifically in the case of certain bidding processes that slow down and make the execution of the work more expensive, or the rigor of technical regulations that often lack the agility to adapt to changes in the sector [2]
High diversity of agents leading to fragmentation	Large and complex projects are carried out, built by temporary alliances of unequal companies, which in turn are involved in other similar projects. Each company involved has different equipment, profiles, training, culture and above all, interests while seeking to complete its activities in the shortest time possible, to be able to use its resources in other projects [21]. Fragmentation in the production process generates a hierarchy of processes with few long-term relationships between teams, generating conflicts between prime contractors and subcontractors and ultimately makes it difficult to integrate the supply chain [2]
Lack of skilled workers	The industry has a low-skilled workforce, with high job rotation, rising average age of employees, with little turnover. This is mainly because the sector is unattractive to young and trained workers (safety, wages, working conditions) [22]
Poor financial management	The industry has financial management problems. Problems in giving payments to the company, from public or private funds, which impact to the company's payments to employees and sub-contractors. This generates problems in the schedule, lack of credibility and bad practices in the construction [1, 22]
Poor asset management	The traditional value chain in the construction sector implies that its agents tend to concentrate their concern and responsibility in the current stage, either planning, construction, operations and maintenance, or demolition. The value progressively decreases working like this, compared to a process considering the complete construction cycle [2]
Design changes during construction	Changes in design during construction are recurrent, for different reasons: inconsistencies, owner modifications, regulatory changes, but above all, early tenders where the economic criteria prevails over the technical quality of the design and energy efficiency or environmental considerations, as second priorities, which cause alterations in the costs and schedule (due to timeouts, demolitions or reworks) [2, 22, 23]
Poor planning and programming	Planning and programming problems in the construction processes, which generate delays and reworks due to the lack of availability of material, equipment, people and other factors [24, 25]
High accident rate	The construction environment and its traditional interaction dynamics generate an accident-prone environment, with low trained and unmotivated personnel lacking a suitable safety culture. These problems are further increased by poor construction health and safety plans, along with well-established bad practices [26]

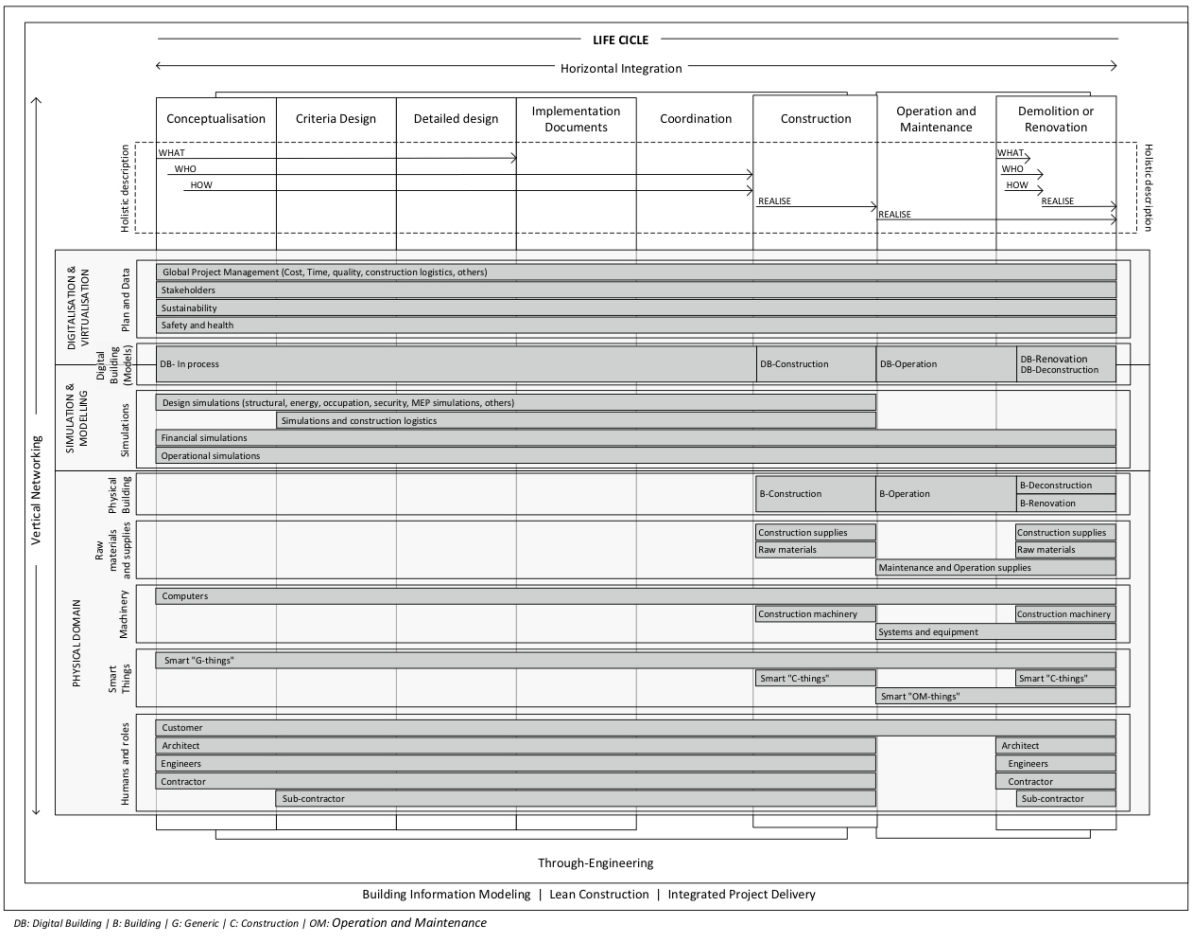
Appendix 5: The "Construction 4.0" environment enabled by intensive use of digital technologies.

Source: (Craveiro et al., 2019)



Appendix 6: Construction 4.0 methodological framework.

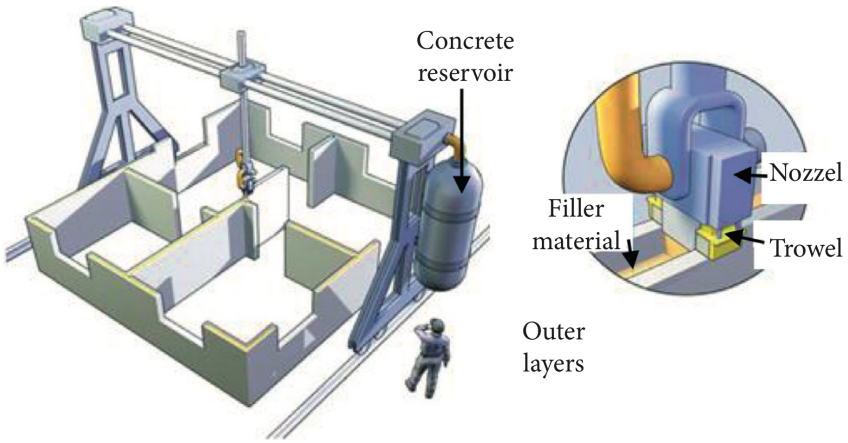
Source: (Muñoz-La Rivera et al., 2020)



DB: Digital Building | B: Building | G: Generic | C: Construction | OM: Operation and Maintenance

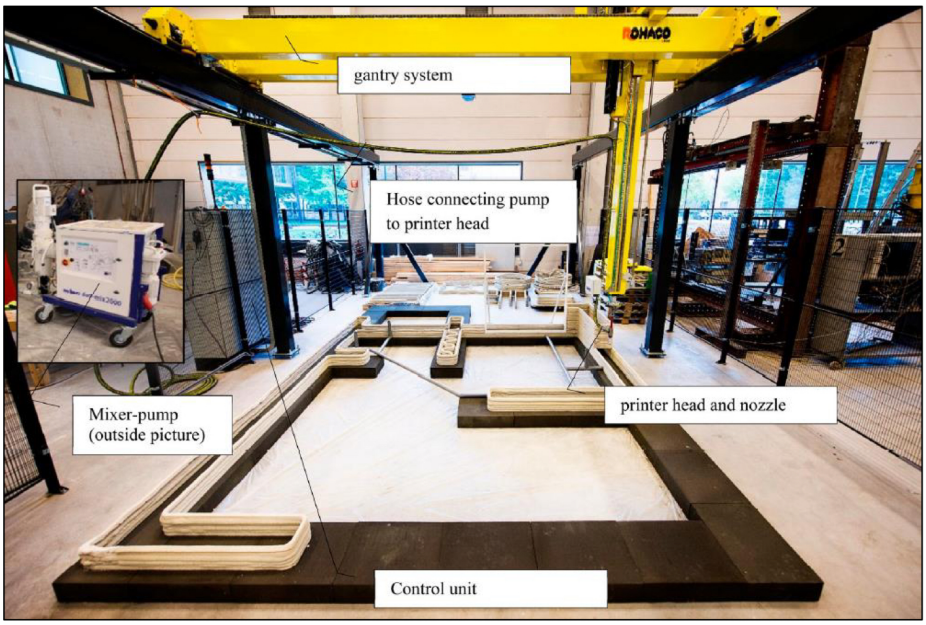
Appendix 7: Contour crafting (CC) in construction operation.

Source: (Zhang & Khoshnevis, 2013)



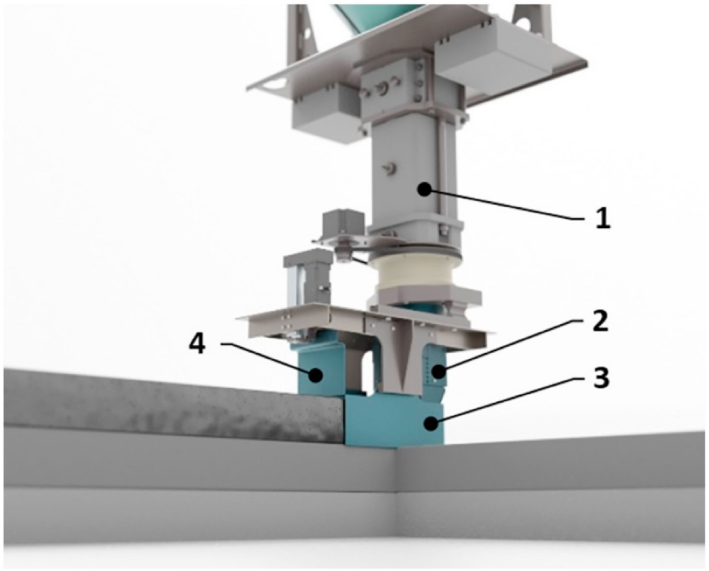
Appendix 8: The components of a 3D printer used in the construction industry (location: TU Eindhoven).

Source: (Truong, 2019)



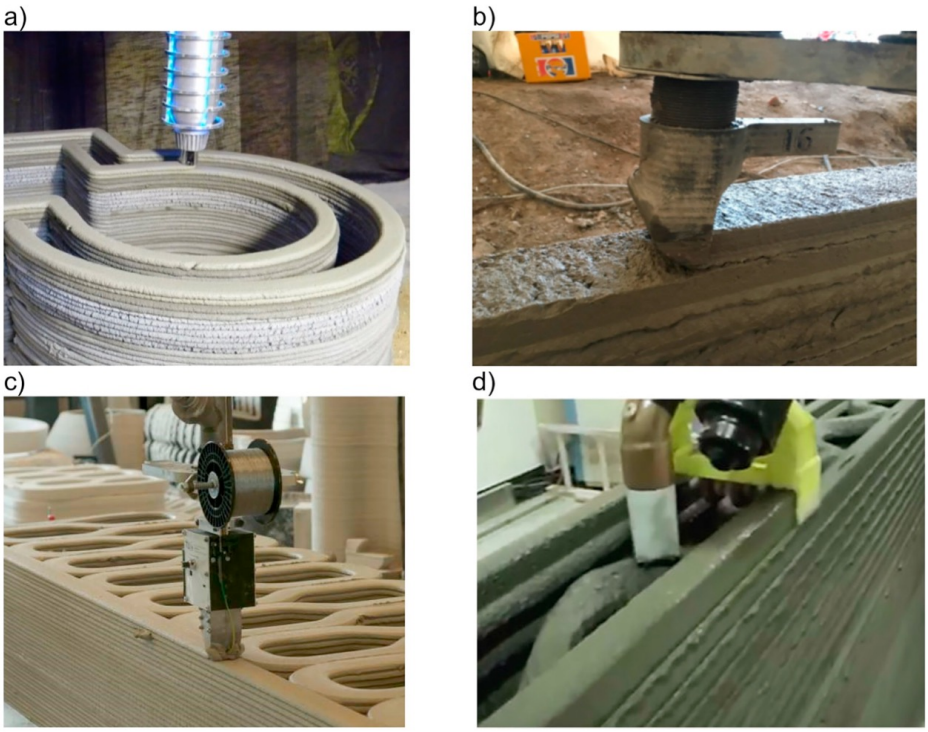
Appendix 9: Printhead under development: (1) extruder and the complex forming system with (2) nozzle, (3) shaping plates, (4) shutter and several actuators for printing various wall cross-sections.

Source: (Mechtcherine, 2019)



Appendix 10: Printheads for concrete printing a) Total Justom, b) COBOD, c) TU Eindhoven, and d) Contour Crafting (CC).

Source: (Mechtcherine, 2019)



Appendix 11: Data and results from the cost analysis of the DFAB HOUSE.

Source: (García de Soto et al., 2018)

Cost for straight concrete wall using conventional construction.

Task	Cost type	Cost (USD)		
		Optimistic	Most likely	Pessimistic
Erect & Strip formwork	Labor		2739	
Erect & Strip formwork	Material		629	
Install reinforcement	Labor		143	
Install reinforcement	Material		100	
Place concrete	Labor		1127	
Place concrete	Material		955	
Place concrete	Equipment		1518	
	Total		7211	

Cost for double-curved wall using robotic fabrication.

Task	Cost type	Cost (USD)		
		Optimistic	Most likely	Pessimistic
Produce steel base	Labor	702	1054	1405
Produce steel base	Material	4635	4635	4635
Produce steel base	Equipment	1500	1500	1500
Place AprilTags	Labor	88	88	88
Calibrate IF	Labor	42	42	42
Fabricate steel mesh	Labor[a]	7613	7654	7732
Fabricate steel mesh	Material	566	566	566
Fabricate steel mesh	Equipment[b]	56	59	78
Install and finish concrete	Labor cost	3175	3175	3175
Install and finish concrete	Material cost	1887	2842	3797
Install and finish concrete	Equipment cost	1648	1648	1648
	Total	21,912	23,262	24,665

[a] Includes cost of specialty technician/robot support for the time the robot is fabricating the steel mesh.

[b] Proportional cost of the robot based on utilization time for the construction of the wall.

Cost for double-curved wall using conventional construction.

Task	Cost type	Cost (USD)		
		Optimistic	Most likely	Pessimistic
Erect & Strip formwork	Labor	6517	8147	9776
Erect & Strip formwork	Material	30,067	40,090	50,112
Install reinforcement	Labor	731	975	1219
Install reinforcement	Material		166	
Place concrete	Labor	2255	2819	3382
Place concrete	Material		955	
Place concrete	Equipment		1518	
	Total	42,210	54,669	67,128

Cost for straight concrete wall using robotic fabrication.

Task	Cost type	Cost (USD)		
		Optimistic	Most likely	Pessimistic
Produce steel base	Labor	702	1054	1405
Produce steel base	Material	4635	4635	4635
Produce steel base	Equipment	1500	1500	1500
Place AprilTags	Labor	88	88	88
Calibrate IF	Labor	42	42	42
Fabricate steel mesh	Labor[a]	6996	7061	7147
Fabricate steel mesh	Material	480	480	480
Fabricate steel mesh	Equipment[b]	51	55	73
Install and finish concrete	Labor cost	2837	2837	2837
Install and finish concrete	Material cost	1738	2693	3648
Install and finish concrete	Equipment cost	1648	1648	1648
	Total	20,717	22,092	23,502

[a] Includes cost of specialty technician/robot support for the time the robot is fabricating the steel mesh.

[b] Proportional cost of the robot based on utilization time for the construction of the wall.

Total cost for different wall types (straight and double-curved) and construction methods (conventional and robotic fabrication).

Wall/construction type	Total cost[a] (USD)											
	Current			Option 1			Option 2			Option 3		
	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum
Straight/conventional	N/A	7211	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Straight/robot	21,328	22,101	23,035	17,743	18,591	19,558	17,459	18,313	19,281	17,133	17,989	18,950
Double-curved/conventional	45,382	53,955	63,571	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Double-curved/robot	22,612	23,268	24,351	18,706	19,465	20,560	18,396	19,163	20,259	18,039	18,812	19,900

[a] Total cost for robotic fabrication includes the proportional cost of robot related to the construction of the wall and cost of specialty technician/robot support for the time the robot is fabricating the steel mesh.

Appendix 12: Benefits related to 3D printing in construction.

Source: (de Laubier et al., 2018)

EXHIBIT 3 | 3D Printing in Construction Offers Many Advantages

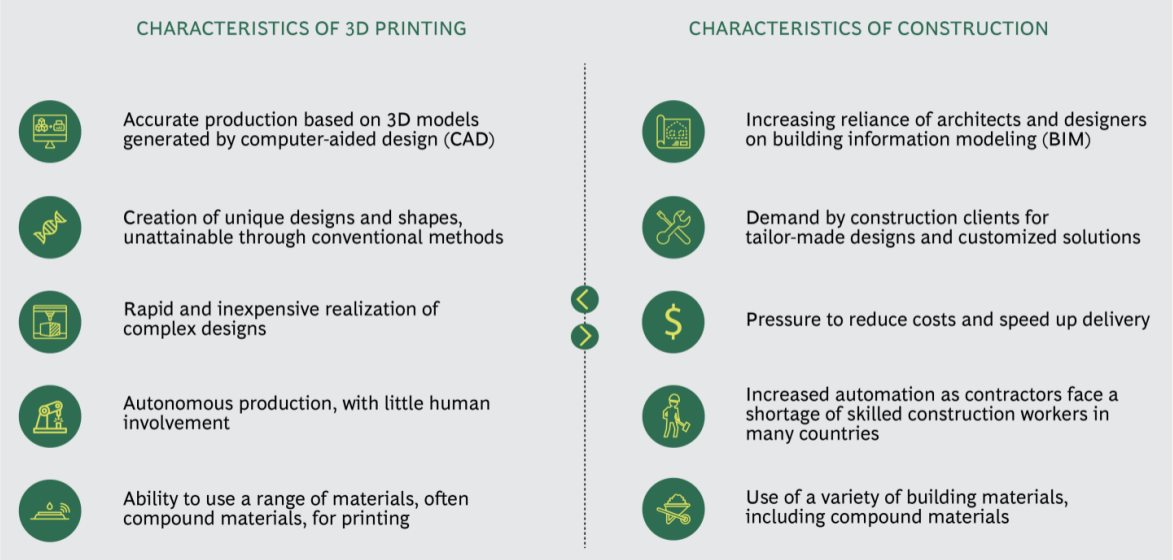
		3D-printed vs. conventional construction
Costs	Labor	Overall savings as 3D design becomes easier and as onsite workforce is reduced
	• Architects, designers, engineers	Need for training to adapt to the new technology, methods, and possibilities
	• Installation	Printers' ability to work autonomously,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

Significantly lower | Slightly lower | Equal | Slightly higher

Sources: Expert interviews; BCG analysis.
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.

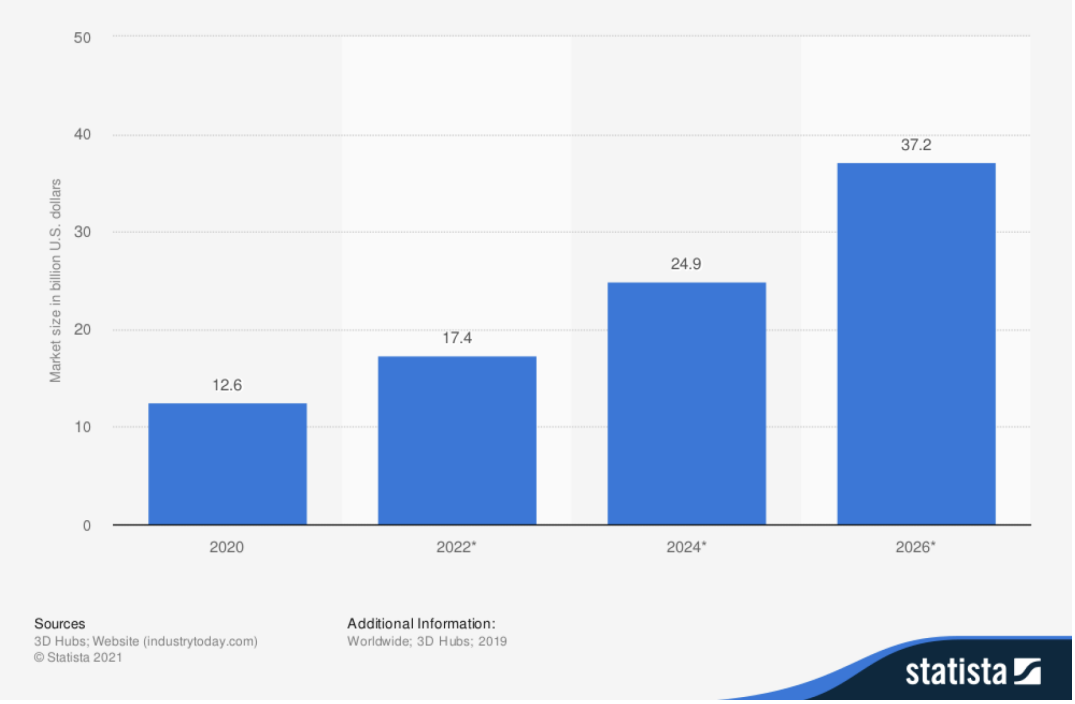
Appendix 13: Reasons why 3D printing is a natural fit with construction.

Source: (de Laubier et al., 2018)



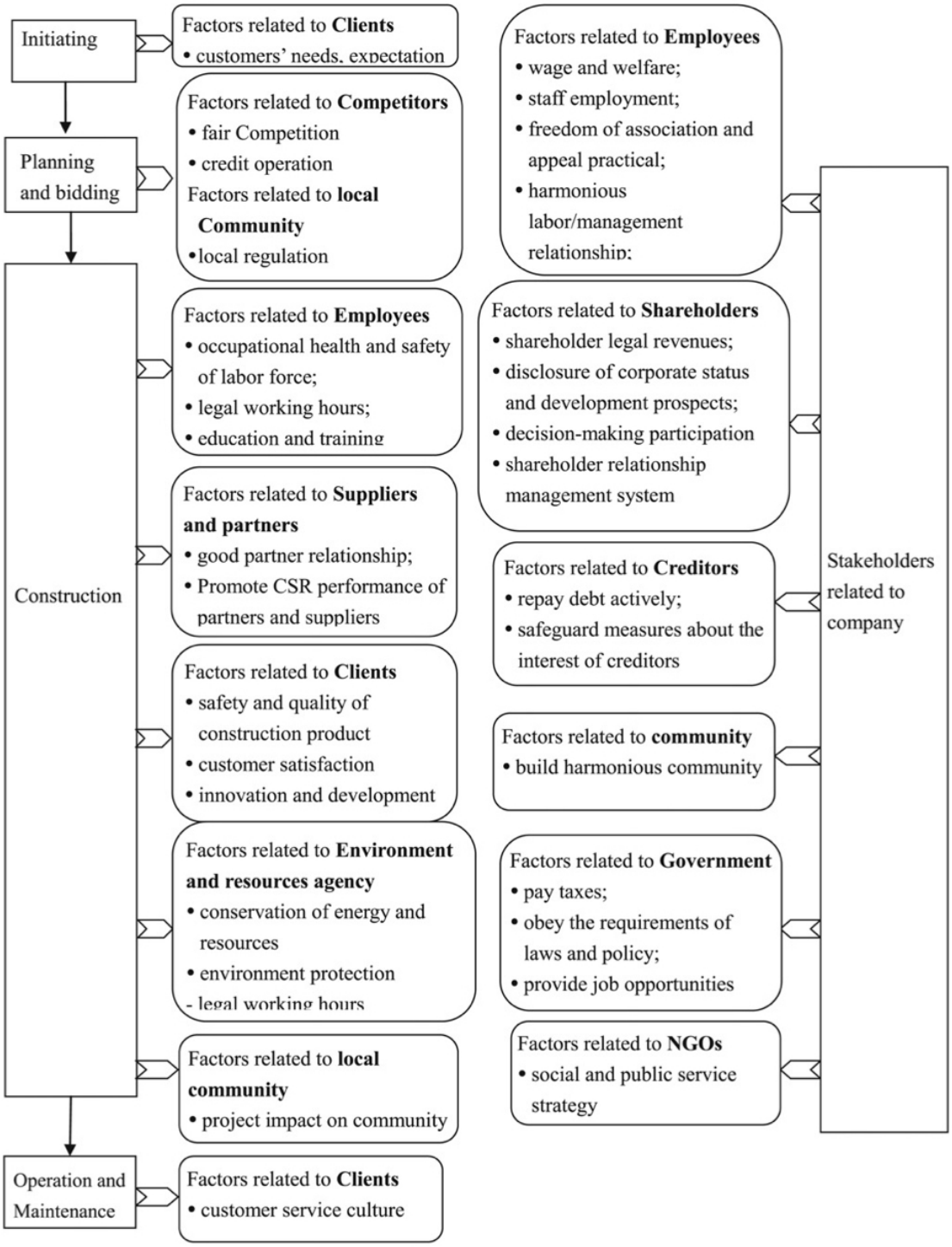
Appendix 14: Global 3D printing products and services market size from 2020 to 2026 (in billion U.S. dollars).

Source: (Statista, 2021)



Appendix 15: Stakeholder groups mapped in the construction industry.

Source: (Zhao et al., 2012)



Appendix 16: Example of recipe used for 3D print the first building in Europe in 2017.

Source: https://cobod.com/

Material	Quantity [ton]	Price DKK	Price EUR	Percentages by weight
Cement	6.12 ton	10,374 DKK	1,391 EUR	32 %
0-2mm sand	3.50 ton	595 DKK	80 EUR	18 %
0-4mm gravel (0-8mm)	3.50 ton	637 DKK	85 EUR	18 %
0-4mm recycled roofing tiles (0-8mm)	4.38 ton	525 DKK	70 EUR	23 %
Water	1.66 ton	62 DKK	8 EUR	9 %
Glenium sky 631 (superplasticizer)	0.04 ton	191 DKK	26 EUR	~0 %
Crackstop fibers	0.02 ton	1,038 DKK	139 EUR	~0 %
Total	**19.22 ton**	**13,422 DKK**	**1,799 EUR**	**100 %**

Presentation of the interviewees

Appendix 17

Benoit Parmentier - BBRI

Benoit Parmentier graduated with a degree in civil engineering from UCLouvain. Since 2005, he has been working at the BBRI (Belgian Building Research Institute) and is today the strategy and innovation coordinator. His role is to bridge the opportunities and needs of all BBRI stakeholders. He is also head of a "Construction 4.0" programme and is passionate about innovation in construction.

Prof. Dr. Michael Henke - TU Dortmund University and Fraunhofer IML

Michael Henke has a doctoral degree in Business Administration from the Technical University of Munich. Since 2013, he is the head of Chair of Enterprise Logistics at TU Dortmund University and director of this section at Fraunhofer Institute for Material Flow and Logistics. He is also a guest professor for Strategic and Development at the Louvain School of Management in Belgium. As well, he is deeply interested in Management of Industrie 4.0 and Platform Economy, Financial Supply Chain Management, etc.

Mathias Rotgeri - Fraunhofer Institute

Mathias Rotgeri has specialized in AM and 3D printing since 2012 when he started as a student building his own 3D printer. He has worked at Fraunhofer Institute since 2014, where he conducts some research projects on Material Flow and Logistics.

Marijke Aerts - Kamp C

Since 2019, Marijke Aerts has been the project manager at Kamp C at Westerlo in Belgium. Kamp C is an autonomous provincial company of the province of Antwerp in Belgium which undertook, among other things, the project to build the first completely 3D printed 2-stage house in Belgium. Kamp C has the ambition to accelerate the transition to a sustainable society by focusing on two principles: sustainability and innovation.

Noël Naert and Arnaud Tandt - FEBELCEM

Noël Naert and Arnaud Tandt both work as consulting engineer-architects at FEBELCEM (Federation of the Belgian Cement Industry) since 1993 and 2018 respectively. Despite its great economic importance, the Belgian cement industry has long remained unknown to the general public. In order to raise the sector's notoriety, FEBELCEM is running a communication campaign about concrete and its applications. The federation also promotes the interests of its sector, particularly in the legal and environmental fields.

Xavier Köttgen - Architect and manager at Section A-A

Xavier Köttgen is an architect working in the company "Section A-A & Associés SRL", which he founded just over 20 years ago. During this period, many projects have been developed for private individuals or developers. In the past, Xavier Köttgen was also the designer of the CBR cement factory stand at several editions of the Batibouw exhibition in Brussels (2000 to 2004) and then of the "Infobeton" stand (2005 to 2009) at the initiative of the Belgian Cement Industry Federation (FEBELCEM). Thanks to these various collaborations, the architect has acquired solid experience in the field of concrete and high-performance mortars.

Gieljan Vantyghem - Concre3DLab - UGent

Gieljan Vantyghem graduated in 2015 with a Master of Science (Building Construction technology) at Ghent University. He then pursued his academic career as a PhD student on Topology Optimization at Massachusetts Institute of Technology (MIT) and Ghent University. As a member of the department of Structural Engineering, he participated in a research project in collaboration with the company Vertico with the aim to build a 3D printed bridge with the smallest possible amount of concrete.

Vytautas Naslenas - COBOD International A/S

Vytautas Naslenas has been working for COBOD International A/S since 2020. He is now the global sales coordinator of the company. COBOD International is the world leading designer and manufacturer of 3D construction printing technology based in Copenhagen in Denmark.

Dr. Fabian Meyer-Broetz - PERI AG

Fabian Meyer-Broetz has been the head of the 3D construction printing department at PERI AG since 2019. The PERI company is one of the leading manufacturers and suppliers of formwork and scaffold systems on the market. More recently, the company has started to supply 3D construction printers worldwide.

Jarett Gross - Construction Technology Correspondent

Graduating with a Bachelor of Science degree in Drexel University, Jarrett Gross has been a freelance construction journalist for over two years. Recently, he has been doing podcasts with renowned 3D printing companies such as Vertico and CyBe Construction.

Interview transcripts

Appendix 18

1. Benoit Parmentier - 10th of March 2021 on Microsoft Teams

Strategy & Innovation Manager at BBRI

Qualitative approach: **Semi-conducted interview**

Florian: Bonjour, merci beaucoup de me consacrer du temps. J'ai eu vos coordonnées grâce à Mr Detemmerman. Je vous explique un peu le contexte : je suis étudiant en ingénieur de gestion et je me suis lancé dans un projet (mémoire) sur les nouvelles technologies sur les imprimantes 3D. Le monde de la construction m'intéresse aussi depuis longtemps. J'ai donc décidé de lier les deux, au vu des différentes possibilités et projets d'aujourd'hui. Je ne suis pas un ingénieur civil. J'étudie la question sous différents points de vue : technique, faisabilité aujourd'hui et demain, le budget, etc. Ma première question est la suivante : « où en sommes-nous aujourd'hui en termes d'évolution ? » Y a-t-il déjà des projets en Belgique ? Ou en Europe ?

Benoit Parmentier: Je pense que je vous ai envoyé un lien vers des publications dans le cadre d'un projet européen qui fait le listing des projets phares en lien avec l'impression 3D. On est dans l'impression 3D à base de mortier, béton. À savoir que l'impression 3D à petite échelle à base de polymère existe depuis un certain temps.

En construction, cette technologie arrive pour le moment à un stade où on teste l'industrialisation. Il y a déjà des projets en place : une maison témoin a été réalisée en Belgique (Flandre) par Kamp C. C'est un projet intéressant de démonstration technologique dans lequel nous avons aussi été impliqués dans le comité d'accompagnement. Au niveau européen et international, il y a déjà beaucoup de projets qui ont été réalisés à des échelles un peu diverses.

Si je prends une autre entreprise belge : Basix. C'est une entreprise belge qui a beaucoup d'activités dans les Emirats, ils ont développé là-bas un laboratoire et ont réalisé un bâtiment témoin pour leur propre usage en 3D.

Florian: Dans mes recherches, j'avais effectivement vu ce bâtiment. Il est beaucoup plus grand qu'en Belgique.

Benoit Parmentier: Aux Emirats, les objectifs sont différents, ils visent à construire 25% de leurs bâtiments via des imprimantes 3D en 2025. Apparemment, c'est une volonté politique.

Florian: Connaissez-vous la raison ou l'avantage d'imprimer en 3D là-bas ?

Benoit Parmentier: Pour eux, l'avantage est que c'est une vitrine technologique pour le pays. Ils transforment par exemple leurs pétrodollars en investissements immobiliers pour attirer des

entreprises ou des touristes. C'est une façon pour eux de dire qu'on est à la pointe et qu'on est un pays qui innove et qui a des bâtiments exceptionnels. Les formes réalisées par les imprimantes 3D étant beaucoup plus organiques, les formes sont très originales. Ils réalisent des bâtiments un peu plus spécifiques qui ne sont pas réalisables via des méthodes traditionnelles. Ce deuxième projet est plus en lien avec une entreprise de construction qui veut faire des choses grâce à l'impression 3D.

Dans le domaine de la recherche, c'est aussi important car il y a toujours beaucoup de défis technologiques liés à cela. Par exemple, nous n'avons pas de béton armé, comme c'est le mix entre le béton et les armatures. Pour faire des grands ouvrages de structure, il faut du béton avec des armatures. Hors, l'impression, c'est simplement couler du béton et il n'y a pas d'armature dedans. Soit on rajoute les armatures par après, d'une certaine façon pour renforcer l'ouvrage (= post-contrainte). Ou bien, on conçoit des éléments qui ont moins besoin d'armatures.

Florian: Grâce à l'impression 3D, est-ce possible de mettre différentes couches les unes à côté des autres pour renforcer la structure ?

Benoit Parmentier: Il y a plusieurs technologies et l'impression 3D est aussi utilisée de différentes manières. On peut soit couler les choses en direct ou on peut, par exemple, couler une sous-structure qui fera office de coffrage. On coule le coffrage avec une forme spéciale et on s'affranchit des contraintes liées au coffrage traditionnel qui sont rectilignes. Avec ce coffrage, on peut couler le béton comme dans un moule et y mettre des armatures ou on peut directement imprimer le mur en direct. On peut donc réaliser des murs courbes. C'est juste pour expliquer qu'il y a plusieurs manières d'utiliser l'imprimante 3D. Et dans les imprimantes 3D, il y a aussi différents systèmes. Ça peut être un bras robotique six axes, un système de cadre avec portique, un système avec des pylônes et des câbles. Les deux principaux sont le bras robotisé ou le portique. La maison réalisée en Belgique était avec un grand portique. Le spectre est assez large, il y a beaucoup de technologies différentes et aussi en termes de matériaux.

Florian: En termes de matériaux : qu'existe-t-il aujourd'hui ? On parle beaucoup de béton mais y a-t-il d'autres matériaux ? Pourrions-nous utiliser des matériaux moins polluants ? De la résine de bois ?

Benoit Parmentier: On a d'abord développé des matériaux cimentaires classiques car c'est le plus connu. C'est un matériau qui est fortement sollicité à son jeune âge et qui doit durcir très vite pour être très stable rapidement. Cela nécessite des propriétés très importantes en termes de rigidité et des quantités de ciment importantes. On est dans des classes de résistance assez élevées quand on parle de mortier pour l'impression 3D. Il nous faut donc beaucoup de ciment. L'impact écologique n'est en conclusion pas terrible. Pour compenser ça, il y a deux manières :

1. On imprime des choses qui demandent moins de volume de béton. On épargne des quantités de béton parce qu'on optimise la forme (qu'on ne pouvait pas faire en utilisant des techniques traditionnelles). On a des formes très spéciales comme des poutres que l'on peut construire en forme de 'i' plutôt qu'en rectangle. Ces formes sont juste adaptées pour reprendre des efforts et ne consomment pas d'excédent de matière.

L'impact écologique environnemental est donc plus faible. On épargne une quantité de matière.

2. On peut aussi changer des matériaux. On pourrait utiliser des matériaux biosourcés plutôt que des matériaux cimentaires. On essaye de remplacer le ciment par des éléments de recyclage, du sable, des matériaux propres à l'industrie (e.g. résidus), etc.

Florian: D'autres projets ont déjà été lancés avec d'autres matériaux ?

Benoit Parmentier: On a déjà des projets qui ont été lancés avec des matériaux locaux: en Italie avec de l'argile et de la paille par exemple. C'est une sorte d'auto-construction finalement. Ils ont testé ces systèmes-là pour montrer si on pouvait construire une maison localement avec des matériaux qui sont déjà sur place. Au niveau environnemental, c'est une des meilleures façons d'avoir un circuit court. Mais il y a aussi plein de questions sur le fait que c'est suffisamment durable et résistant ?

Florian: J'avais également entendu parler des projets avec de la résine de bois.

Benoit Parmentier: Il existe effectivement aussi des composites bois–ciment où on introduit une partie de fibre de bois dans un certain pourcentage, comme les matières plastiques par exemple. On peut rajouter des éléments ligneux par exemple pour avoir une matrice plus environnementale.

Florian: Selon vous, quels sont les avantages d'imprimer en 3D aujourd'hui et pour le futur? Construire un bâtiment en 3D prend déjà moins de temps. Quoi d'autre ?

Benoit Parmentier:

1. 1er avantage : Il n'y a pas de coffrage comme pour le béton, et ça met du temps à installer, ça met du temps à désinstaller, etc. Les coffrages peuvent représenter jusqu'à 30 à 50% du coût quand les bâtiments sont entièrement coulés sur place. Avec l'impression 3D, si on supprime ce coût, cela devient très intéressant.
    a. Dans le béton, il y a 2 domaines : le béton qu'on met en place et le béton préfabriqué. Mais même avec le béton préfabriqué, on doit parfois rajouter une couche de béton (ex: les planchers alvéolés ont des creux à l'intérieur car il y a des endroits où on n'a pas besoin de matière, ce sont des éléments de plancher légers préfabriqués en usine qu'on installe sur le chantier pour construire une maison ou un bâtiment). Mais il faut quand même une couche de béton supplémentaire pour solidifier l'ensemble, pour faire en sorte que ce soit quelque chose de continu au niveau de la structure. Il y a aussi des ouvrages où nous ne faisons que du béton coulé en place.
2. 2ème avantage : On peut réaliser des géométries plus complexes pour une diversité architecturale importante. On peut dessiner des murs courbes, on peut dessiner des portes à faux, des formes et des structures complètement originales et ce n'est pas plus compliqué à réaliser avec des machines d'impression. Alors qu'avec un coffrage, même

réalisé en usine, ça aurait coûté beaucoup plus. Réaliser un coffrage spécifique seulement pour un ouvrage coûte très cher.

3. 3ème avantage : On peut aussi optimiser la matière ? C'est de l'optimisation topologique. Par exemple, si on prend l'exemple d'une poutre rectangulaire et son coffrage ou moule rectangulaire. C'est très facile, on coule dedans et c'est réglé. D'un point de vue structurel cependant, ce n'est pas de l'optimisation car la forme rectangulaire n'est pas la forme optimale pour les efforts de chargement. En fait, la forme optimale est plutôt un "I". et donc, on a un excédent de matière (toute la matière qui existe dans le rectangle qui n'est pas dans le I), et on consomme pour rien. L'impression 3D permettrait de faire ces "I" beaucoup plus facilement. Si on optimise bien les éléments de structure pour reprendre les efforts en fonction de la charge, on peut dès lors fabriquer des formes exactement bien pensées pour reprendre la sollicitation qui est envisagée. Donc, on évite la consommation de matière.
4. 4ème avantage: Dans certains endroits autres que la Belgique avec des environnements agressifs où il n'est pas très agréable de travailler et des zones difficilement accessibles ; c'est alors plus simple de faire travailler une machine que des hommes.

Florian: Le premier projet que j'avais vu dans la presse parlait effectivement de l'impression 3D pour aller sur Mars.

Benoit Parmentier: Effectivement, on pourrait juste envoyer la machine et elle construirait toute seule les bâtiments avec des matériaux locaux, etc.

Florian: Mais ici sur Terre, en Asie ou en Afrique, cela pourrait dès lors être intéressant ?

Benoit Parmentier: En effet, les endroits où c'est compliqué ou là où il y a des zones dangereuses.

5. 5ème avantage: L'hybridation. C'est à dire qu'on confère à un élément de construction plusieurs propriétés en une fois (comme dans un téléphone avec plein d'applications différentes). Les éléments de structure réalisés par impression 3D pourraient avoir plusieurs propriétés : on pourrait mixer les propriétés esthétiques, structurelles, acoustiques, la résistance thermique, etc. Cette structure pourrait avoir des propriétés acoustiques grâce à une abortion, des non-réverbérations tout en ayant une fonction structurelle. Au lieu d'avoir plusieurs couches d'un mur pour les différentes fonctions (structure, isolation, etc.), on n'en aurait qu'une en dessinant bien la forme de l'élément imprimé en 3D. On gagne en fonctionnalités, en espace, en temps d'assemblage (on ne doit pas rajouter une couche par après), et en quantité de matière. La résistance thermique aussi : pour éviter les ponts thermiques, on peut optimiser l'élément pour éviter les transferts de température ! Tout dépend en fait du système de couche. En ce moment, on imprime surtout la structure de base (murs et colonnes). Après, on pourrait projeter l'isolant à l'intérieur du mur imprimé en 3D parce qu'il y a de l'espace. On pourrait aussi faire une injection de polyuréthane.

Pour les ouvrages rectilignes très simples, ce n'est pas là où l'impression 3D sera utile et intéressante. Si ce n'est qu'elle va complètement automatiser le système mais l'investissement sera trop important par rapport à la rentabilité. Pour des murs droits, on va préférer acheter des murs préfabriqués en usine et les installer car il n'y a pas d'investissement pour l'entrepreneur. Pour une construction 3D, il y a tout le temps d'installation de la machine. Il faudra beaucoup de mètres carrés avant que ce soit rentabilisé. Si les murs sont courbes ou les parties d'ouvrage plus spécifiques, ça sera plus rentable d'utiliser une imprimante 3D.

Au niveau de la structure de coûts, tu peux regarder certains articles qui montrent par exemple la différence entre le coût du travail, des matériaux, etc. par type d'ouvrage : des murs droits conventionnels, des murs droits par imprimante 3D, courbes, avec doubles courbures. Dans notre bibliothèque, c'est le livre Garcia de Soto en 2018.

Florian: Les coûts m'intéressent beaucoup aussi pour voir si on peut proposer cette idée aux entreprises dans les années à venir.

Benoit Parmentier: En effet ! Et on peut faire une étude de coûts en allant voir où on peut gagner en quantité de matière, sur la rapidité de réalisation, sur le fait qu'on évacue des coûts comme le coffrage et qu'on optimise la forme de l'ouvrage pour correspondre exactement à ce dont on a besoin par rapport aux efforts sollicités.

Florian: J'avais une autre question concernant les bâtiments modulaires. Cela pourrait-il se faire avec des imprimantes 3D ?

Benoit Parmentier: La modularité est plutôt généralement apportée avec des éléments légers ou le bois. Ce sont des matières qui facilitent les connexions, les déconnexions, le démontage, etc. Il n'y a pas trop d'intérêt d'avoir de l'impression 3D ici. Là où il y a d'autres marchés très clairs comme tout ce qui est égouttage ou imaginez, si on avait un système qui pourrait permettre de construire rapidement des piscines sur mesure en « mass customisation » avec des murs courbes. La machine fait ce qu'on veut, elle n'est pas tributaire de la géométrie. Il faudrait voir si c'est un projet qui pourrait intéresser le public. Mais ça serait très facile à installer.

Florian: En termes de projets, on parle principalement de maisons mais j'imagine qu'il y a d'autres projets en rapport avec le génie civil comme la construction de ponts ?

Benoit Parmentier: Il y a plusieurs domaines pour l'impression 3D:
- Les petites maisons (ou lots de maisons) ou habitats sociaux en France.
- Il y a aussi des projets sur des passerelles pour les piétons qui ont été lancées aux Pays-Bas (comme à Eindhoven : le groupe BAM et TU Eindhoven). Des éléments de la passerelle sont réalisés verticalement et ces modules sont assemblés par post-tension (on laisse des trous à l'intérieur et on fait passer les câbles par après à l'intérieur ; c'est comme un collier de perles que l'on tend). Si on tend suffisamment fort, c'est suffisamment rigide et on peut marcher sur ces passerelles après (pour des sollicitations pas trop importantes).

Florian: Ma dernière question est simple. Selon vous, quel est l'avenir de l'impression 3D dans le monde de la construction ?

Benoit Parmentier: Il y a un réel potentiel. Il faudra voir en fonction de la maturité de la technologie d'une part et il y a encore quelques questions techniques qui doivent être résolues. Il y a bien un marché qui est pour le moment en test. Il y a des industriels qui sont très intéressés et à fond dedans. Il y a des grandes sociétés comme Vinci, BAM et Basix qui ont investi et d'autres qui vendent des robots. Cela participe à l'image mais ces entreprises vont certainement aller chercher des marchés (peut-être pas de masse au début) et peut-être pas en Belgique mais aux Émirats, etc. À court terme, ce n'est pas pour une grande adoption d'ici les 5 prochaines années, je pense. On est encore au début de la technologie.

Nous, on investit au CSTC. Le CSTC a installé pour le moment une machine d'impression 3D, dans leur laboratoire, qui sera exposé dans un bâtiment dédié aux nouvelles technologies à partir de l'année prochaine. On pourra bientôt le visiter. On va tester pas mal de use-cases. Ils ont identifié des scénarios dans lesquels l'impression 3D pourrait être utile. Il faut vraiment identifier les meilleurs scénarios d'application de la technologie. D'un point de vue économique, est-ce que cela en vaut la peine ? de réaliser une passerelle par exemple en 3D ? J'avoue ne pas avoir encore vu beaucoup d'études qui documentent le retour sur investissement. C'est là que je pense que votre travail sera intéressant. Ça serait intéressant d'impliquer un bureau d'étude, de faire un design traditionnel et un design avec une impression 3D et essayer de quantifier les 2 volets pour voir où on en est d'un point de vue structure de coûts. Donc, vous avez un rôle important à jouer.

Florian: Très bien. Auriez-vous aussi des recommandations ou conseils pour la réalisation de mon mémoire ?

Benoit Parmentier: Il y a 2 volets : l'aspect purement technologique et l'aspect innovation. Je pense que l'innovation journey est importante : le fait que la technologie percole un moment dans le secteur. Rien que cela c'est intéressant à étudier : quelles sont les phases d'adoption (cycles d'adoption et innovation). C'est intéressant de voir comment ça peut se développer, sous quels mécanismes, etc. C'est une thématique un peu plus générale. Et puis, sur la thématique de l'impression 3D, si on regarde le spectre, il y a 2, 3 thèmes majeurs :

1. Résoudre les problèmes technologiques (ce qui existe).
2. Les problèmes liés aux certifications. Car, lorsqu'on a une innovation qui arrive sur le marché, en particulier pour la construction qui est un secteur relativement conservateur avec pas mal de normes, règlements, etc. Dans quelle mesure cela pourrait être accepté d'un point de vue réglementaire ou normatif ?
3. Le dernier est le business model. C'est très disruptif. Cela remet en question les fondamentaux au niveau de la construction. On parle de robots qui construisent des choses sans aide d'humains ou presque.

Il faut trouver les bons use-cases : dans quel cas cela pourrait être pertinent d'un point de vue technique et économique. Pour revenir sur l'aspect innovation, il y a aussi une transformation humaine. C'est un peu moins votre focus mais c'est une technologie qui perturbe à tel point

qu'elle va révolutionner la manière dont le business va être réalisé dans la construction. C'est une création de jobs d'un côté et une destruction de jobs de l'autre. Il doit y avoir des jobs plus spécifiques au niveau de la conception et au niveau des matériaux qui doivent être mis en œuvre. C'est un peu en fonction de votre sensibilité. Si vous êtes plus sur la gestion, j'imagine que le principal est d'arriver à identifier les niches prioritaires dans lesquelles cette technologie peut être appliquée.

Florian: Tout à fait, l'aspect environnemental m'intéresse aussi beaucoup. L'industrie du béton est tout de même l'une des industries les plus polluantes.

Benoit Parmentier: Il y a alors aussi tout un volet sur le « life costing » qui est centralisé sur l'analyse de cycle de vie et analyse des coûts sur l'ensemble du cycle. Ce sont aussi deux éléments qui sont également intéressants à étudier pour l'impression 3D. Ça participerait au développement de la technologie si on arrive à montrer que l'impression 3D va permettre de pallier à pas mal de problèmes et certainement environnementaux ou au moins l'apprécier objectivement. « On commence moins de matières mais la matière utilise plus de ciment par mètre cube ». Ça serait donc intéressant de faire un peu l'exercice. Si on prend un cas basique de mur que je veux analyser de ce point de vue. Que puis-je faire pour analyser les deux solutions ? La solution « impression 3D » et la solution traditionnelle. Si vous voulez aller plus dans cette direction-là, j'ai une collègue qui s'appelle Laetitia Delem (**laetitia.delem@bbri.be**). Elle est spécialiste sur ce sujet. Même si elle n'a pas encore travaillé sur l'impression 3D.
https://www.youtube.com/watch?v=fDmmwMWBKwQ

Florian: Merci beaucoup !

Benoit Parmentier: N'hésite pas à consulter régulièrement ces sources. Il y a beaucoup de projets qui sont décrits là. On travaille justement sur un projet où on est en train d'effectuer cet exercice pour faire l'état de l'art par rapport à tout ça pour développer l'année prochaine un gros projet de recherche. On aura donc certainement une publication dans le courant de l'année concernant cette thématique.

Florian: Cela pourrait être intéressant d'au moins le mentionner dans mon étude.

Benoit Parmentier: Une autre personne de contact, plus dans l'opération, est Mme Julie Pierard (julie.pierard@bbri.be) qui est la responsable du labo technologique du béton et qui va travailler sur cette thématique-là, plus du côté du matériau.

Pour terminer, pour la structure de coûts, on a une division qui s'occupe de l'aspect gestion d'entreprise. Ils analysent les coûts et appliquent les technologies de planification, etc. Pour une question liée à la structure de coûts, ils pourraient éventuellement vous intéresser. Vous pouvez contacter Dominique Pirlot (dominique.pirlot@bbri.be).

Florian: J'enverrai un mail sans fautes. Je vous remercie pour le temps que vous m'avez consacré. Je vous enverrai un mail avec des questions plus spécifiques.

Benoit Parmentier: Bonne fin d'après-midi. Au revoir.

Appendix 19

2. Prof. Dr. Michael Henke - 24th of March 2021 on Microsoft Teams

Head of Chair, Chair of Enterprise Logistics at TU Dortmund University and Director of this section at Fraunhofer IML

Qualitative approach: **Semi-conducted interview**

Michael Henke: Hi Florian.

Florian: Hi. Do you hear me?

Michael Henke: Yeah, I can hear you.

Florian: Good to see you again. It's such a long time. Actually. Maybe you don't know me a lot.

Michael Henke: I can remember your name quite well. You always replied to my questions.

Florian: I contacted you for my thesis because I knew that, when you talked about the industry 4.0, procurement, etc. that it was related to my thesis. My thesis is actually about new technologies and disruptive technologies. More specifically, 3D printing in the construction sector. I talk a lot about the environment, the fact that it's disruptive, I would like to analyze what is happening today and what could be the future of it. That's why I'm contacting you because I think you may have some recommendations on that subject or maybe some information about it. Even more in Germany, because I don't know what is happening in Germany. So, that's my first question: what do you know about 3D printing today in the construction sector?

Michael Henke: Thank you very much, you are thinking of me and asking me for some help with your thesis or let's say some sparing opportunity for your thoughts. I think 3D printing has a great future ahead of it. We see a lot of different types of 3D printing procedures evolving. From my perspective, but I'm not an expert in 3D printing, honestly speaking. From my perspective, the different methodologies are getting faster and faster. So, at the same time, the usability and the security level that have to be met also for 3D printed materials and products is also increasing. So, the room for application is getting bigger and bigger. At the same time, this has a dramatic impact on existing value chains and value chain procedures, because you

do not have to deliver a pre-material from one supplier to another one, work a little bit on it, and then send it from there to an OEM and make the final product out of it. But you rather just buy some ingredients like plastic material and then print something out. That's the big advantage but this is very simply spoken. I know that in the industry set up, there are more differences that have to be taken into account.

Nevertheless, the future is very promising. It has not only an impact on the material flows that can be somehow simplified by using 3D printers instead of all suppliers, but also the financial flow is impacted. Because you do not have to store material, pre-material for a long time somewhere, but you just have to build up with a 3D printer and the 3D printer thinks out.

And also some logistics aspects have to be also considered like the delivery times for spare parts, for example. This is already an existing market. In the past, we flew around the world. If it did go down somewhere in South America, for example, and we brought a spare part from Germany to South America. Nowadays, we just send the file via email attachment and say: “Okay, here's the construction file. Please print it out”.

Florian: You can even use the materials that are on site like sand.

Michael Henke: It's faster, it's way more efficient and it saves at the same time costs for transportation, it saves fuel and many other things. So, at the end of the day, I personally think 3D printing also has some sustainability advantages. So, there are a variety of different aspects that you can think of by applying 3D printers in the industry.

Florian: In terms of supply chain, there are a lot of changes and some things to apply in the construction industry because we know that the construction industry is very pollutant, but it's also very regulated. My question is: What do you think about the disruptive aspect on workers but also on regulation? Because I am a bit afraid that, because of all these rules, we will not be allowed to deploy all these technologies.

Michael Henke: I guess, you have to, at a certain point in time, also integrate a blockchain into the deployment of 3D printing because you have to share data and secret information that should be just exchanged between two parties that use the very same blockchain. That's the reason why I can confirm what you've said. You're absolutely right. The disruptive impact on humans and also on regulations when it comes to 3D printing is definitely there. But for me, it's a little bit hard to just concretize it. I cannot really tell you which kind of rules have already been changed by the application and deployment of 3D printers. And these rules are connected in the working environment to human beings who exchange information with the technology and work together with it. Right? So that's something I have not very much insight into. What I can do Florian is to connect you to a colleague of mine. His name is Mathias Rotgeri who is the head of our 3d printing activities.

Florian: It would be amazing.

Michael Henke: And I mean, the advantage is that he is really using 3D printers for our own technology developments in logistics. So, he uses the latest versions of 3D printers. He has a good understanding of all the developments when it comes to regulations. Maybe he also can better explain to you the impact of 3D printers also on us as human beings.

Florian: Why not! Because I was thinking about the construction industry and you have a lot of jobs behind it, but a lot of them are not engineers specialized in new technologies. Cutting all these jobs and replacing them with specialized people in computer sciences, for example, will be very disruptive.

Michael Henke: I just looked for a slide that I can also share with you during our conversation, and I can explain this a little bit to you if you want. Matthias Rotgeri is also heading this project. Now, you should be able to see the slide. This is a project that just started last year, and you can see it's called "Polyline cross project", where we bring different 3D printers and different technologies together. It's a crossroad check with leading industry partners. On the left bottom of the slide, you see the different companies and research organizations involved. And the aim is to completely digitalize the whole production line with the integration of additive manufacturing. I guess this is something that could be very interesting for you in general, but also in the light of your master thesis. This is the presentation I just referred to. What we tried to do here is also to integrate the bank into the whole procedure to somehow also integrate the financial flows, because this is also, and I guess I mentioned this in my lectures, something that we have, from my perspective, on our agenda. 3D printers help us also to even better connect the material with the information flows.

Florian: I have another question about that, what would be the advantages to 3D build buildings such as houses or bridges? Compared to traditional methods? Taking into consideration the environmental aspect behind it. In the near future? In the five to 10 years?

Michael Henke: As said before, I'm not an expert in the construction industry and that's the reason that I just would repeat the more general advantages, like time and efficiency: if I print out parts of houses, maybe this is done in a very short time compared to the traditional "putting together" bricks and build it out from scratch. So, you print out just bigger parts of the house and this is what we see already when we look at wooden houses or "ready to go" houses. And I can imagine that 3D printers also can be used for even faster processes or construction activities. If you take the example of a bridge, you can maybe really specify a bridge to the environment where you want to integrate it. I mean, when I think of traditional bridges built again together out of bricks, I would say this is also an advantage because the architecture of these 3D printed things are so precise.

Florian: Do you know any projects in Germany?

Michael Henke: No, but Mathias can also give you one or other project example. He's also not an expert in construction, but from his background in 3D printing, I guess he has a lot more examples to share with you than I can.

Florian: I also had some questions about the costs. I talked to a construction specialist in Belgium and he gave me the advice to compare 3D printers to more traditional buildings. I have to identify what are the best situations when we could use a 3D printer in the construction sector.

Michael Henke: The idea is quite nice: to compare existing houses and compare them with buildings, compare them with more complex ones. Because that's another advantage, I guess, of 3D printers. You can really manufacture things that wouldn't have ever been possible before with traditional procedures. And, I think that's the case for all new technologies. They help us to manage increasing complexity. And this comes along with industry 4.0. Everything is getting more and more complex. Maybe technology is the reason for it, but at the same time, that technology helps us also to better cope with the increasing complexity and that's a fair thing: to compare existing projects cost-wise with complex projects that you calculate. Then, you have a better understanding.

Florian: With regard to your lecture, do you think there is any possibility to mix another technology with 3D printing? We could build more connected houses? Maybe if it's an open door to more possibilities?

Michael Henke: For sure, I would definitely think so because, with traditional methods, you can make smart homes. Then, you just have to rely on existing structures, on walls that are in different directions and integrating new technologies, then I guess it's easier with 3D printing. From an architecture point of view, the opportunities to build houses are way more diverse and way bigger than ever before, because houses usually look the same, right? But this technology provides us new opportunities.

Florian: As I am not a civil engineer, of course, I'm a commercial engineer. The management aspect is also important to me. I don't want to focus only on this technical aspect. That's why you will talk with your colleague about the cost management and human aspect.

Michael Henke: Absolutely, you also have to think about the acceptance of 3D printed products, buildings, parts of buildings by human beings. Is there really a market for such an innovative and disruptive solution? At the end, you are again with the final end user and customer who maybe has a very traditional point of view and said: “Okay, I'm overwhelmed anyway by new technologies but I want to just have a house with four walls and a rooftop and that's it”. This is something you have to take into account definitely. But that's something that we discussed if I remember correctly also in my lecture. We have to find the right balance between technology, organization, human beings, information and bring this into the right incremental process for the development of it. But you're absolutely right, think of the customer expectations.

Florian: I had a question related to my internship in fact. I have just started an internship within the European parliament for a period of five months. I will work with them in the directory

general in technology. Do you think anything from this experience could be added in my thesis? Like collecting information about the legal aspect or human aspect?

Michael Henke: Yes, I think so. First of all, congratulations, that's a great internship to work with the EU and have a look into the different processes there. I can imagine it's complex right? Maybe you can extend your career there after you finish your studies.

Florian: Why not? Yes.

Michael Henke: I think it's just an idea. You can think of it and see if you really want to use it or not, to look into the whole horizon of the Europe program and look for the ideas that are reflected there, look for proposals that are published, call for proposals, and maybe, in the one on the other, you find also 3D printing. This also gives you some more evidence that this is a technology that's really and will be really now used. And then, at the same time, if there is a call out there, you can discuss with your peers and the context that you made, and see if, from a legal perspective, it is also in line with existing rules and things like that.

Florian: In fact, when starting my research, I didn't want to focus only on Belgium which is a pretty small country. Actually, in Belgium, we have a house entirely 3D-printed. But I know there are others in Europe and in the world. My last question: do you have any recommendations for my thesis? In what direction could I go to make my study useful and relevant? Because I think that's an important subject today.

Michael Henke: I think, what would be interesting for the reader of your thesis and I guess also for yourself, if you manage it to somehow derive from the insights that you gain in the construction industry, some elements that can be used in other industries, because otherwise you would always face the counter argument: “Okay Florian, listen, I read your thesis. It is very interesting, but I'm from the automotive industry and I can tell you here, the whole game is completely different. We cannot make use of your results at all.” And that would be a pity, right? Because then you're very limited to the construction industry. But if you really manage to derive some general recommendations out of the findings that could be interesting in other industries. Then, I guess, it's fruitful and worthwhile to read people outside the construction business.

And the other point and this is just a confirmation for the track you've already chosen is that you combine different technology elements and do not only look at 3D printing. Look at it from an ecosystem perspective and ask yourself “How can I use other technologies to further evolve 3D printing technologies". And what's the impact on different aspects, not only on the technology itself, on the processes, but also on the organization, on the human beings. So, this interdisciplinary perspective that you've already taken is great but it's definitely good to look at it from an integrated technology perspective. So, ask yourself what kind of different starting points do I have to others. And then, if you manage to broaden the scope at the end and find some more general remarks to your findings, then it's perfect. At least, you have a starting point to write up a PhD thesis afterwards about the use of new technologies in order to digitize

European companies. Then you can do this as a member of the EU or offices in Brussels or as a member of a company or at the university, that's all possible.

Florian: Yeah. That's not planned, but why not?

Michael Henke: You can do a lot more research activities.

Florian: That's a good suggestion. Thank you. I will soon share a survey on my thesis to collect some opinions from the market.

Michael Henke: You can share it with me, definitely. And I'm happy to give you a friendly review and then maybe together with Mathias, we can share it also with one or the other company from our country. As I understand you, you want to really extend the scope and not only look at Belgian companies, but also into other European countries. So, that's perfectly fine. I will do my very best to support this.

Florian: Thank you so much.

Michael Henke: Is it okay for me to share your email with him? No problem! I will try to reach him now immediately after our call and give him a little bit of a background and then he should just shoot you an email and offer you the one or the other date in the next few days to have another Team speaking. I would like to take it one step further, immediately. Otherwise, Easter will come, and other topics are on my agenda, so better to stick to it right now and continue this.

Florian: That's perfect to me. Thank you so much. And I think I will talk about supply chain and procurement in my research.

Michael Henke: Absolutely. Do not hesitate if you have any questions. I wish you all the best. Thank you very much for thinking of me and approaching me. It's always good to keep in touch and to stay in contact. Looking forward to talking to you about this interesting topic again. Have a good day. Bye. Stay safe.

Florian: Bye.

Appendix 20

3. Mathias Rotgeri - 26th of March 2021 on Microsoft Teams

Research assistant in Material Flow and Logistics at the Fraunhofer Institute

Qualitative approach: **Semi-conducted interview**

Florian: Hi Mr Rotgeri.

Mathias Rotgeri: Nice to meet you Florian.

Florian: I was a student in the class of Mr Henke in the procurement option. We spoke a lot about disruptive technologies, blockchain, and a lot of things around that. And now, I'm doing my thesis on 3D printing in the construction sector and I would like to ask you some questions because I heard that you are specialized in 3D printing. Not in construction I think you will help me to have a new sight on my thesis. Maybe Mr Henke already introduced my thesis.

Mathias Rotgeri: He only mentioned that you are making a thesis on 3D printing and construction. But he didn't go into detail. He just said that he was able to answer some of your questions, but some got a bit more into detail and he was not really able to answer those. And I'm not sure if I can, but maybe I have a bit more insight into 3D printing in general.

Florian: I will tell you exactly what I'm doing. I'm doing my thesis on 3D printing. The goal of it is to study the construction sector, but also from an environmental point of view. So, I want to compare what is done today with traditional means and what could be done in the future and now, because there are already some projects. I don't know in Germany, but in Belgium we have one or two.

Mathias Rotgeri: I think in several countries, there are different prototypes like in the Netherlands. I heard from a colleague that was in Amsterdam two years ago that they have some projects and some houses already built.

Florian: They even have a bridge not far from Belgium. So, I am studying that subject from different points of view. The first aspect is the technological aspect, because I'm an engineering student. And the second aspect is the management aspect, and that's really important to include that aspect because of the management part of my studies. Two other aspects are the environmental aspect (we know we use a lot of cement and it’s the most polluting industry today) and the human aspect because it's a disruptive technology. There are a lot of jobs in the construction sector and I want to know what would be the impact of such a technology on the job market. My first question is: What do you know about 3D printing in the construction sector? And do you know any projects? What do you think of the advantages that would bring to the sector?

Mathias Rotgeri: So, I've been in the 3D printing area in general since 2012 when I started as a student already building my own 3D printers and so on. From there on 2013-14, we got our printer here in the Institute and started working with it and researching things with it. We have been researching the technical parts like lasers and powders and so on. We also have a research project on material flow.

During all that time, there were many workshops, discussions, presentations, and so on. And I think these projects that were in the construction area were already at that time with very prototypes, like builds and very rough contours that were made and so on with these big printers. They were very tangible. So, everyone could relate to that. There was a house that got printed. It is always a good point to start a presentation and so on. I have a rough overview over that sector, but it is always interesting when something new happens.

In general, that was never really the focus of my work. I would always print some things for myself but not a house. What I heard and what I read was that in the last years in the sector there, like in every other sector, there was a big improvement of the technical details, the different robots like normal six arm robots and so on. And I think, what was a bit better is the understanding of "why would I need to print a house or what are the benefits of that"? It's not a question of "I do because I can", but "I do it now because there are some advantages". I picked up some projects that are very public like a few in the Netherlands and so on.

Florian: But you have a view on 3D printing. What do you think would be the benefit to change the traditional methods by 3D printing? I heard about using materials on site. So, we don't have that complicated supply chain of materials.

Mathias Rotgeri: In normal 3D printing, there are some advantages that the technology has over traditional means. For example, you can create very complex structures or geometries without any more costs. Or you are very flexible and you can design individual things or implement some functions that, otherwise, you could not. And from my understanding, those will also be advantages in the construction sector. If you have houses that are not standard in any way. Then, it gets interesting. On the other hand, it's also the other way around: if an architect knows "I'm able to do some individual things with it and it does not cost more". Then, maybe there are a lot more houses that are built that way. The other thing with material, it's like pouring concrete nowadays, always when you have a continuous motion. The supply might be even more problematic than with the current house building. For example, I think many houses are pre-built, then go by truck and only are stacked up onsite. With that, if a delivery gets delayed for an hour, it's not a problem. But, with concrete, for example, it's always a big problem if something is missing and that might also be the case for such a 3D printed version. And the other thing of course is: from what I saw, most techniques that are currently used are very place consuming because the robot needs to be bigger than the house. In any way, I guess that can be fixed with mobile robots, with other techniques, but currently the machines are huge. You need the place to do it. I think, in a street with many houses, it's not possible. It's something that's not the case in America very often. That might be a difference.

Florian: With your experience in 3D printing, what do you think about using concrete? Do you think there would be any possibility to use another material in the future? Maybe to make it more sustainable or environmentally friendly?

Mathias Rotgeri: It's an interesting question. I think, from what I heard, the main technique that is currently used is “material deposition”. You basically have some kind of fluid material but that is hardening very fast and it's not flowing very much like cement or something like that. And it needs to be even harder or less fluid than the normal cement that you're pouring on site. I think you can always add different materials but in the end I, I don't think you can really do something environmentally friendly like wood. It might be tricky in that regard.

Florian: And a combination of different materials, maybe?

Mathias Rotgeri: It's always possible. Even in the normal 3D printing world, there are material developments that are always progressing and all the techniques like powder-based, resin-based, filament-based and so on. On the other hand, 3D printing is very focused on plastics in general which is something I would not consider any more environmentally friendly than, for example, concrete. I think the material itself, the concrete, is not the problem, but the process making is. What might be interesting environmentally wise is using less material if you print very precisely and you can print thin walls. Then, you can make structures inside those walls and have those walls isolated from the outside, without any isolation material that you need because you have the air inside your concrete wall basically. That might be something very interesting. I think that the amount of material might be an option to make it more environmentally friendly. It's also the same for the plastic-based things. You can print with layers inside that are not full, with only support structures inside, and then have less material. Because, on the outside, it is important for that.

Florian: You only build what is necessary to the construction and not more. I was speaking about disruptive technologies, how disruptive is 3D printing for the future? There are a lot of regulations and laws at all levels in the construction sector. How disruptive 3D printing is on the human aspect and for the organizations?

Mathias Rotgeri: This is also quite an interesting question. With normal 3D printing, even though I'm a big fan of it. I think, if you look at it realistically, it's one method of building something of many methods. I don't think “disruptive” in that case is the right word. It's more like “additional”. It's a new method that lets you build things that were not possible before. But, at least, with current methods, it's a very niche use case. You must have, for example, very expensive paths, very detailed paths, and some functions. You need to create something that can make the bigger price disappear basically.

If you look at the construction sector in general, I believe that, in the construction sector, there have always been a lot of developments. There are thousands of methods to building a house. You can do it with wood and still, there are houses that are made with stone brick. It’s all used

nowadays, even though you could say that you only use concrete walls that are prepared and you only need to set them up. And I believe that for 3D printing, we will see the same thing. It might get used. It might get used very much but it will not be the only method. I think "disruptive", from my perspective, is not the right word for that. It's only an additional method of building something.

And for many use cases, it might be a better way. For many other use cases, it might not. I believe, for example, that if I want to build just a standard house that is cheap. I don't think 3D printing is the right way because you can basically not mass produce something. Everything is individual in that case.

Florian: So, if I ask you, what is the future of 3D printing, you will answer that it won't be applied on the large scope. Just for some cases, like some specific cases?

Mathias Rotgeri: That would be my guess, yes.

Florian: About this future, do you think there will be other improvements? Do you see any big improvements? In some specific sectors?

Mathias Rotgeri: Yes, for sure. The main problem with 3D printing if you look at the method from an historical viewpoint: it was developed in the eighties. It was an idea: different methods for creating prototypes. The reason was because the quality wasn't very good in the past. And then, all of the different companies started developing, researching, creating new methods of production (powder based, filament based, and so on) and the main focus was always bad quality. That was the main focus of research until 2010 or so. And then, at more or less some point in time, from 2014, the paths got to a point whether we are good enough. The bad quality reached at some point a level where everyone said: "Wow, that's something we can use ". And then, they had all these products and machines that were able to produce high quality parts on a prototype level. So, very individual, very slow and so on. And all the companies said: "okay, I need that, but I need 1 million parts of that in a week or so".

And then, the research shifted a bit and that was the beginning of mass production. In most use cases, it is still, or was always, very manual work. You need to preprocess the powder or the materials. You need to manually put everything into the machine, you need to program everything manually. And then all the post production of the parts is all manually done.

And in recent years (five years), all the companies then started developing machines and brought already some to the market that had some kind of line integration. That was still not a production line in that sense, but at least there were a few connections between those elements. And that is the key research.

And now, simultaneously, research is on the speed. It needs to be faster. So, I believe, by looking at the recent years, how everything developed, the companies will continue on with their products and their methods. On the other hand, it is not unlikely that maybe other methods will get found, that might be even faster than the current methods. So, I believe that in the next

few years 3D printing will get a lot better: quality-wise, speed-wise, integration-wise, etc. There are research projects, and all the companies are working on them. And, already now, with this very manual work and the high costs of everything, there are sectors where 3D printing is very useful like dental production. The teeth are the perfect use case. It's a product that is small that is always the same size but all are individual. That's like the perfect use case for 3D printing. Other cases like aerospace, where you have the budget you do not care to spend some money, because over the lifetime of a plane, it will save 40.000€ on kerosene.

Florian: That's actually one of my questions: the return on investment and the cost behind are really important.

Mathias Rotgeri: With 3D printing, currently, only specific use cases have a product that is cheaper built with 3D printing than with traditional means. On the other hand, you can always calculate something against that. So, for example, spare parts, you don't need to have a huge warehouse where you have thousands of parts that I will use in the next 40 days. You just have the 3D model and you only have to produce it if you use one of those.

In aerospace, you can maybe combine different functions in one component and calculate with that. This cost-based approach and all the research will lead to lower costs. I believe we will never really reach production levels of other methods. Maybe in some use cases, I'm not sure but it's a solution. It's one additional means of solving a problem of having parts for a company. All the companies need to ask themselves the question: “Do I build it, do I produce it with traditional plastic means or do I 3D print it or whatever?” It's one additional option that may be useful for many cases in the future.

Florian: From a cost perspective and technology perspective, I would like to share a survey with some companies to know their thoughts on 3D printing. It’s quite difficult though to calculate the costs.

Mathias Rotgeri: Even us, we have tried many times to calculate the price of what we print. We know the method, we know the cost of the material (for example, a standard plastic powder we use is 60 euros per kilogram, which is a bit more than those filament based products). But there are so many variables:

1. What is the part
2. How much prowder do we need?
3. It depends on the part orientation in the machine.
4. Etc.

There are a thousand things to calculate and, in the end, we just use some very basic numbers. That's very, very hard to calculate.

Florian: My last question would be: do you have any recommendation of direction I would take to make my research useful?

Mathias Rotgeri: I would say that it's always useful to have some overview of what is currently being used or some projects that you describe. So that everyone has a rough understanding of what is meant with 3D printing in construction. An idea I would have is what I did the whole talk, it’s to compare the development of 3D printing in the construction business with the development of 3D printing in other areas that are maybe a bit more advanced already. And of course, there's a huge difference between those sectors, but maybe one can gather a little information from that. Like I said, the development is very fast and there will be progress. Maybe you can adapt something from that.

Florian: I think that would be also interesting to study the human aspect and what is the return of the market. Because it's not easy to implement a new technology in the market. The market also has to approve it.

Mathias Rotgeri: I'm just thinking about another direction, so that you have a comparison with some other disruptive technologies. There are maybe some key disruptive changes in how you build houses in the last few years. How did they change the whole industry? In the Institute, we always compare the introduction of 3D printing to the introduction of our water jet that we got in 2002. I mean, it was basically a completely new means of building something. It changed the mindset of every engineer in the Institute on how to build something. It really changed the approach of development. I guess that, for 3D printing, it's the same. If I'm an architect and I know that this is a method I can use, then I will go maybe for something totally different than currently. I don't think we are the ones that are able to tell in which direction that goes, but it might be interesting.

Florian: I will think about that. Thank you very much for all this information.

Mathias Rotgeri: Yes, no problem. And good luck with your thesis.

Florian: Thank you so much.

Mathias Rotgeri: Have a good day. Bye.

Florian: **Bye.**

Appendix 21

4. Marijke Aerts - 12th of April 2021 on Microsoft Teams

Project manager at Kamp C Westerlo

Qualitative approach: **Semi-conducted interview**

Florian: Good afternoon Ms Aerts. Nice to meet you. Thank you for taking some time for me.

Marijke Aerts: No problem.

Florian: So, I think you read my email. I'm a student of the Louvain School of Management, currently doing a thesis on 3D printing in the construction sector. So, you are one of the main actors in Belgium regarding 3D printing. I actually had some questions about the project. First, that's an amazing project. I saw a lot of pictures of what you did with that 3D printed building. You also made it possible to visit the building last year. Unfortunately, I did not get the chance to do so.

Marijke Aerts: Due to the Corona crisis, we can't have too many people around here. But hopefully, when the crisis is over, we can set it open for a big public. The house is on the site of Kamp C. If you are in the neighbourhood, you can visit outside. So maybe, that is already an opportunity for you.

Florian: My first question is to know whether you know projects regarding 3D printing. Taking into consideration you are one of the main actors in Belgium, I think you will have some answers to that question. I think you are also one the first actors to build a totally 3D printed building in Belgium.

Marijke Aerts: In Belgium, I think we were the first ones to build a house in 3D printing. But, at this time, and I think between today and a few weeks, there will be a second house that has been printed in Bruge. It's near the sea, but it's a house that has been pre-made in a fabric and the parts are transported on-site to Belgium. They are going to assemble it onsite. So it won't be printed with the stable printer on the site itself.

Florian: It’s modular? They print the different parts off-site and they are putting them together as Lego’s?

Marijke Aerts: Yes, something like that. That's the second one that we know about in Belgium when it comes to houses.

But, in Germany, France and Italy, there are already other projects as well with 3D printing of houses.

Florian: Would it be possible to share some links or documentation on recent projects such as the one of Kamp C?

Marijke Aerts: Yes, I can send you some references. I'm going to write that down. So I won't forget that.

Florian: Thank you! Actually, I had the opportunity to interview some actors of the construction sector. And my most important question is the following: I am studying 3D printing from different aspects because it's a new concept and I cannot only focus on a single aspect. One of the main aspects is the environment and the sustainable materials used for the construction of the building. I'm looking at what can actually be made with 3D printing regarding the environment. Today, there are a lot of rules and laws in the construction industry.

Marijke Aerts: You mean « better » for a sustainable future and for the environment?

Florian: Yes, exactly.

Marijke Aerts: On one hand, 3D printing with concrete is not really a nice material to use when it comes to sustainable materials because it's quite chemical. Especially the one we used for 3D printing because the cement mortar must dry very fast to make the print process happen.

Florian: To have a second layer on top of the first one?

Marijke Aerts: So, the material that we use at this moment is not a clean material. On the other hand, the way you build with 3D printers creates less waste onsite. You use less material to print that because you only print the part where you need the material. All the other parts are hollow. So, you use less material. You need less people to work with it. So, on that hand, I think it's a more sustainable way of building. And you can also integrate lots of techniques into this technique. Because you can insert electricity cables in your design. When you can do that, you can foresee hollow spaces, and you can make your cabling into the hollow spaces of the walls. In that way, you don't need to reopen your walls again and to put all your electricity cabling in it and shut it down. So, all that kind of stuff makes that this technique could be more sustainable than the classical technique that we use in the building of houses.

Florian: So, you think about the building beforehand and you think about the electricity, piping, etc. and all kinds of stuff you can foresee it in your design mode?

Marijke Aerts: Everything you can foresee in your design mode makes an advantage in terms of use of materials. The print process will go very fast, and you can work very fast and use less material by doing it. You can also foresee less construction faults because you can think about it, rethink about it, redesign about it in the design phase beforehand. And then, when you have a good model, it's like one click on your computer and the house rolls out.

Florian: Yes, I see. About concrete, have you heard about any other solutions that exist today and that you could use as other material to build the houses? Or a combination of different materials?

Marijke Aerts: There are different innovative thoughts about that already. In Italy, they are trying to print with a local clay material. So, they use sand and clay from the soil on-site and then they try to make a solution to print the house with the clay. They cover it with a wooden rooftop. So, when you use cleaner and more sustainable materials, it can be beneficial for the environment. I think the techniques are ready to do so.

Florian: Of course, with materials on site, even the supply chain is easier to manage.

Marijke Aerts: Of course, last week, we also had a conversation with a company that is trying to form a new sort of cement mix without the cement in fact. So, it's a new sort of mortar where you don't use the classical Portland cement. We use a new kind of cement that has a much lower impact on our environment. So, when this can have the same properties like the cement we are using at this time, then I think it could be possible to also print in concrete, but with a more sustainable kind of governance.

Florian: That's really interesting. So, you built the building like the first one, but maybe the color will be different but you have the same properties. And that is what we are looking for in the environment.

Marijke Aerts: I can also send you that link. I'm also involved in another project where they are trying to find out a new kind of concrete that is made with other binders than the classical Portland cement binder, and also with the aggregates coming from other industries like waste from other industries. It's really a sustainable way of building. It's really a whole bunch of different things you have to try and to see if there is a more sustainable way in the total project.

Florian: That is still the beginning of course. 3D printing has existed since a long time, but not in the construction sector. So, I imagine you have a lot of different possibilities. Besides, I am a student in business engineering. So I am also looking at the feasibility of the project in the future, but also from a cost aspect. I don't have a lot of numbers and information relating to the costs on 3D printers in the construction sector. I was wondering if you had more detailed information about the size of the building. I would like to make a comparison between a 3D printed building and a building built traditionally. I would like to see what the size of the building is and what would be the difference in budget.

Marijke Aerts: At this moment, for us, it's a little bit difficult to say what were the costs of the building on our side, because really it is an iconic building. It's the first one, it’s a pilot building. We worked together with a lot of companies which helped us to finish it. So, it looks like a house. We don't know if it's affordable at this moment. But you have to see it like an opportunity that was not there yet. So, if you know that, with 3D printing, you can do a lot of other things than with classical ways of building: when you think about the shaped form or when you think

about overhanging walls and all that kind of thing without using a formwork for it, you know that you save a lot of costs in debts. But of course, when you choose a curved form for a house, you know it will be more expensive than just straight walls.

Florian: Because you need a mould that is expensive with traditional ways of building, but not here because it is automatic.

Marijke Aerts: So, it's not that easy to compare it, you know? It's a little bit tricky to compare one with another. And we use the printer that was put on site. We printed it in wintertime. We used a heating system. It was not the purpose, but at that time it was necessary. We used that system to make the cement binding at the right moment when we were printing. Because, at that time, it was freezing. So, that's not a good way to build of course. It's not a good idea to install a heating system just outside. It's nice for the birds we always say, but it's not nice for our planet. So, maybe there is a bigger market to print in an environment where you have good conditions like in a fabric. That's, for example, what they do at Weber Beamix in the Netherlands. They really have a fabric, and they print inside, and they always have the ideal parameters to print and then they assemble it at a place where it needs to be assembled. Maybe, that's an even more sustainable way of using this technique in the construction sector.

Florian: Obviously, for you, that's a first try. I saw that there were a lot of projects in the United Arab Emirates, because they have the money, the budget, they also want to show that they are able to do a lot with the new technologies. Besides, do you have any idea about the numbers I could add to my thesis to demonstrate how 3D printing could be a solution for the future and the environment?

Marijke Aerts: We have made a kind of comparison. At that moment, we could conclude that printing is not really more expensive than a classical way of building. Of course, it depends on how you want to finish it, which form you want and all that kind of stuff. I can give you some figures about the cost of the mortar, but I don't think it tells you anything when you put it in your study. I can send you some plans of the building and you can see what the dimensions of the building were.

Florian: To conclude, I have two more questions. One is about the disruptive aspect of 3D printing. What do you think about the future of 3D printing? According to the fact that you don't have the same workers on-site as for a traditional building. We need more engineers working on site. What do you think about it and the labour market?

Marijke Aerts: First of all, of course, it's necessary to work with more people that are trained to use computers and technology. You cannot say that that is not happening with this kind of technology, because it's controlled by a computer, of course. But, at Kamp C, we are not technicians, we work together with students who are 20 years old. Of course, we had some companies on which we could lean on to hear about their expertise. But if you know that within less than a year, we could print a house like we did. Then, you also know that the technique is not that difficult, and I really believe that you can train people to use it and that you can retrain

your constructor employees if you want. I think it's really not a difficult technique to use, but of course, you need some IT people who can support you on the whole process.

Florian: But you don't only need civil engineers on-site ?

Marijke Aerts: I don't think so. To work with the printer, you don't need to be an engineer. It's not necessary to be an engineer. Of course, when you want to design the house and develop it in its most opportune way and print it, then you need to be an engineer. But, I don't think it works like that, you always need several people who work together and then you have the most interesting solution.

Florian: Where do you think 3D printing will have an impact, according to the projects ? Only buildings? Bridges?

Marijke Aerts: I'm not even sure if it's really the best technique to print buildings as a whole project. But I strongly believe in printing special forms that are printed in a fabric and brought together. In that kind of solution, I really believe in it and it's really happening already at this time. Even when we look at the last year, we can see that there are many companies that are trying to find all kinds of solutions for their own products. And that's interesting. We don't believe at Kamp C that printing houses will be the future. Maybe, maybe not. But we even believe more in trying to find out, for your own business, that the print technology can be a better solution for your building process. For example, we have for now at this moment a second project. And in that project, we are trying to find how we can accelerate the markets. So, they can use or see what the printers can do for their own building process. So, in that part, for example, we have a conversation with the company and they are building some kind of round foundations for thanks for oil and they are always like a round circle. So, now we are trying to see if, just for that kind of business, maybe the printer is very interesting because it can print really a round solution, maybe even onsite. So, the company doesn't need to put an expensive formwork every time that they want to do it. So you can work with them and the printer is already your formwork.

Florian: That’s interesting. I spoke with a manager of the Confederation of construction in Belgium and he is one of the main actors in the construction 4.0. and he was speaking about building a swimming pool with a 3D printer. That's kind of the same project and that's interesting.

Marijke Aerts: Another partner of ours has already made a swimming pool with 3D printed elements. It was near Antwerp. They made a new sports complex, and there is also a swimming pool inside. They printed the walls in segments, and then they brought it over there. On site, they put everything together.

Florian: : What about the layers when you print something with water? We see the layers on the building, do we see them also in the swimming pool or?

Marijke Aerts: I don't know if they use it like that, but it's also possible that you use another printing head and you put some kind of flips on the sides of the printing head. So, you put a layer, and when you put a next layer on top the flaps will slice on the surface and then you'll have a flat surface. So that's also a possibility. We haven't used it in our building because we wanted to show the layers, so you could see how it was made. Maybe you can just use it as a form of work, and then you can finish it also with the finishing layer. That can be smooth or flat as well.

Florian: I didn't know that, that's really good. My final question is more focused on the following steps of my thesis. Do you have any recommendation, have you heard about any thesis on that subject and do you know what direction I could take for the following steps of my thesis. I want to answer my research question while staying in the scope of that question. Is there a future for 3D printing in the construction sector?

Marijke Aerts: There are already a lot of studies going on of course : studies about how to use the steel cabling for the reinforcements in the printing work, what about heat or fire with printing, etc. I don't know, there are so many things to study. I can tell you about the thing that we are doing at this moment. That's maybe interesting as well.When you print new elements, you'll also have to move them and replace them. How can you find a good solution to replace it? Because, when you print something, you always need to print on a flat surface because the printer needs to start on a smooth and flat surface. So, how can you easily find solutions to move your pieces once they are printed? Because concrete is really heavy. You need to move with machinery because you can't move into it by hand. How can you use some elements that are not really visible, but that need to be strong enough? You can't actually put some things in when you are printing because it doesn't work because your printing head is always moving on the top layer. So maybe, there are things to do here.

Florian: Maybe I could write a section on the thesis in my thesis. I will also obviously study the ecological point of view.

Marijke Aerts: Also, how can you, when it comes to sustainability, how you can combine several materials that can also be deconstructed afterwards. How can you only separate your printed parts from all the other layers that are needed in the building once you want to demolish it afterwards and you want to reuse parts. It's important in a circular economy, of course, that you need to also think about what happens after the lifespan of my building. How can I reuse it or how can I separate my materials to reuse them again? It really comes with standardization of some elements, but it's a little bit in conflict with the total form freedom of the whole printing process, you know. So how are you going to standardize some things, so you can reuse them easily afterwards.

Florian: On one side, you are free to build anything with 3D printers. On the other side, you want to reuse materials. I understand. Thank you for the ideas that I think I will use in my thesis. Finally, when you have some free time, I will send you a survey that I created to add a return

from the market in my work. just to have feedback for the printers. Thank you once again for everything and for the information.

Marijke Aerts: Okay. So if you want, I will send you some links to some projects that are happening at this moment in Germany and in Italy. I can also send you some plans, so you can take a look at our building. I will also send you the link of the partner that made the swimming pool with the 3D printer.

Florian: Perfect, thank you so much. Maybe I will visit you soon in person.

Marijke Aerts: When you are in the neighbourhood or when you're planning to come, we can see if I can be there. Lots of success with your thesis. Bye!

Florian: Thanks. Have a good afternoon. Thank you. Bye.

Appendix 22

5. Noël Naert & Arnaud Tandt - 26th of April 2021 on Microsoft Teams

Engineering Consultants at FEBELCEM

Qualitative approach: **Semi-conducted interview**

Florian: Bonjour, enchanté.

Noël Naert: Bonjour, enchanté.

Florian: Je vous remercie du temps que vous me consacrez pour ces informations au sujet de mon mémoire qui me seront certainement très utiles. Je collecte les avis des différents acteurs de la construction. Ce qui m'intéresse, c'est ce que vous en pensez.

Noël Naert: J'ai justement invité un collègue à rejoindre l'appel. Mais nous pouvons déjà commencer. Juste une question, comment connaissez-vous Xavier Köttgen ?

Florian: C'est le patron de ma meilleure amie. Elle m'avait fait part de l'intérêt de Monsieur Köttgen pour les différents projets de construction comme l'impression 3D et l'immobilier. Nous avons discuté pendant 2 heures sur ce sujet.

Noël Naert: Il a été pendant quelques années le concepteur attitré de notre stand à Batibouw.

Florian: C'est lui qui m'a conseillé de vous contacter au vu de votre implication dans le béton. Et le béton est un des matériaux principaux dans l'impression 3D. D'ailleurs, vous m'avez

envoyé récemment un article sur l'entreprise Kamp C qui a réalisé un bâtiment en 3D et il se trouve que j'étais en contact avec une project manager de cette même entreprise il y a 2 semaines. Monsieur Kottgen m'avait d'ailleurs conseillé de réaliser une comparaison de coûts entre 2 projets similaires dans mon mémoire : l'un construit avec des méthodes traditionnelles et l'autre imprimé en 3D. Une approximation des coûts est assez compliquée à réaliser comme il s'agit de nouvelles technologies et il y a très peu de coûts associés.

Noël Naert: On a parlé de ce sujet entre collègues et il faut savoir que le ciment, d'ici quelques années, ne sera plus le ciment d'aujourd'hui. Il y a toute une série d'évolutions qui sont en train de se faire. Il suffit de lire un article de temps à autre dans les journaux qui disent que le béton est un fléau pour le monde. Il y a beaucoup d'émissions de CO2 associées à sa fabrication. La raison est simple : le béton est victime de son succès. C'est par les énormes quantités de béton qui sont fabriquées qu'il y a autant de pollution. C'est aussi un matériau qui représente une vision sur la modernité et la construction d'un modèle. Aujourd'hui, il n'y a pas d'alternative. Il y en a qui disent qu'il faut remplacer le béton par du bois ou d'autres matériaux. On ne peut pas imaginer le nombre d'arbres qu'il faudrait abattre pour réaliser toutes les constructions en bois et remplacer tout le béton.

Florian: La replantation est intéressante mais beaucoup de temps est nécessaire.

Noël Naert: La façon dont on coupe les arbres et on détruit les forêts. Ensuite, nous replantons les arbres mais ça n'a plus rien à voir avec une forêt naturelle. Toute la biodiversité associée à une forêt naturelle est complètement vouée à disparaître. Certains pays comme la Suède ou la Finlande sont soucieux de la problématique des plantations artificielles. D'autres pays comme le Brésil, l'Indonésie ou la Malaisie le sont moins. On constate même dans ces pays que ce n'est pas une façon qu'on pourra continuer à perpétuité. Ce genre de plantation n'a pas une ambiance naturelle.

Florian: C'est une solution mais ça ne remplace en rien le béton?

Noël Naert: Oui, en effet.

Florian: Aujourd'hui, il y a des études pour développer un nouveau type de béton ?

Noël Naert: Nous sommes bien entendu conscients de l'impact que l'on a sur l'environnement. Mais on sait que la façon de fabriquer le ciment va changer prochainement. Nous ne parlons pas de demain, mais d'ici 2050. Il y a une sorte de roadmap disponible sur le site de l'association européenne du ciment CEMBureau.eu. On parle d'une stratégie des 5'C'.

Arnaud Tandt : Bonjour, je m'excuse de mon retard.

Noël Naert: On vient de commencer. J'étais sur le point de dire que le CEM Bureau a publié une roadmap et qu'il est question des 5'C'. Et j'étais sur le point d'aborder le premier C. Le premier C, c'est le C du Clinker. C'est le produit de base, ce qui sort du four à ciment. Il s'agit

de granules. C'est la partie chimiquement active du ciment. Il y a des ciments avec beaucoup de clinker mais aussi des ciments avec peu de clinker. C'est la bête noire du ciment car, pour fabriquer du clinker, il faut émettre beaucoup de CO2. Il faut décarbonater la pierre calcaire et il faut utiliser beaucoup d'énergie. C'est de là que viennent les émissions importantes de CO2. C'est donc le premier 'C'. Il y a des projets et des recherches pour diminuer encore le contenu en clinker du ciment.

Florian: C'est donc le contenu qui pollue le plus dans le processus de fabrication du ciment ?

Noël Naert: C'est surtout parce qu'il y a une grosse consommation d'énergie et donc de CO2. Chimiquement, il faut décarbonater la pierre calcaire et il faut brûler la pierre.

Le deuxième 'C' est le C de « Cement ». Il y a des études pour définir les différentes compositions de ciment qu'on peut envisager.

Le troisième 'C', c'est celui du « Concrete » (béton). Il y a des façons de reformuler le béton avec moins de ciment ou avec d'autres composants : des adjuvants, etc. On veut fabriquer d'autres types de béton en fonction de l'application.

Le quatrième 'C' est le C de « Construction ». Il y a des études qui sont entre les mains des ingénieurs pour voir comment on peut dimensionner plus efficacement des poutres, colonnes, des dalles, etc.

Parmi les 'C', c'est là que rentre en jeu l'impression 3D. Elle peut contribuer ou apporter des solutions partielles. Il faut encore attendre cependant l'aboutissement d'études et certains développements pour maximiser l'utilisation de cette technologie.

Le cinquième 'C'est le C de « (re) Carbonatation ». En fin de vie, lorsqu'on expose le béton à l'air libre, il y a une partie du CO2 qui est réabsorbée de l'atmosphère dans la pierre. La carbonatation est en fait un phénomène qui est destructif pour le béton car ça provoque l'oxydation et la corrosion des armatures. Il y a des éclats de béton qui partent. C'est un phénomène naturel : le noyau du béton n'a jamais été en contact avec l'atmosphère mais dès que le CO2 de l'atmosphère pénètre dans le béton, il y a un processus de dégradation du matériau C'est purement de la chimie mais ça peut dans certains cas contribuer à une réabsorption du CO2 de l'atmosphère dans le matériau. Il existe des techniques pour accélérer l'exposition des morceaux de béton pour exposer ce matériau au CO2 pour capter le CO2.

Arnaud Tandt: C'est seulement avec le béton armé qu'il y a un problème. Le béton, s'il n'y a pas d'armature, durcit.

Noël Naert: Le béton devient moins poreux au fil des années à cause de la carbonatation. Dans le cas du béton armé, c'est un phénomène à éviter. Il faut prévoir une surépaisseur ou un enrobage des armatures pour protéger les armatures contre l'exposition à l'air.

Tout ça pour dire que les 5 ‘C’ constituent une stratégie globale :

- Clinker
- Cement
- Concrete
- Construction
- Re-Carbonatation.

Comme tu l’auras remarqué, la construction 3D se situe quelque part dans cette démarche, dans cette stratégie et il se pourrait que dans certains cas, cela pourrait apporter des avantages par rapport aux façons traditionnelles de construire. Il faut aussi garder en tête que « Sustainable construction » n’est pas uniquement une question d’environnement (protéger la nature et la biodiversité). Il y a toujours les 3 dimensions du développement durable qui restent importantes. À côté de l'environnement, il y a aussi l'économique et le sociétal.

Florian: J’étudie l'aspect écologique de l'impression 3D. Mais aussi l'aspect perturbateur de cette technologie. Dans cet aspect perturbateur, il y a trois différents aspects que j'étudie :

- L'aspect réglementaire car on sait que le monde de la construction est un secteur conservateur..
- Il y a aussi l’aspect humain car le monde de demain ne sera plus le monde aujourd'hui. L'impression 3D implique qu'il y aura moins d'ouvriers sur le chantier.
- Il y a aussi les coûts. On est toujours à une phase de concept dans l’impression 3D en construction.

Ces 5 ‘C’ nous permettent donc de bien visualiser qu’il est important d’agir sur différents tableaux et pas seulement la technique de construction ou les matériaux.

Noël Naert: Il y a aussi la notion d'économie circulaire. Lorsqu'on veut diminuer l'impact sur l’épuisement des matières premières. Là aussi, il y a des choix à faire. Recycler et réutiliser sont aussi 2 concepts importants à prendre au sérieux. Là aussi, la disponibilité de matières premières locales. Ce n'est pas seulement une affaire de technologie. Les matériaux doivent être prêts à être utilisés. Mais il y a aussi un aspect économique et un aspect social. Avoir à sa disposition des matériaux ou des ressources localement est aussi un élément important à prendre en compte.

Florian: Que pensez-vous du futur de l'impression 3D ? Où la situez-vous ? L'impression 3D par rapport à ce qui se passe aujourd'hui dans le secteur de la construction ?

Noël Naert: Aujourd’hui, il y a déjà tout un éventail de débouchés. On peut construire une installation entière à partir d'une installation que l'on dispose quelque part sur un chantier mais qui ne s’arrête pas avant que toute la construction soit terminée, c'est le plus spectaculaire. Et c'est aussi un coup de pub. C’est une option. L'autre option, c'est lorsque les architectes découvrent les possibilités et constatent que cette technologie stimule en quelque sorte la créativité. En effet, cette technologie peut leur permettre de créer de nouveaux types de bâtiments ou de parties de bâtiments, qui n’étaient pas réalistes auparavant. Ces bâtiments

deviennent d'un coup possible à réaliser. Le fait qu'on peut coupler cela à des logiciels et qu'il est possible d'envoyer des instructions à une unité de fabrication depuis son ordinateur est très intéressant. Il y a simplement une tête d'extrusion à paramétrer sur place pour le début de l'impression et le reste se fait automatiquement. Il y a aussi toute une autre série d'applications que l'on pourrait imaginer comme la préfabrication avec des imprimantes 3D. Un camion amène le béton et le béton coule dans un bac ou un coffrage. On pourrait donc imaginer une unité d'impression 3D dans une usine de préfabrication qui réalise toute une partie d'un assemblage. On peut aussi imaginer des installations à plus petite échelle comme des robots qui grimpent le long d'une façade pour, par exemple, réparer des parties de construction, faire des injections, du colmatage, etc. ou dans des conditions compliquées pour les ouvriers pour travailler. Il y a donc tout un éventail de possibilités et de situations.

Florian: Que pensez-vous des différents projets liés à la l'impression 3D ? Pensez-vous que l'impression 3D n'est utile que pour des bâtiments ou aussi pour des ponts par exemple ?

Noël Naert: En effet, c'est d'ailleurs l'article que je t'ai envoyé avec le projet qui a été réalisé à l'UGent. Ces structures sont plus légères et faciles à transporter.

Arnaud Tandt: Il y a aussi un projet aux Pays-Bas où ils ont construit des balcons en impression 3D. Il y a aussi un bâtiment qui a été à la fois construit traditionnellement et en impression 3D. Il y a certaines formes dans cet appartement qui ont été imprimées car elles étaient plus faciles à construire avec une imprimante 3D. Nous avons aussi discuté de l'impression et de la possibilité de réduire l'impact environnemental. Est-ce qu'il y a une réduction de matériaux ? Est-ce que la formule du béton utilisé pour l'impression 3D ne comporte pas trop de ciment ? Combien de réduction de matériaux avons-nous besoin pour couvrir l'excès de ciment dans le béton ? Nous n'avons pas besoin de coffrage avec l'impression 3D, il y a donc une réduction aussi de ce côté. Je pense qu'il y a moyen d'avoir une comparaison assez facile, pour la maison construite par Kamp C par exemple, entre un mètre carré de ce bâtiment imprimé en 3D et le comparer avec un mètre carré d'une maison construite avec des méthodes traditionnelles.

Florian: L'un de mes projets est de comparer les coûts de construction d'un bâtiment comme celui construit par Kamp C à un autre construit avec des méthodes traditionnelles. Le problème avec mon étude, c'est que peu de chiffres sont disponibles. Les coûts de construction du bâtiment de Kamp C ont été répartis avec entre plusieurs partenaires tels que Weber Saint-Gobain, Beneens, Trias architecten, etc. Il y a aussi eu un investissement des fonds européens. Ils n'ont donc pas d'information précise sur le prix total de la construction. J'en ai discuté un petit peu avec la Confédération de la construction. Nous avons discuté des avantages et de la réduction de pertes de matériaux. Et par exemple, si on avait besoin d'une poutre en forme de 'I' pour un certain bâtiment, on pourrait le faire grâce à l'impression 3D. Ceci est impossible avec des méthodes traditionnelles ; nous utiliserons une structure en forme de rectangle et il y aura une perte de matériaux considérable. La question que vous venez d'énoncer est très intéressante : à partir de quel moment l'impression 3D commencerait à être pertinente dans la construction d'un bâtiment. Cependant, il est compliqué d'y répondre précisément avec le peu d'informations à disposition. Les matériaux utilisés dans l'impression 3D sont polluants. Le

béton utilisé est riche en ciment car le béton doit durcir très vite pour éviter un effondrement de la structure.

Arnaud Tandt: Il y a en effet cette question de stabilité mais aussi la question technique de liaison entre ces différentes couches. Il y a aussi des possibilités de mettre du sable pour éviter que la structure bouge.

Florian: Lors de mes interviews, on m'a parlé de plusieurs techniques afin que la structure soit stable. On m'a mentionné la possibilité de réaliser un coffrage grâce à l'impression 3D afin de couler du béton directement à l'intérieur. Il est aussi possible de construire un bâtiment avec une tête d'extrusion qui posséderait des palettes afin de lisser les bords inférieurs à chaque passage de la tête. La question importante maintenant, c'est de savoir s'il est possible de répondre : « À partir de quel moment l'impression 3D devient-elle intéressante ?

Arnaud Tandt: Si nous regardons au niveau du CO2, Si nous connaissons la formule du mortier que l'on utilise dans l'impression 3D, il serait alors possible d'avoir une réduction d'émission. Cependant, nous pourrions tout aussi réaliser une construction avec des méthodes plus traditionnelles avec des murs plus fins. D'un point de vue structurel, je ne suis pas sûr que l'on ait gagné en réduction d'émission alors. Si le contenu du béton en ciment est deux fois plus grand que dans un béton traditionnel, ce n'est alors pas intéressant. Ce n'est alors peut-être pas la meilleure des solutions.

Florian: J'ai reçu récemment des informations quant à la formule du béton utilisé pour la construction de Kamp C. Il y a apparemment des études en cours sur un béton plus écologique.

Noël Naert: Avez-vous des contacts avec l'Université de Eindhoven ? Il y a 4 ans, Kamp C avait organisé des soirées et l'une d'entre elles était consacrée à l'impression 3D. La dernière session était une visite à l'Université de Eindhoven. Dans les bâtiments de l'Université, il y avait ce type d'imprimante avec un grand cadre. C'était qu'il avait réalisé des études sur les matériaux, la fluidité de la construction, à partir de quelle hauteur la probabilité d'affaissement augmente. L'Université de Gand réalise aussi ces études.

Florian: Je vais alors entrer en contact avec l'université de Gand. Je suis déjà rentré en contact avec L'Institut technologique de Dortmund. Ils viennent tout juste d'acquérir une nouvelle imprimante 3D dans leurs locaux. Ce n'est que le début.

Noël Naert: Pour comparer les coûts. Vu que l'impression 3D se trouve dans un contexte un peu artificiel et déconnectée de la réalité économique avec toutes sortes de subsides. Ils se permettent des tests et des essais. Il est très compliqué de comptabiliser tous les coûts réels. Il y a beaucoup de similarités avec l'utilisation de béton auto compactant. C'est au Japon que l'on a découvert des possibilités d'un béton auto-plaçant afin de construire des bâtiments qui résistent par exemple aux tremblements de terre. Le béton a ensuite été importé en Europe et on a découvert ses avantages. Lorsque vous devez choisir entre le béton de l'avenir ou le béton

high-tech, il y a aussi des arguments économiques et pas seulement écologiques. Pour le béton auto compactant, on peut aussi se poser la question du « footprint ».

Florian: En effet l'aspect économique est tout aussi important. Cet aspect sera certainement un frein dans les premières années de l'adoption de l'impression 3D dans le secteur de la construction.

Noël Naert: De plus, il n'y a plus de main d'œuvre lorsqu'il y a une imprimante 3D, il faut prendre cela en considération.

Florian: C'est vrai, on remplace en quelque sorte les ouvriers par des ingénieurs qui coûtent plus chers.

Noël Naert: Ton défi est de décrire le contexte artificiel de tout cela. Qu'est-ce qui est pris comme « acquis » et utilisé à grande échelle.

Florian: Il y a déjà en effet des projets qui ont été lancés dans les Émirats et en Italie. Le budget n'est pas le même là-bas. Ils ont beaucoup de projets en développement. Le plus intéressant pour l'impression serait de s'implanter dans des pays où les conditions climatiques ou de terrain sont plus compliquées. Il se pourrait aussi qu'il y ait déjà des matériaux disponibles sur le site de construction. En Belgique, ce n'est peut-être pas l'environnement le plus propice à adopter l'impression 3D.

Noël Naert: Généralement, on retrouve l'impression 3D dans des pays où il y a une pénurie de logement. On pourrait alors imaginer que ce type d'industrialisation (l'impression 3D) puisse être utile afin de construire rapidement des cellules de base (des noyaux de béton équipés). Ensuite, ce sera le tour aux personnes qui y habitent de compléter leur habitation avec des extensions. C'est un travail répétitif où la machine construit en chaîne ces différentes cellules. Ces notions de « répétitivité » et « industrialisation » sont au cœur de l'impression 3D. Le sur-mesure aussi est à prendre en considération. Le marché devient de plus en plus intéressé par la personnalisation des bâtiments et l'originalité. Grâce à l'automatisation et la robotisation, on peut faire du sur mesure. Grâce à l'informatisation, tout cela est possible. Nous avons des logiciels qui nous permettent de nous dire quand nous devons laisser des encoches pour les équipements électriques.

Florian: Ce sont en effet les deux avantages de l'impression 3D : cette notion de répétitivité mais aussi la notion de personnalisation. C'est un gain de temps et de matériaux. Je vous remercie pour toutes ces informations. Tous ces avis sur le secteur de la construction et de l'immobilier me sont très utiles pour mon projet. Je vais maintenant rentrer en contact avec l'université de Gand.

Noël Naert: Tiens nous au courant de l'avancée de ton mémoire. Tu peux aussi entrer en contact avec Beamix aussi, qui est un fabricant de mortier prêt à l'emploi (des mélanges pré-dosés commercialisés dans des sacs). Tu n'es pas un technicien du béton, cela serait intéressant

de rentrer en contact avec eux pour leur poser la question (dans quel sens ce matériau est différent par rapport à un mortier ou un béton traditionnel en termes de performance à court terme et long terme ?).

Tu as déjà contacté la Confédération de la Construction et donc le monde des entrepreneurs (les grands entrepreneurs) ?

Florian: Je suis rentré en contact avec le responsable de la construction 4.0 de la confédération il y a quelques semaines.

Noël Naert: Certains grands entrepreneurs ne sont pas encore au courant des différents types de béton exotiques, high-tech, etc. C'est encore nouveau.

Dans l'article de Gand, tu as aussi le nom d'un doctorant et le responsable du projet du pont imprimé en 3D à l'UGent.

Florian: Je vous remercie pour votre temps, vos avis et vos conseils.

Noël Naert: Pas de soucis, n'oublie pas le CemBureau et leur roadmap des 5 'C' dans ton étude. Notre entreprise a aussi intérêt à divulguer cette stratégie des 5C. On ne demande pas mieux car notre industrie est souvent critiquée. Il faut retenir que le béton est à la fois low-tech et high-tech, il y a des évolutions en cours, surtout aujourd'hui. Je te souhaite une bonne continuation dans ton projet.

Florian: Merci à vous deux. Bonne après-midi.

Appendix 23

6. Xavier Köttgen - 8th of April 2021 in face-to-face

Architect and manager at Section A-A

Qualitative approach: **Semi-conducted interview**

Florian: Bonjour Mr Köttgen.

Xavier Köttgen: Bonjour Florian. Je viens tout juste de parler du sujet de votre mémoire avec un collègue. Le sujet est très vaste. Je ne le connais pas forcément. D'ailleurs, je suis allé rechercher la vidéo. En fait, j'avais vu un bâtiment en 2020 dans un container qui était aménagé. Ils avaient mis une imprimante 3D et ils fabriquaient des chaises. Et donc, c'est vrai que lorsqu'on voit la machine travailler, c'est impressionnant. Ce qui est étonnant aussi, c'est que tu peux partir. Tu te dis « bon bah, je reviendrai dans deux heures, trois heures ». Et mon truc est fini. C'était peut-être des choses basiques parce que j'imagine que ça évolue assez fort.

Florian: Ma première question est : avez-vous déjà entendu parler de projets 3D dans la construction ?

Xavier Köttgen: Dans les publications que je reçois par mail, il y a parfois des sujets traités sur ce sujet. C'est vrai qu'on n'a pas tendance à trop y prêter attention dans le sens où on est on a nos projets et on a une méthode plus classique de construction. Et je trouve que pour ce type de projet, c'est difficile de le transposer à ce que, nous, on réalise. Et souvent, on réalise du sur mesure. Or ça, c'est plus un mode de standardisation. En tout cas, c'est mon point de vue. Je me trompe peut-être complètement et en fait, j'ai associé ça en quelque sorte à des systèmes de construction que j'appelle moi les « blocs Lego ». Donc, en fait, ce sont des blocs isolants qui sont creux, que l'on empile les uns sur les autres. Les gens peuvent auto construire. C'est vraiment des modules, que l'on met les uns sur les autres. Comme les Legos et on les empile. On y place des armatures métalliques à l'intérieur et on y coule du béton. Ce sont des coffrages perdus qui sont isolants, dans lesquels on coule des parois de béton. Mais c'est vrai qu'on est tributaire d'un module, c'est à dire un bloc. C'est cette dimension-là, plus ou moins 50-60 de long sur cette épaisseur-là. Et on se rend bien compte qu'il y a une limite au système. On ne sait pas commencer à dire « moi, je veux mon mur à trois mètres 46,5 ». Par rapport à la façade, si je dois me caler au module de bloc, je vais agrandir ou rétrécir. Mais j'aurais toujours un petit problème, un petit décalage. Ou alors, l'avantage du système modulaire s'estompe parce qu'on revient à devoir créer du sur-mesure avec quelque chose qui n'est pas prévu au départ pour. Donc dans ma tête, on se dit qu'il faut vraiment que dès le départ, on puisse s'adapter aux modules, aux types de construction. Donc j'imagine que pour des constructions en 3D, c'est certainement plus souple. Mais quand on connaît la technicité qui aujourd'hui se cache derrière les bâtiments en termes d'isolation thermique, d'étanchéité à l'air, etc. On se pose la question de dire « Comment est-ce que je pourrais transposer ça pour que dans un projet concret, on puisse le réaliser ? » Et donc, au final, je me dis que si on a des projets dans des pays en voie de développement, dans des pays qui ont été sinistrés par des tremblements de terre comme par exemple à Beyrouth où il faut reconstruire rapidement, je pense que ça peut être une solution.

Mais ce sont souvent malheureusement aussi des pays où il y a moins de contraintes thermiques. Il y a d'autres contraintes qu'ici. Donc, il faut pratiquement s'adapter d'une part au système et d'autre part, aux populations, aux pays dans lequel on pourrait envisager construire avec ce principe-là. J'avais aussi suivi un projet de maisons de repos où là, on ne construisait pas en 3D, mais on amenait les morceaux de mur entiers sur le chantier. Et là, le principe de construction, c'était : on est dans un hangar. Donc, on est au sec. Qu'il pleuve, qu'il vente, on est au sec. Et on a une sorte de robot qui place le mortier au bon endroit. Et on a des opérateurs (ouvriers) qui ont des machines spéciales qui les aident, comme des exosquelettes. Ils vont donc sur un plateau élévateur et ils se retournent. Ils ont des machines qui pincent les blocs et ils les posent et ainsi de suite. Une fois que le tas est terminé, je pense qu'ils appuient sur un bouton et le robot sait qu'il doit mettre la colle. Quand il y a une fenêtre, il s'arrête et il redémarre après la fenêtre et ainsi de suite. On fait des murs entiers. Une fois que le mur est terminé, la machine vient le mettre et vient le faire sécher à côté de ceux qui viennent d'être réalisés et on continue. Quand c'est terminé, on achemine sur le chantier. Et le chantier, c'est un puzzle. Et là aussi, il y a des limites au système.

Florian: Et ça, c'est du modulaire ?

Xavier Köttgen: C'est une sorte d'industrialisation. L'impression 3D, au final, c'est pour industrialiser un processus. Et c'est aussi, et c'est là, à mon avis, qu'on peut en retirer le plus grand profit. C'est pour réaliser des choses qui, certainement réalisées de manière conventionnelle, ne serait pas faisable par rapport à des formes. Je ne sais pas, par exemple, si la construction 3D est capable de construire avec une sorte de béton liquide haute performance où on pourrait avoir des formes très organiques et libres. Quand on imagine le coffrage que l'on aurait dû réaliser pour pouvoir le faire de manière conventionnelle, tu oublies. Certainement qu'il y a des avantages au système et finalement, on les connaît très mal. C'est à chaque fois très discret comme système. C'est vraiment des produits de niche. Je ne sais pas aujourd'hui s'il y a réellement des projets qui ont été réalisés comme ça, mais aussi si on a des parties de mobilier. On voit que dans le domaine automobile, il y a plein de pièces qui se font déjà comme ça. Et aussi des trucs pour personnaliser un intérieur de voiture. Donc, on pourrait transposer ça à l'habitat. Je ne pense pas qu'il y aurait de problèmes. Le souci est de se dire qu'on construit réellement une enveloppe avec ce processus là et ce procédé-là et donc on imagine aussi la taille de l'engin.

Florian: Déjà au niveau l'imprimante 3D. Ce n'est pas que décoffrage. Il y a moyen de faire déjà de beaux projets. Il y en a qui ont déjà été faits, dont un en Belgique en Flandre. C'est une maison entière qui a été construite grâce à une imprimante 3D. Ce n'est pas une maison qui était destinée à être habitée. Mais c'est une maison, un projet, un concept qui a été fait par l'entreprise Kamp C. C'est une petite entreprise et c'est assez sympa. L'un des premiers projets a été réalisé en Arabie saoudite. Alors pourquoi en Arabie Saoudite ? Pour montrer qu'ils savaient le faire, pour attirer les investisseurs aussi. Mais au niveau de la technologie en elle-même, ce n'est pas que des coffrages. Il y a moyen de réaliser des pièces directement sur place, avec des matériaux sur place comme du sable, par exemple. Et moi, ce qui m'intéresse, c'est aussi de savoir si tous ces projets sont faits en béton ou bien il y a d'autres matériaux. Ce qui est assez intéressant avec le modulaire, c'est le bois. Et c'est vrai que le bois redevient un petit peu à la mode comme l'industrie du béton est très polluante.

Xavier Köttgen: On te dira que oui et non. C'est vrai que moi, j'ai été très béton. À un moment, je faisais même les stands du CBR à Batibouw. CBR, c'est les cimentiers qui produisent notamment du ciment blanc. Ce sont les seuls à produire du ciment blanc. Et quand tu veux du béton blanc, tu dois mettre en œuvre du ciment blanc. Parce que du béton blanc et du ciment gris, ça ne le fait pas. Et ça permet aussi de faire du béton coloré et de ne pas avoir des teintes qui partent avec le gris du ciment parce que le gris ternit des teintes.

Florian: Voici des photos de ce projet qui se trouve à Westerlo.

Xavier Köttgen: La machine fait le mélange ? Ou bien faut-il lui apporter ?

Florian: C'est avec un réservoir et une pompe.

Xavier Köttgen: Et la fluidité du béton est étudiée pour qu'on puisse repasser ? Et quelle est la durée de construction?

Florian: Je pense qu'ils ont mis maximum 3 semaines, tout en continuant avec certaines pauses pour la recharge en béton. Dans le monde de la construction, si je vous dis qu'il a des projets comme ceux-ci, quels seraient selon vous les avantages liés à l'impression 3D ?

Xavier Köttgen: Il faut examiner un projet dans sa globalité. Donc là, on y voit directement un intérêt par rapport à la résistance du matériau. On sent qu'il y a un renforcement à l'intérieur de la paroi qui ne serait pas possible si on construisait de manière traditionnelle. Donc, si on a par exemple des constructions « simples » de type barrage, de type mur de soutènement. On a une application qui vraisemblablement est très efficace. Après, ce qui se passe, il faut voir la partie du robot par rapport à tout le reste. Si, pour compenser les limites du robot, on doit retravailler après pour rectifier, corriger, cacher et faire en sorte qu'on ne trouve pas bizarre la construction finie. C'est ça qui est intéressant d'étudier, pas simplement la magie de « ça se construit tout seul ». Mais malheureusement, en Belgique, on a besoin d'une étanchéité : imprimante 3D ou imprimante 3D, il faut rendre étanche et il faut isoler. Il y a des fenêtres à mettre. Il y a la partie gros œuvre et puis tout le reste. Mais c'est évidemment avec des projets comme celui-là que l'on peut tester, que l'on peut dire s'il y a un intérêt de continuer les recherches, le développement de projets pareils et aussi, quand on parle de « robotisation », le consommateur lambda, lui, qu'est-ce qu'il y voit ? Il y voit « rapidité d'exécution » et « économie ». Je pense que ce sont les notions qui sont associées à ce type de procédé. Il ne va pas forcément viser la personnalisation à tout prix.

On ne réinvente pas le principe de la construction. On a toujours des pièces qui sont avec des murs droits. Même si on peut envisager de faire, avec ce procédé-là, une paroi qui part en vague. Mais là, on touche déjà une sphère de la population qui va avoir une sensibilité prête à accepter d'avoir, en quelque sorte, une œuvre d'art dans son intérieur et d'en subir les conséquences (e.g. où placer les meubles) et on doit voir si on ne s'en lasse pas au final.

Nous, on doit construire un bâtiment avec comme objectif que les clients se sentent bien dans leur chez-soi. C'est-à-dire que les attentes qu'ils ont transmises doivent se sentir dans leur intérieur. On crée un espace à leur service par rapport à comment ils vivent ou telle communication d'espace en fonction de telle communication d'espace, en fonction de la grandeur de la famille, de l'évolution de la famille. Et, finalement, le client qui ne s'y connaît absolument pas et sait à peine lire un plan : quand il arrive et que la maison est terminée, il doit dire « Ah, entrepreneur, tu as bien travaillé et je suis fier de mon bâtiment ». Là, on a réellement fait notre job et c'est valorisant. Au départ de rien, tu as conçu quelque chose qui correspond à quelqu'un d'autre.

Quand je dis qu'on ne réinvente pas les manières de construire, il y a quand même certaines règles immuables. On veut aussi construire de manière fiable. On n'est pas là pour construire, comme si on avait une écurie de formule-1. On ne pousse pas les bâtiments à l'extrême. On ne peut pas se le permettre. Les budgets sont tels que, l'investissement dans un ménage d'un

bâtiment est “tel qu'on regarde à deux fois ce qu’on fait ». C’est à dire qu’on a toute une série de contraintes qui, lorsqu’on les transpose à une construction de ce type-là, je crois qu’on va réellement réduire très fortement le potentiel que peut offrir l’impression 3D avec toutes ses libertés et son aspect créatif. Ou alors, il faut se limiter à des parties très limitées comme des petites pièces ou des subtilités.

L’industrie du béton avait commencé à développer le béton ductal. Ce n’est plus un béton. C’est un mortier haute performance. Dans le béton, il y a des granulats (cailloux) et dans le béton ductal, il n’y a que du sable, du ciment, de l’eau et des adjuvants. Pour faire en sorte que les pièces de béton puissent se réduire en épaisseur pour avoir la même résistance que le béton. Mais on ne coule pas en place du béton ductal. On réalise ça en atelier et on plaçait ensuite les pièces. On arrivait à retrouver ces larges libertés en termes de forme et d’épaisseur. On n’est pas habitué à avoir une paroi de béton qui fait seulement 3 centimètres d’épaisseur sur des dimensions importantes. Il y a une exposition permanente à Paris où ils ont recouvert le sol et les parois de béton ductal. Le sol est incliné et il y a une courbe et ça revenait avec le plafond. On peut aussi réaliser du mobilier en béton ductal (chaises, tables, etc.). C’est assez déroutant parce que le béton dans ma tête, c'est lourd, c'est massif et ici, c'était très léger. Cette notion de liberté de conception montre qu’on doit malgré tout rester dans un concept relativement simple, que l'on aurait très bien pu faire avec une méthode beaucoup plus traditionnelle. Ce n'est pas parce que on avait la technique de l'impression 3D que l'on est arrivé à la forme que l'on propose là-bas. Maintenant, peut-être qu'à l'intérieur, il y a des choses qui sont tout à fait étonnantes et qu'on a travaillé de manière très lisse à l'extérieur et qu'à l'intérieur, c'est comme si on avait creusé dans une galerie. On peut tout imaginer. Mais le regard que l'on a de ce projet-là est que ce n’est pas flagrant que ça a été construit grâce à l’impression 3D.

Florian: J'ai été en contact avec la Confédération de la construction, dont le représentant de la Construction 4.0, qui s'occupe de tous ces projets. Il m'a expliqué qu'il y avait moyen de construire, par exemple, des murs ou des structures hybrides avec plusieurs spécificités pour une seule structure. Par exemple, une isolation thermique, sonore et un côté esthétique. Au lieu de construire trois murs différents. Je ne sais pas si ça va remplacer les techniques de construction demain et je ne pense pas.

Xavier Köttgen: Ça ne remplacera certainement pas non. Mais par contre, dans certains domaines d'application, je pense qu'il y a un intérêt : dans des conditions extrêmes, sur des chantiers ou en mer. On pourrait très bien imaginer d'avoir des systèmes comme ça pour réaliser des fondations, des fondations d'éoliennes, des fondations de plateformes offshore. Je ne sais pas. Il y a toute une série d’applications qui vont s'éloigner de l'habitation, mais qui vont avoir recours à tous les avantages de l'impression 3D parce qu'on n'expose pas des hommes à des risques inconsidérés. On arrive à garantir quoi qu'il arrive, quelles que soient les conditions météo, à continuer à produire et à faire avancer les choses. Le sujet est vaste.

Florian: Et la toute première fois qu'on a parlé de l'impression 3D, c'était pour aller sur la Lune. Parce qu'on ne pouvait pas y placer des ouvriers. Le bâtiment aurait été construit quand on serait arrivé. On en parle peu dans ce domaine, on en parle aussi beaucoup à Paris parce qu'ils

sont en train de reconstruire des pièces de Notre-Dame grâce aux imprimantes 3D qui sont difficilement reproductibles.

Xavier Köttgen: Il y a une évidence beaucoup plus grande dans la conception de pièces qui viennent s'intégrer à un bâtiment, qui lui fait appel à d'autres techniques de construction plus traditionnelles. Et ça part dans tous les sens. Notre Dame est un exemple. Justement, on va à la fois associer des techniques très pointues et on va trouver des éléments qui vont être faits plus traditionnellement.

Florian: Ça, c'est vraiment l'aspect créatif. Mais il y a aussi un aspect très important dans mon mémoire que je compte étudier, c'est l'aspect environnemental. Quels sont les vrais avantages, selon vous, de construire de cette façon ? Il y a par exemple toute la supply chain des matériaux qui doivent venir sur place, qui sont peut-être déjà sur place, qui pourraient déjà être sur place.

Xavier Köttgen: Il y a forcément la limitation des déchets parce que c'est clair qu'on ne construit uniquement ce dont on a besoin. Donc oui, il y a un intérêt à ce niveau-là. Ça, c'est évident. Il y a certainement moins de dépenses énergétiques pour pouvoir réellement construire. Si on prend deux bâtiments identiques, cette technique-là va produire moins de carbone. On est parti dans toute cette chaîne qui est assez difficilement quantifiable de manière précise et rigoureuse, parce que c'est toujours ça le gros dilemme. C'est que lorsqu'on essaye de démontrer par A+B qu'une voiture électrique n'est pas moins polluante qu'une voiture normale, on doit aller vraiment très loin : les matériaux rares que l'on met dans les batteries, ça vient d'où ? C'est vrai que, ici, on arriverait à mieux cerner la problématique, mais toujours avec cette hésitation d'être réellement catégorique en disant : « Voilà, j'ai ce procédé-là, je produis autant en CO2… ». Après, il y a la notion de main d'œuvre. Ce sont plus des maçons mais des informaticiens.

Florian: Ça vous dérangerait justement, vous, si vous étiez à la tête de cette entreprise de mettre de côté des ouvriers pour recruter des designers, des informaticiens, etc. ?

Xavier Köttgen: On trouve de moins en moins de maçons. C'est clair que l'avenir est à la préfabrication. Aujourd'hui, beaucoup de bâtiments, peut-être pas des maisons unifamiliales, mais des bâtiments multi résidentiels sont construits avec un système de blocs qui sont qui arrivent sur chantier prédécoupées par rapport à des zones de fenêtres, etc. Donc les hommes ne coupent plus. Ils doivent juste mettre la pièce numéro untel à tel endroit comme des Legos. Et ce sont des blocs lourds et qui sont manipulés par des petites grues que l'on met d'étage en étage au fur et à mesure du chantier qui se construit. Donc, le fait de mettre une certaine main d'œuvre de côté pour privilégier d'autres professions plus techniques, peut-être plus artistique. Moi, je n'y vois pas d'inconvénient. Le problème, ça sera l'expérience de ces gens-là. Ces gens seront transposés du jour au lendemain sur du concret. La machine devra forcément s'adapter et il faut voir comment transposer l'arrivée de ce mastodonte sur chantier. Tous les terrains ne sont pas forcément compatibles. Donc, c'est très bien quand on est dans des conditions idéales : terrain plat, parfaitement accessible, les dégagements latéraux, etc. Aller construire en 3D dans le centre de Bruxelles, c'est compliqué. Ou alors, on construit avec une solution hybride et on

commence par la cage d'ascenseur. Et la cage d'ascenseur se monte et puis après, on fait le reste. Avec peut-être plus de facilité que si on devait mettre des échafaudages.

Donc aujourd'hui, pour arriver à réellement un processus global. C'est-à-dire, de se dire « je n'ai pratiquement plus de limites ». Il va déjà falloir étudier un système qui est hyper polyvalent. À mon avis, cette hyper polyvalence aura une limite. On ne va pas savoir réellement répondre à tous les cas de figure qui peuvent ceux qui peuvent se poser dans le monde de la construction. Quand on construit une voiture, même si les formes des designers sont très créatives, on est quand même toujours rattrapé par les normes de sécurité, l'efficience en termes d'aérodynamisme, etc. Donc, on ne va pas, du jour au lendemain, modifier totalement la forme d'une voiture. Lorsqu'il y a des grosses différences, on s'attache à une partie de la voiture. Mais après, il faut voir si le processus d'industrialisation, de commercialisation, et de fiabilité de ce type d'engin tient réellement la route. Et encore, une voiture, c'est un objet de consommation. Après X années, tu la jettes et on en achète une nouvelle. Pour une maison, la réflexion est que le fait de faire changer les mentalités va toujours être beaucoup plus long. Un maçon à qui on dit : « Demain, tu ne mettras plus tes blocs avec du mortier, mais tu vas mettre de la colle ». Il va se demander ce qu'il va faire.

Florian: Il y a vraiment cet aspect perturbateur « disruptif », sur le marché du travail, sur l'homme, etc.

Xavier Köttgen: Et il faut voir si cette technique de construction ne va pas plutôt être utile à développer dans le cadre de projets un peu exceptionnels : des musées, des choses un peu grandioses, des gares, etc. On se dit allez, les techniques existent et on le fait encore quand même encore à l'ancienne. Alors que là, on s'en fout un peu des budgets. Il y aurait à mon avis un intérêt à pouvoir fabriquer des pièces qui seraient tout à fait transportables, mais au lieu de les coffrer sur place mondiale, tu les crées et tu fais aussi une sorte de puzzle 3D.

Florian: Quel sera l'avenir des imprimantes 3D finalement ? Dans 5 à 10 ans ?

Xavier Köttgen: Oui, on aura vraiment des projets de grande envergure. Si on revit une pandémie par exemple, il y aura peut-être un intérêt de construire des modules très rapidement à la chaîne pour concevoir des bâtiments ou bien des hôpitaux comme en Chine.

Encore une fois, on est dans du spécifique à grande échelle, pas du spécialisé. Ou alors pour des trucs qui sortent de l'ordinaire. Ou alors, on a réellement le budget à consacrer pour faire évoluer une technique en même temps que l'on produit des pièces. On améliore alors les processus qui serviraient peut-être pour d'autres projets. Après, je crois qu'il y a un intérêt, mais à nouveau, c'est pour des niches qui sont très ciblées.

Au niveau des coûts, ce serait intéressant de savoir ce que coûte en l'occurrence le bâtiment qui se construit avec cette imprimante. Mais surtout, de voir si la technique est utilisée juste pour le gros œuvre ou si on va au-delà. Parce qu'il faut pouvoir comparer le poste gros œuvre si c'est le cas avec un poste oeuvre plus traditionnel de la même maison, si on le fait de manière.

Florian: En fait, je voulais vraiment comparer une structure traditionnelle imprimée en 3D avec une construite avec des méthodes dites traditionnelles.

Xavier Köttgen: L'intérêt de ce procédé, c'est quand il y a des choses qui sont impayables, si tu veux les faire de manière normale.

Il y a aussi un côté esthétique avec le béton apparent, alors que c'est très décrié parce qu'on a construit à outrance dans les années 60-70 avec du béton. C'était mal foutu. Mais nous, les architectes, c'est vrai qu'on a une sensibilité et on nous a montré des projets en béton apparent qui étaient beaux et c'est un peu notre religion. Les murs sont lisses et ils ont ce côté magique. Dans l'impression 3D, tu vas perdre ça. Il faut voir si, en voulant faire ça (et c'est pas très compliqué), est ce que l'on aurait la même texture et le même fini de la pièce en béton ? Je ne pense pas qu'on aurait quelque chose de parfaitement lisse. On peut tirer parti des couches. L'avantage du béton coulé en place, c'est qu'il reprend toutes les imperfections du coffrage. Donc, si on a envie d'avoir des fines lignes pour avoir un dessin à la surface du béton. Il suffit de le réaliser dans le coffrage. Il faut voir si oui ou non, l'impression 3D va pouvoir réellement copier ça. Je ne pense pas. Donc, ça veut dire que déjà, il y aura un choix à faire dans le mode de construction d'un projet et se dire « Quel effet est-ce que je souhaite donner à mon bâtiment ? ».

Après, peut-être qu'il y a moyen de couler le béton à plat et en ayant une fluidité de béton qui permet justement au béton, avant de sécher, de s'égaliser, de ne plus avoir ce côté « strate ». Bon, après, je ne sais pas si c'est envisageable.

Après, le gros inconvénient d'une technique traditionnelle de coffrage, c'est que l'on doit réaliser la pièce en pensant au décoffrage. Donc, ça veut dire qu'il y a des formes qui sont impossibles à réaliser. Et là, il y a des limites au système. En impression 3D, tu n'en a plus. Donc, il y a vraiment un choix stratégique à faire et de se dire « Qu'est-ce que je veux esthétiquement ? » et « Qu'est-ce que je veux techniquement ? » Il y aura, me semble-t-il, toujours une réponse plus adaptée pour un type de projet par rapport à d'autres types de projets. Il y aura toujours cette concurrence. On pourrait aussi penser à la préfabrication, mais la préfabrication pourrait faire appel à une technique d'impression 3D.

Florian: On a fini il me semble, merci beaucoup pour cet entretien !

Xavier Köttgen: Avec plaisir !

Appendix 24

7. Gieljan Vantyghem - 1st of June 2021 on Microsoft Teams

Concre3DLab - PhD researcher at UGent // Topology Optimization - 3D Concrete Printing

Qualitative approach: **Semi-conducted interview**

Florian: Hi, can you hear me?

Gieljan Vantyghem: I can hear you very well.

Florian: So, no problem, thank you so much for taking some time for me. I already had some interviews and one of the intervenes talked about your project and I was really interested to hear about it because I read a lot of things and articles in the press.

Gieljan Vantyghem: Who was that person?

Florian: Someone from the FEBELCEM: Noël Naert. He sent me a lot of articles and talked about your project and said that there was some research about a new kind of cement they were looking to make (more sustainable). So, we talked about your project and the fact you reduced the amount of cement necessary to build the bridge.

Gieljan Vantyghem: I never heard of him. It's great to hear other people talking about it. So yeah, it's already an old project.

Florian: I had the opportunity to talk with someone from Kamp C, the company that built the 3D building.

Gieljan Vantyghem: With Marijke Aerts?

Florian: Yes, it was really interesting.

Gieljan Vantyghem: Yeah. They also have achieved a lot. I visited a few times. We had some professors that participated in the project, but I was not.

So, maybe I can talk first a little bit about myself: my name is Gieljan Vantyghem. I'm a PhD student at Ghent university. I have been a PhD student for some years, I'm now in my sixth year: sixth and final year. So, my PHD has been written and it's to be submitted next week.

Florian: Congratulations!

Gieljan Vantyghem: I am really closing everything off, ending everything. For my master's thesis, I studied structural topology optimization. I don't know if you're familiar with it?

Florian: A little bit, but I'm not a civil engineer. I'm a commercial engineer. So I'm not as technical as you.

Gieljan Vantyghem: That's cool! It is all about finding the most optimal shape. That's what I did in my master year. What we can see is that with topology optimization, you have a large degree of freedom. So, the result of the optimization is that most of the time you get very complex shapes (that are very hard to produce using traditional techniques). So, that was one of the findings. Another finding was the fact that we can achieve some large amount of reduction of material and without affecting structural properties. So, of course, it's a technology that has been around for quite some time, but it is not used often in the construction industry because of the limits, for example in the way of production, which is very traditional. The shapes and building construction are also very linear and conventional. In aerospace, where the weight saving is much more important, there you can see that topology optimization is used more often already since some decades ago in fact. Because for a plane, one kilogram of material can save you in the long term more 20K or 30K $. It is very important in the aerospace industry. In the construction industry, the costs of the material are not as much as the cost of the persons who need to place it and, or the person who needs to think about it. So, that's a little bit of a problem. Of course, when these tools evolve, they become more and more accessible. That's the reason why, for example, if you need to construct 200 bridges who are all the same. In Belgium, for example, you have two or three types of bridges. So, if you were the manufacturer of all these bridges, you can save a bit of material, which could mean it is important because you can do it a lot of the time. Also, if you can reduce the weight, you can reduce the weight in your foundations and so on. So that's also one of the findings of my master thesis.

Then for my PhD, I started my first years studying also further going on the topic of structural topology optimization, but also the thermal aspects. So, in the construction industry and building industry, if you have a wall that is supporting itself or needs to support loads, but also you have some thermal insulation quality that you need (or acoustic as well). And if you combine the two, for example, then you could maybe find a solution where you do not have, for example, a brick layer of bricks, a layer of insulation, a layer of bricks, etc. But just one structure which is optimized for everything. So, if you can have some foam concrete (concrete with some air bubbles), and we have a wall system where we have a flow of strong concrete where it needs to be strong, some flow of insulating material that needs to be insulating, it's possible to optimize it. But of course, it's very hard to produce it. So, that was also one of the questions that I get when I was presenting my research. How can we make that? It's impossible. So why do you do this research?

So then, starting from my third year, I started focusing more on the manufacturing side of these optimized results, because if you cannot make them, what are we doing? So, that's when we get

into contact with 3D concrete printing. Well, I had some experience, and I was very fascinated by 3D printing like you see here.

I like it very much too to show what we can do on a small scale. But of course, in the building industry, everything is big and large, and we need to have a methodology to print things on a big scale. So 3D concrete printing is one of the techniques that allows us to do it.

In my third or fourth year, I went to MIT in the United States in Boston. And I was connected to some researchers from Israel, who is also one of the co-authors on this paper about the bridge.

And he had a script written that does not only optimize the shape of the bridge, for example, but also the optimal trajectory of the post-tension cable, which was something I never saw before. And it was very inspiring. And he had a very interesting presentation, and it was really at that moment, I went to speak with him. At that time, we had the idea in Gent in our lab to 3D print a small-scale bridge which was topology optimized. But he, of course, had a better script than what we had. So, it was very nice to have some interactions. We could, of course, 3D print the bridge and he could help us with the optimization of more than only the concrete lab, but also the post-tension cables.

Florian: So, he added the idea to add a steel cable that could be added under the bridge? Or on the bridge to make it stronger?

Gieljan Vantyghem: Okay. So, I can maybe show some pictures while I'm speaking about it. Some of the pictures may be confidential, but I will tell you when it is.

So, this is maybe a nice picture of the end results. And here on the left side, if you can see my mouse, you can see that this is the main post-tension strength that runs through the bottom side of the bottom side bridge, which takes the main tension force of course.

This was the original topology optimization process. So, this is a CGI, so it's a computer-generated image, but just maybe to show me what is “topology optimization” very quickly. It’s a method of finding out where the blue pixels are. We remove pixels until you're left with the most optimal structure. So, the red pixels, in this case, are like the final topology. The blue ones are the pixels that don't influence the design a lot. So, in fact, you have here a load in the middle, and we are looking at how much material we can take out without affecting the defection too much. You can do it in three dimensions as well. And there are some other constraints, but I will not get into this too much.

Then, you also have some other designs for a two-span bridge or a single span with different loadings. But also, you can see that the blue line or the shape of this blue line is also optimized, and this was something very special. And the reason why we were attracted so much to this study was because our lab “Magnel” is famous for post-tensioning. Some years ago, the professor Magnel built a lot of large bridges with post-tensioning and concrete. He was on the forefront of this concrete research in Europe. So, the fact that we could combine concrete technology with post-tensioning and the structural optimization part was very interesting.

Florian: Yeah. I can imagine that. We heard a lot about 3D printing in the construction sector for buildings. On the other hand, we do not hear often about bridges, except in the Netherlands.

Gieljan Vantyghem: Yes, there was one in Gemert and then a new one still in process. They are still constructing it.

Florian: I make my thesis on 3D printing and the construction industry. My goal is proving whether or not 3D printing is a possibility in terms of cost, in terms of feasibility, is it something of the future and not just a suggestion?

Gieljan Vantyghem: We really have to think about what scenario 3D printing can be used the best. So, I always remind myself what 3D CP can be used for and what 3D CP should be used for. I am not convinced that you can make a house cheaper with 3D concrete printing and using pre-prefabrication. So, there is no benefit in using 3D concrete printing. Why? Because:

- I think that the amount of material reduction for a house is very limited. In my study, we saw that in fact, if you use the bricks, this is already minimal material usage. We cannot take any more material out from this brick or from a concrete block. It's very efficient. So, the material is where it should be. And it's very hard to make it even more slender. That's what many companies say: “the wall uses 40% less material”. But, for 50% or 60% less material, I'm not really convinced that it is.

Florian: We have to see what projects 3D printing would be interesting. And I identified two different extreme situations: the customization or the standardization (a same building built several times).

Gieljan Vantyghem: Yes. So just to clarify further. In 3D printing, they build walls where you have like a layer of 10 centimeters, 10 centimeters, 10 centimeters, for example. The sum is 30, but then they say: “Okay, from the original wall of 50 centimeters, we use only half of the material”. That's tricky because in reality, if you have a conventional structure, you will only have a smaller slab of 10 or 15 centimeters of concrete. So, I think it's not fair to say that they are saving material in houses. Still, I think there are benefits in printing houses, but it is in printing very complex or organic shapes or for houses.

Or if you take a look at, for example, other countries where there's really a need of a fast production for a house: the speed and the efficiency of the robot that can print during the night and can reduce the cost of the human labor could be efficient. But printing houses in Belgium or in the rest of Europe, I don't think it will ever be economical to apply on a large scale. So, it will be used for very complex projects or by architects that really want their vision very organically shaped. Then it would be more cost efficient because this crazy idea to make it using foam work would be very expensive.

Florian: What is difficult in this study is that, in Belgium, if you want to have some projects with 3D printing, it is really complicated to find some cost information. It is hard to compare a

3D printed building with a traditional one and see how much we have saved using one way or the other. We don't have a lot of cost information, but in the end, I do think we are not in a country where 3D printing will be the most useful. I talked a lot about it with Kamp C. They told me they did not have a lot of information about costs because all the costs come from different organizations, etc.

Gieljan Vantyghem: I can tell you that they had a very large budget from Europe, so indeed they just wanted to realize it. But in fact, they should draw some conclusions. For example, for any company that uses 3D printed industrial arms, the cost of such robots is not that much. I think it's about 50, 60.000€. But if you want to buy their system, at this moment, it costs you a lot of money, around 180.000€, and it's only for a printing prefabricated structure. So, it's like if you have a concrete prefabricated's lab, how much does that cost? It's a lot cheaper printing it in your lab like this. In Paris, the robot does not cost that much but buying it from them, which is adapted to printing with concrete, you get the material, to service, the training, the system, the pumping system, etc. It costs you half a million euros. At this moment, if you want to buy this very expensive machine, you have to think twice. It's really an initial market, I think it can be reduced by a large number. So, I think your infrastructure costs will go down, but a lot of construction companies do own a crane by themselves. They own a lot of trucks. They own heavy equipment. I think it will be similar. So, you can already see that there's an increased presence of machinery and large industrial cranes on sites. And my personal vision is that 3D printing onsite will use these large crane structures that are already present. At this moment, it's not possible because it's not optimized for automated control. So, the motors and the separate motors need some small updates for that. But in fact, it's not that difficult. It's just not there yet.

Florian: What do you think about printing onsite and offsite? Is there a situation where one is preferable? Today, we talked a lot about modular construction and just building parts and putting them together on site.

Gieljan Vantyghem: I think 3D printing will be done in an industrial whole off site. So, not on the production side, which will have some benefits. I think off site will be implemented more and more, but it will only be used for designs. It will be a matter of what is the cheapest. For example, for a historical restoration, it's very costly to make molds but in fact, it's not that expensive. I was wrong about this, I thought that the future of 3D concrete printing could be that, in the future, we just print these elements. But I spoke with some people who are into this business, and making a 3D printed mold is not that expensive compared to all the other problems that 3D concrete printing has. So, more and more, we will see offsite production techniques for special occasions like this bridge that we made.

Florian: Here, the molds in orange in your picture are made with a 3D printer?

Gieljan Vantyghem: Yeah, it could be.

Florian: And after, they just add the cement in it?

Gieljan Vantyghem: Yes. The person that I spoke to used a foam mold. They said that it's very cheap. I think this project indeed was like a prototype to see if 3D concrete printed molds were also efficient, but I think the plastic is very expensive in fact, on a large scale. That's the benefit of concrete. Concrete is a very cheap material. When printing a bridge, you can print all the segments and then assemble them and make your bridge and bring it to the sides. And the benefit is that you have a very high control about temperature, humidity, and surface quality. You have a lot of benefits! But still, my vision is that, in the future, most 3D concrete printing will be done on site. I really believe in that because the benefits of 3D printing is that you don't need to transport your materials. Or your material comes on site in a very compact way. It's in a large truck with just fluids, concrete or bags of sand and stuff like that. And you bring something that is much bigger than you originally had because you have the voids in it. So, you have your role and your shape. When you have holes in the structure and you need to transport them, they can break and you need to think about transportation loads and the supply chain, etc. It's more complicated. I think, for houses, most of them will be made onsite. Nice example is the building printed in Italy. It's a presentation I recently gave to a Dutch audience. I can send you a recorded version of it but it's in Dutch.

Florian: No problem, thank you so much. That would help me for the end of my project.

Gieljan Vantyghem: I can also send you this presentation. So, first it's about concrete printing, 3D printing, material extrusion, and the difference with subtractive manufacturing. I'm not claiming one is better than the other, but just to be sure that 3D printing is more than just material extrusion. You have a lot of technologies. But if we talk about concrete printing, most of the time, the "3D printing" that we are talking about is the material extrusion technique.

Florian: I had another question because I have two important aspects in my thesis and one of them is the disruptive aspect of 3D printing but also the environment. Do you think that there would be any possibility to have new materials, other than cement, used in 3D printing in the construction sector?

Gieljan Vantyghem: Other materials than cement? I think it is definitely feasible. For one, we can have different types of cements: cements that produce less CO2 when they are processed. Concerning durability, one of our colleagues working with universities is highly involved in making a 3D printable concrete more sustainable and durable. I think the type of cement can be changed. I'm not a material scientist, so to answer this question, it is more difficult. In fact, now, we use twice as much cement as normal concrete for all the projects you see around the world. I think it's fair to say that the amount of cement that is used in the concrete mix is about two times as much. And if you know that cement is the main contributor to the CO2 emissions, then you know that we have about two times worse materials. So, two times worse than conventional concrete. So, if they say, "we use less material", then we are back at the start. The main problem with the materials used in 3D printing, is that, at the moment we are printing using progressive cavity pumps. It's a pump that gives you a constant flow. For larger concrete grains, we use different pumps, but you get another constant flow, which is not a problem if

you want to pour a slab. Then it does not matter how fast or what is the flow of the material. But if you are printing, you really need a constant flow.

Florian: Otherwise, the construction is in different parts and not as strong?

Gieljan Vantyghem: Yes, and if you use a cavity pump (only used at that moment for cement streets). So, it's mostly used for very fluid light materials. So, the amount of aggregates… You're maybe not that technical, but concrete is made of aggregates, like sand, cement, and water. But now, this one is not used in most of the projects that you see.

Florian: What projects? 3D printed projects?

Gieljan Vantyghem: All of them around the world because most of the limits you see in concrete printing is "the max size of your aggregate which is approximately two millimeters". The conventional pumps are still not yet adjusted to use large aggregates. The moment we can start including these larger pieces, the amount of cement can also be reduced. The cement is like glue. So, if you have very small sand particles, then you need a lot of glue. But if you have larger ones in between, then you need less glue, so less cement and the CO2 emissions go down. So, in the future, when these pumps get adjusted, we can expect that the CO2 emissions will be about the same as conventional concrete. So, it's not that much of a problem, but people are still looking at replacing parts of this cement with some other additives, which are, for example, flying ashes. There are also other products which we already applied a lot, so that we can reduce the amount of cement. I think, concerning durability, we will fix this. No problem.

Florian: So, 3D printing is trying to reduce the waste of material, but we are also trying to reduce the amount of cement needed.

Gieljan Vantyghem: I think it's a combination of both. So, we will make the concrete better and we will make the result topology optimized. So, it needs less material and then, if you combine it, we will have a very good improvement. And of course, you can see them separately as well. We can have a conventional structure which uses better concrete. So then, 3D printing is not adding anything. If you have a more durable concrete, you can use it in your conventional structure as well.

Florian: At the end, we would use only 3D printing for complex structures?

Gieljan Vantyghem: I think topology optimization is the main force to using 3D concrete printing because we cannot make it cheaper with conventional structures. So, durability is important, but it's not the main aspect for my vision.

Florian: I will add this point to my thesis. I had a list of questions for you, especially the future of 3D printing, but we will see according to the materials and the projects.

Gieljan Vantyghem: I think, for a bridge, it's easier to optimize it and take out materials where it's not needed in comparison to a house. But still, I think that there will be a future for 3D printing of houses for very special cases, very organic pavilions where there is some money, but they really want to make something that was not possible before. I think that will be the main initial fields where we can use it.

Florian: If I talk about the disruptive aspect and the fact that there will be fewer manual workers on site, because of the 3D printer, do you think there will be a big consequence?

Gieljan Vantyghem: I think that will also be a driving force behind it. A few weeks ago, we had to rebuild some parts of a small wall and I think they were two people. They spent a whole day working on a two-meter wall and one and a half meter height. They use a special type of brick and they had to cut it in half for some reason, but they spent a lot of time on a very small piece of wall, and it was just a straight line.

So, if you increase the accessibility of robots on sites for larger projects, like I said before, and if you already have cranes that are present there, and if you could use them to make something like you see on this slide, then I think "why not use the robots to help you more and more".

Florian: It could even be used at night.

Gieljan Vantyghem: They could continue working during the night, but of course, in the beginning, it will be for very special occasions. The main problem for me is that I don't have a lot of practical experience. In fact, I should be in the coming years, I should be on-site and see how it all works. In the construction industry, there are always a lot of problems, changes, a lot of rules, rules concerning safety if you have a large crane which is operating automatically, and you have some people working below, etc.

Florian: There will always be a lot of rules in the construction industry, and I hope it's not a problem for the future of new technologies in the construction sector.

Gieljan Vantyghem: One day, the robots will be working and another day, the humans will finish up the problems that they've made. Maybe the robots will first print on Mars and the Moon, and then we will do it on Earth. It's really a little bit crazy maybe. Actually, I think we are not that far from printing on the moon and printing on Mars than people might think.

Florian: You're right. I hear a lot of stories about that in the press like SpaceX. Things are progressing quite fast.

Gieljan Vantyghem: If you see the time evolution of 3D concrete printing, you also see that we have an exponential growth at the moment. This is already from 2019, when we had only a couple of projects. Now, if you follow the right groups on LinkedIn and Facebook every day, you see new projects which are mind-blowing. You can see how many new companies are

coming and new spin-offs. So, it's a very fast evolving field. And I think we can expect a lot of it in the coming years and all the problems will be solved.

Florian: I think that's not a sector that was impacted by the COVID-19 but I was thinking it could.

Gieljan Vantyghem: I don't think so because it started already before COVID and it just continues to grow. But in fact, it's true that the construction industry was not that impacted. In fact, I think the opposite happened. I think a lot of people are renovating and the value of your home has increased. I work 90% from home and a lot of people I know are working from home. So, if you can make her home a little bit better, if you don't have all these large cracks, it's beneficial. The value of a house and a garden is going up and also the renovating sector and the building sector in general.

Florian: That's true and I am at 100% at home because I have my internship at 100% in teleworking.

Gieljan Vantyghem: And so, you were making a commercial market study about 3D printing?

Florian: So, yes, I'm a commercial engineer, specialized in procurement and supply chain. I am in love with new technologies, and I deeply wanted to do something about it. Of course, I'm not a civil engineer, so I will not enter into too many technical details. I would like to thank you so much for all this information and I will be waiting for your references and recommendations on my project.

Gieljan Vantyghem: We're also working on a second bridge. It's already printed a long time ago, but we still need to assemble it. It’s the same concept but with a larger deck. So, this is one of the pieces which is 2-meter high. I think it took us half an hour to print it two times, and then we were done.

Florian: Do you think one day, these bridges will carry more weight like cars?

Gieljan Vantyghem: At this moment, most of the time, it's like a pedestrian or a bicycle bridge. It's easier to design it. It's already very complex. If it works, we can continue to make other kinds of bridges. But if you look at this bridge, it is so heavy. I think a car could go on it.

Florian: Where is it?

Gieljan Vantyghem: In Nijmegen in the Netherlands. It is the longest 3D printed bridge. There is also one in China but there are two that claim to be the longest, apparently.

Florian: Now, I will try my best, according to your information and the interviews I had to carry on.

Gieljan Vantyghem: Do you know our YouTube channel?

Florian: You have a YouTube channel? I saw only one video.

Gieljan Vantyghem: The name of the channel is Concre3DLab Ghent. These videos are mostly experiments that we filmed and made public.

Florian: It's interesting. I will check your videos on YouTube.

Gieljan Vantyghem: All right. If you have any more questions, you can always contact me on Teams. Most of the time, I'm available.

Florian: Thank you so much already for your time. Good luck with your PHD presentation. Have a good afternoon. Bye.

Appendix 25

8. Vytautas Naslenas - 3rd of June 2021 by e-mails

Global Sales Coordinator at COBOD International A/S

Qualitative approach: **e-mails**

Florian: Dear Mr Naslenas,

I am a business engineering student in Belgium currently doing my final thesis on 3D printers in the construction sector.

A few weeks ago, I had the opportunity to get in contact with a project manager of Kamp C, Marijke Aerts. She introduced me to COBOD.

I would like to know if it is possible to receive some information on the Kamp C project or a similar one (BOD building in Copenhagen, etc.)?
To complete my research, I would need a cost approximation (total or by square meters) to print a traditional building.

In the FAQ section on your website, you offer the possibility to determine the cost of a 3D construction thanks to a cost calculator.
Unfortunately, the calculator on the bottom of https://cobod.com/bod2/ is not working (error 404).

I am curious to know more about your projects. If your agenda allows it, a quick call on Teams/Zoom is also possible.

Thank you for your consideration,
Kind regards,
Florian Spitaels

Vytautas Naslenas: Hi Florian,

I will be able to help you out.
If you could send me some questions that you want to cover it would be great.
We could schedule a short call sometime next week?

Florian: Hi Mr Naslenas,

Thank you for your quick reply. Your opinion will help me a lot with my project.

Here is a list of questions I would like to cover on that subject:

1. The most important: I want to introduce a cost section in my thesis and compare the cost of a building printed thanks to your 3D printer and a similar one built thanks to traditional methods.
    a. Is it possible to have an approximative price for a structure similar to your project in Denmark (BOD building) or your project in Belgium (Kamp C)?
    b. What will represent the price if we include the transport and rent costs of the printer?

2. For what case do you think 3D printing in construction is relevant?
3. What are the opportunities and challenges of 3D printing today? And most importantly, tomorrow?
4. Most 3D printers use cement to print buildings. Do you have any other solutions related to the materials used?
5. Finally, what do you think about the future of 3D printing?

I am quite flexible next week. What is your preference for a short call?

Thank you again for your consideration and time,
Kind regards,
Florian Spitaels

Vytautas Naslenas: Hi Florian,

Thank you for your email.

To answer your questions:

1. The BOD building that we did was a little smaller than 50 square meters. The cost for printing the interior and exterior walls (double walls) was 2.000 USD. We unfortunately do not have documented costs of transport and crane usage. Yet a longer open bed truck can be used to transport medium sized BOD2 machines and a crane can be hired for 1 working day or so to assemble the printer on site.
2. It is relevant for most cases where: Access to a skilled labour force is hard, which drives labour cost up. Places where there is a major deficit of dwellings, therefore the need for speedy project execution. Companies in essence are looking to shift from traditional processes to 3D printing as they want to address various issues by using new technology and automation. Yet as the technology itself is quite young, many smaller risk averse companies hesitate approaching it, due to construction market often being quite competitive (= low margins)
3. The biggest technical issue (for us and all of the providers) is material control. As for each region/country/area a different mix may be used, due to weather conditions (temperature, humidity) also the mixture should be adjusted for local materials (as only using local aggregates makes sense).
4. We personally have only worked with cementitious materials. Yet, there are companies exploring green (no/less cement) 3D printable material.
5. The future is quite exciting when thinking about this technology. Large companies are finding it more and more worthy of investing in, companies are starting to see the advantages of this technology. Of course, in the start there is a need for major investments when going into this field, yet the potential is immense in terms of how the technology can alleviate some pains mentioned in nr.2.

Florian, hope these short answers help you.

Florian: Hi Mr Naslenas,

Thank you for all this insightful information for my work. Your answers help me a lot.

I have three more questions about what you explained. I hope you don’t mind.

1. Concerning the costs, do you know what does the 2.000 USD include for the BOD building? The direct material and/or the manufacturing overhead cost? I mean: the cost to print the whole structure of the building and the costs associated (the materials, their supply, energy costs to run the machine, etc.)?
2. What type of cement did you use for the construction of the BOD building/Kamp C building? A special mix? Do you know its composition (not in details)?

3. What impact do you think printing a building like the BOD building instead of building it traditionally have (and will have in the future) on the environment?

Thank you again. I am looking forward to hearing from you when your agenda allows it.

Have a good day,
Kind regards,
Florian

Vytautas Naslenas: Hi Florian,

1. The costs were only for materials used to print the exterior + interior walls for the building. The image below will help to understand it better.

3D printing of The BOD – all parts; exterior and interior walls			
Material	**Quantity [ton]**	Price DKK (1 eur = 7,45 DKK)	Percentages by weight
Cement	6.12 ton	10,374 kr.	32 %
0-2mm sand	3.50 ton	595 kr.	18 %
0-4mm gravel (0-8mm)	3.50 ton	637 kr.	18 %
0-4mm recycled roofing tiles (0-8mm)	4.38 ton	525 kr.	23 %
Water	1.66 ton	62 kr.	9 %
Glenium sky 631 (superplasticizer)	0.04 ton	191 kr.	0 %
Crackstop fibers	0.02 ton	1,038 kr.	0 %
Total	**19.22 ton**	**13.422 kr.**	**100 %** 7

2. In the BOD building we used 3DCP'able concrete as seen above. Kamp C used Weber dry mix mortar material, I think they have mentioned somewhere the exact mix in their press, but cannot find it?
3. With new possibilities for materials (like you can see we included recycled materials as aggregates) will give companies the possibility to incorporate more sustainable materials in the mixtures or even create their own 3D printable/buildable materials which are more green.

Florian: Dear Mr Naslenas,

Thank you for your quick return on these questions.

The chart as well as the information provided by Kamp C make everything clear about the materials.

One of the most important aspects of this research is the future of 3D printing, its impact on the environment and its disruptive aspect. If you ever hear about green materials for 3D printing or other types of "green cement", I will be happy to hear and learn about it.

Thank you again for your help and time.

Kind regards,

Florian Spitaels

Appendix 26

9. Jarett Gross - 20st of July 2021 on LinkedIn

Construction Tech Correspondent covering cutting edge firms in the building industry

Qualitative approach: **e-mails**

Florian: Dear Mr Gross,

I am a business engineering student in Belgium currently writing my master's thesis on 3D printing in the construction sector.

The project manager of Kamp C, Marijke Aerts, has just introduced me to your work and recommended that I send you a message.

I want to show that 3D printers are a solution of the present (and the future) in the construction sector. To do this, I am looking for figures related to construction time and costs in existing projects. Thanks to this data, I would be able to compare it with traditional construction.

I would like to know if you can help me with this topic?

If your agenda allows, a quick call to Teams/Zoom is also possible.

Thank you very much for your consideration,

Kind regards,
Florian Spitaels

Jarett Gross: There isn't transparent cost data available from anyone.

I've heard vague estimates of 20-40% more expensive than traditional construction.
I would be fascinated to know if you find out.
Printed farms told me they'll share a cost analysis with me in the fall so then I'll let you know.

Florian: Thank you for your quick reply Mr Gross.

I have also had estimates and ideas but no certainty about the costs. I will let you know if I receive any information on that subject.

Plus, do you have an idea of the time saved for a 3D printed structure compared to a structure built thanks to traditional methods (for the same dimension)?

Looking forward to receiving news from you about the cost analysis!

Jarett Gross: I'm sure the Kamp C team can tell you that it depends on the exact dimensions, number of corners, windows ect and knowledge of the other method used for comparison

Most projects don't go perfectly so the schedules get delayed and the majority of the regular construction activities take the same time they usually do. Most of the benefits haven't been realized at this stage in the industry growth curve.

Florian: Thank you for your opinion!

If you have any reference or source of information that could make my study a success (for instance, some figures or statistics to support my arguments), I am always interested.

Looking forward to hearing from you and thanks again!

Jarett Gross: Likewise!

Appendix 27

10. Dr. Fabian Meyer-Broetz - 25th of July 2021 on LinkedIn

Head of 3D Construction Printing at PERI AG

Qualitative approach: **e-mails**

Florian: Dear Mr Meyer-Broetz,

I am a business engineering student in Belgium currently doing my final thesis on 3D printers in the construction sector.

A few weeks ago, I had the opportunity to get in contact with the Global Sales Coordinator of COBOD International, Vytautas Naslenas. He introduced me to PERI 3D Construction.

I would like to know if it is possible to receive some information about your 3D printed projects such as the one in Wallenhausen in Bavaria in Germany?

To complete my master's thesis, I would need a cost approximation (total or by square meters) and the time needed to print the whole building. Indeed, I am looking to demonstrate that 3D printers are a solution of the present (and the future).
I am curious to know more about your projects.

If your agenda allows it, a quick call on Teams/Zoom is also possible.

Thank you for your consideration,

Kind regards,
Florian Spitaels

Fabian Meyer-Broetz: Florian,

We generally do not share information on cost and times of client projects. Hence, I unfortunately cannot help you with the information you are looking for. Furthermore, as we are very busy with client projects right now.
The earliest I can make myself available for a call is October. Does this fit into you thesis' timeline?

Best
Fabian

Florian: Dear Mr Meyer-Broetz,

Thank you very much for your quick reply. I fully understand that it is not possible for you to send me this information.

However, does PERI have any answers or "general" information on this topic?
For example:

- Is it generally cheaper or more expensive to 3D print a building compared to traditional methods? In terms of materials and overall cost?
- Do you only use cement-based materials? Or other types of materials as well?
- If you have any written information/references or statistics about 3D printing in construction, to make my thesis a success, I will be more than happy.

Unfortunately, the deadline for my thesis is before October. So, it will not be possible to have a call in October (even though it could be really interesting).

Thank you for your help and consideration,

Kind regards,
Florian Spitaels

Fabian Meyer-Broetz: Florian,

Generally speaking, it will be cheaper to 3D print buildings compared to traditional methods.

A certain learning curve to adapt 3D printing to the respective local buildings methods will be needed however.

We are material-open, meaning we can print with various materials and we have also printed with cement free concrete before.

Best
Fabian

Appendix 28 - Interview guide on 3D printing in the construction industry

1. **Introduction to the subject and presentation of the structure of the interview**

2. **Personal information**
    a. Present yourself
    b. Present your company/job and position

3. **Interest in 3D printing and disruptive technologies**
    a. What do you think of disruptive technologies?
    b. What do you know about 3D printing? In the construction industry?
    c. Do you know any existing use cases or future projects? Which ones?

4. **Opportunities and challenges faced by 3D printing in the construction industry**
    a. What are the advantages and disadvantages to using 3D printing compared to more traditional methods?
    b. What is the impact on the business model and the supply chain?

5. **Environmental aspect**
    a. What is the impact on the environment?
    b. Have you heard of materials other than cement used in 3D printing in the construction industry? With a lower impact on the environment?

6. **Related costs and duration of construction**
    a. Is it more expensive or cheaper to build a structure thanks to 3D printing? Compared to more traditional methods? Why?
    b. What about the building duration for a construction printed in 3D and the same built thanks to more conventional methods?

7. **3D printing and disruption**
    a. How disruptive do you think 3D printing is in the construction sector?
        i. From a reglementary/legal point of view?
        ii. From a social and ethical point of view?

8. **Future of 3D printing in construction**
    a. According to you, what is the future of 3D printing?
    b. Is there a market or an opportunity?

9. **Conclusion of the interview**

***Appendix 29* - Online survey "3D-Printing in construction" - for the players of the construction industry only**

Question n°	Link	Question asked	Type of variable	Possible answers
		3D-Printing - Your thoughts		
Q1	Moderator variable	Have you already heard about 3D-printing in the construction industry?	Multiple choice (one answer)	● Yes, I am involved in it ● Yes, thanks to my colleagues/clients/company ● Yes, in the press ● No, only for small objects in polymers ● No, never
Q2	Moderator variable	Have you heard of practical projects? If yes, what and where? (if no, do not answer)	*Open Question*	*Open Question*
Q3	Perceived development	(TECHNOLOGY) Where do you think 3D-printing is positioned in the innovation cycle?	Multiple choice (one answer)	● 1. Idea ● 2. Feasibility ● 3. Testing ● 4. Pilot Project ● 5. Deployment ● 6. Assess & Refine ● 7. Scale & Mainstream
Q4	Perceived position	(YOUR POSITION) Where do you think you stand concerning 3D-printing?	Multiple choice (one answer)	● 1. Innovators ● 2. Early adopters ● 3. Early majority ● 4. Late majority ● 5. Laggards
Q5	Perceived	For what reason would you opt for 3D-printing?	Multiple choice	● Use of materials on site

	value	(multiple answers allowed)	(one or more answer(s))	● Less time-consuming ● Less materials needed for a same construction (less losses) ● Less working force needed = better productivity ● Ability to build creative construction without extra costs (e.g. curved walls) ● Ability to give several specificities (hybrid) to the construction (e.g. acoustic isolation, thermic isolation, aesthetic, etc.) ● To further develop the technology ● Build similar buildings in a shorter time
		Technical aspect		
Q6	Perceived usefulness	For what type of construction would you be interested to use 3D-printers in your activities? (multiple answers allowed)	Multiple choice (one or more answer(s))	● Houses and buildings ● Civil engineering (pedestrian bridges, gateway, etc.) ● Specific parts of buildings (that are unique) ● Water structures (canal, swimming pool, etc.) ● Blocks of houses (e.g. social housing)
Q7	Perceived challenge's importance and perceived cost	Please choose among the options the one that best matches your opinion for every question below: - To what extent does the size of the machine matter to you? - To what extent does the price of the machine matter to you?	Multiple choice (one answer)	● Not important at all. ● Negligible small impact. ● Undecided. ● Take into consideration. ● Really important.

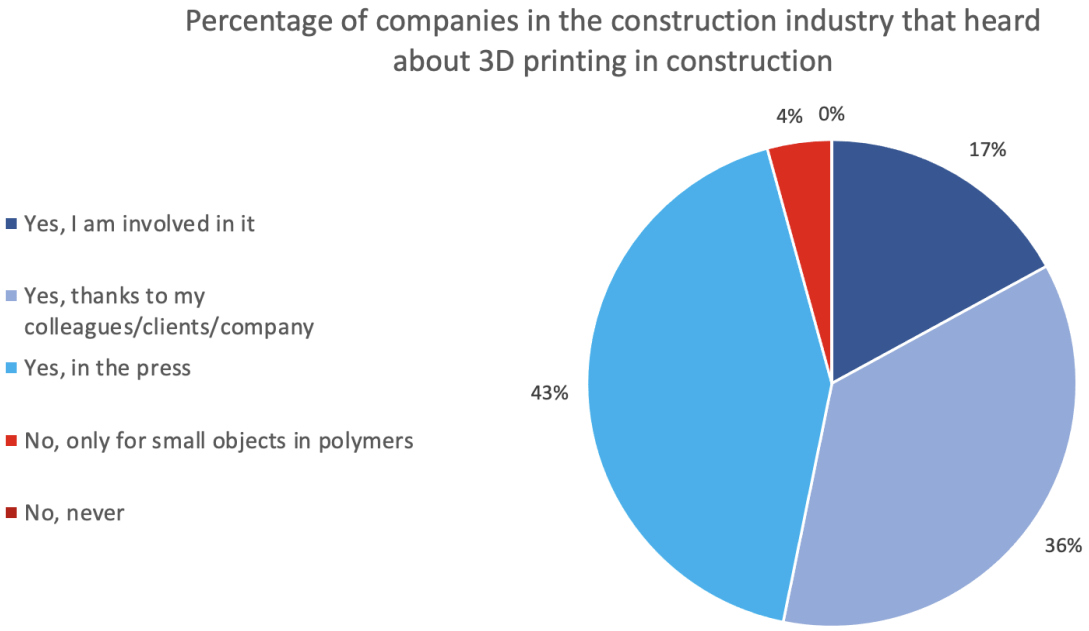
Q8	Perceived usefulness	To what extent are you interested to build more creative structures? - Curved walls - Specific structural parts (e.g. Notre Dame de Paris) - Hybrid construction (one wall = multiple features) - Topology optimization (build a structure with no excess of material)	Multiple choice (one answer)	● Not interested at all. ● Not very interested. ● Undecided. ● Interested. ● Very interested.
		Costs and price		
Q9	Perceived value and cost	For your organisation, you think there is a real Return On Investment if you invest in-3D printers.	Linear scale (between 1 and 5)	1 - Strongly disagree 5 - Strongly agree
Q10	Perceived value and cost	Give a case in which your company would benefit from 3D-printers (if any):	*Open Question*	*Open Question*
		3D-Printers = a "disruptive" technology		
Q11	Perceived social impact	In the years to come, how do you rate the impact on the job market?	Linear scale (between 1 and 5)	1 - Very bad, lots of unemployment 5 - Very good, new jobs on the way
Q12	Perceived impact	What negative impact could 3D-printing have in the future?	*Open Question*	*Open Question*
Q13	Perceived legal impact	Do we need more regulations towards 3D-printing?	Linear scale (between 1 and 5)	1 - Needs to be highly regulated 5 - More freedom for new technologies

Q14	Perceived legal impact	If yes, what kind of rules or laws should be implemented? (otherwise, do not answer)	*Open Question*	*Open Question*
		Impact on the environment - A green solution?		
Q15	Perceived environmental impact	3D-printers will have a green positive impact on your activities.	Linear scale (between 1 and 5)	1 - Strongly disagree 5 - Strongly agree
Q16	Perceived environmental impact	Justify, for what reason?	*Open Question*	*Open Question*
		The Future?		
Q17	Perceived outcome	Where do you see 3D-printing in the construction sector in the next 5 to 10 years?	Linear scale (between 1 and 5)	1 - Nowhere 5 - It needs to be implemented on a larger scale
Q18	Perceived value	On a scale from 1 to 10, how do you rate the benefit 3D-printers can have on your activities TODAY?	Linear scale (between 1 and 10)	1 - It is only a current trend 10 - Very beneficial, it is a must
Q19	Perceived outcome	On a scale from 1 to 10, how do you rate the benefit 3D-printers could have on your activities TOMORROW?	Linear scale (between 1 and 10)	1- We will forget about 3D-printing 10 - 3D-printing is the future
Q20	Adoption intention	Are you willing to adopt this technology in your organisation in the near future?	Multiple choice (one answer)	● I have already implemented 3D technologies in my activities ● Yes, in the 5 years to come ● Yes, in the 10 years to come ● No, I do not see the added value

		Conclusion		
Q21	?	Do you have any suggestion or recommendation to make this thesis a success? If yes, what?	*Open Question*	*Open Question*
		Some informations about you		
Q22	Moderator variable	Where are you located?	Multiple choice (one answer)	• Belgium • France • Germany • Luxembourg • Netherlands • Switzerland
Q23	Moderator variable	Private or Public sector?	Multiple choice (one answer)	• Private • Public
Q24	Moderator variable	Your sector of activity?	Multiple choice (one answer)	• Construction (general contracting) • Building engineering office • Architects • Real Estate • Technology, telecommunications
Q25	Moderator variable	The number of employees within your organisation?	Multiple choice (one answer)	• 0-10 • 10-50 • 50-1000 • >1000

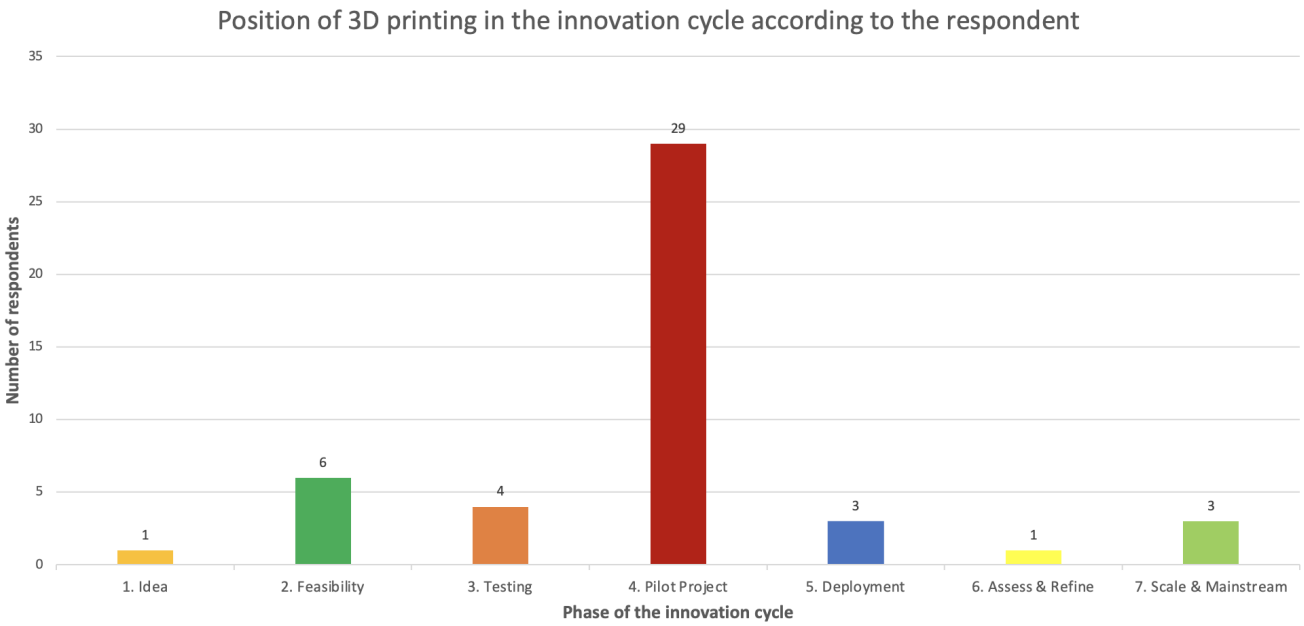
Appendix 30 - Graphs derived from online survey responses on "3D-Printing in construction" - from the construction industry only

Q1

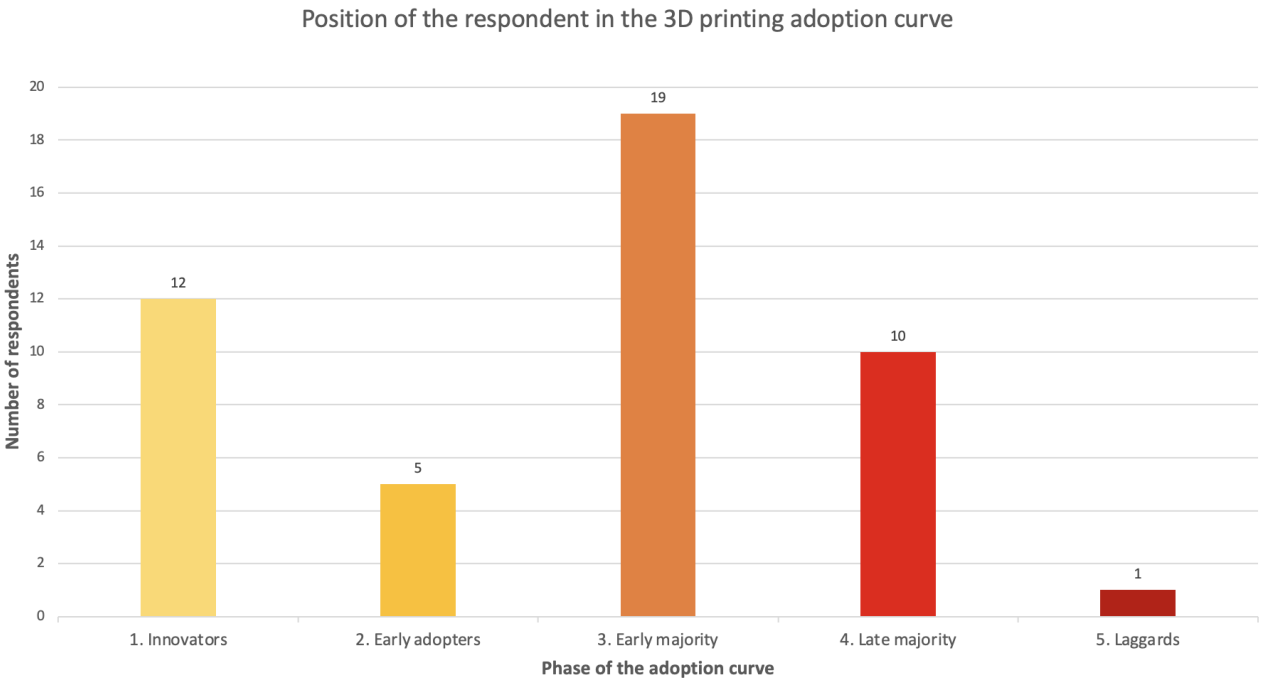


Q2 *Open Question*

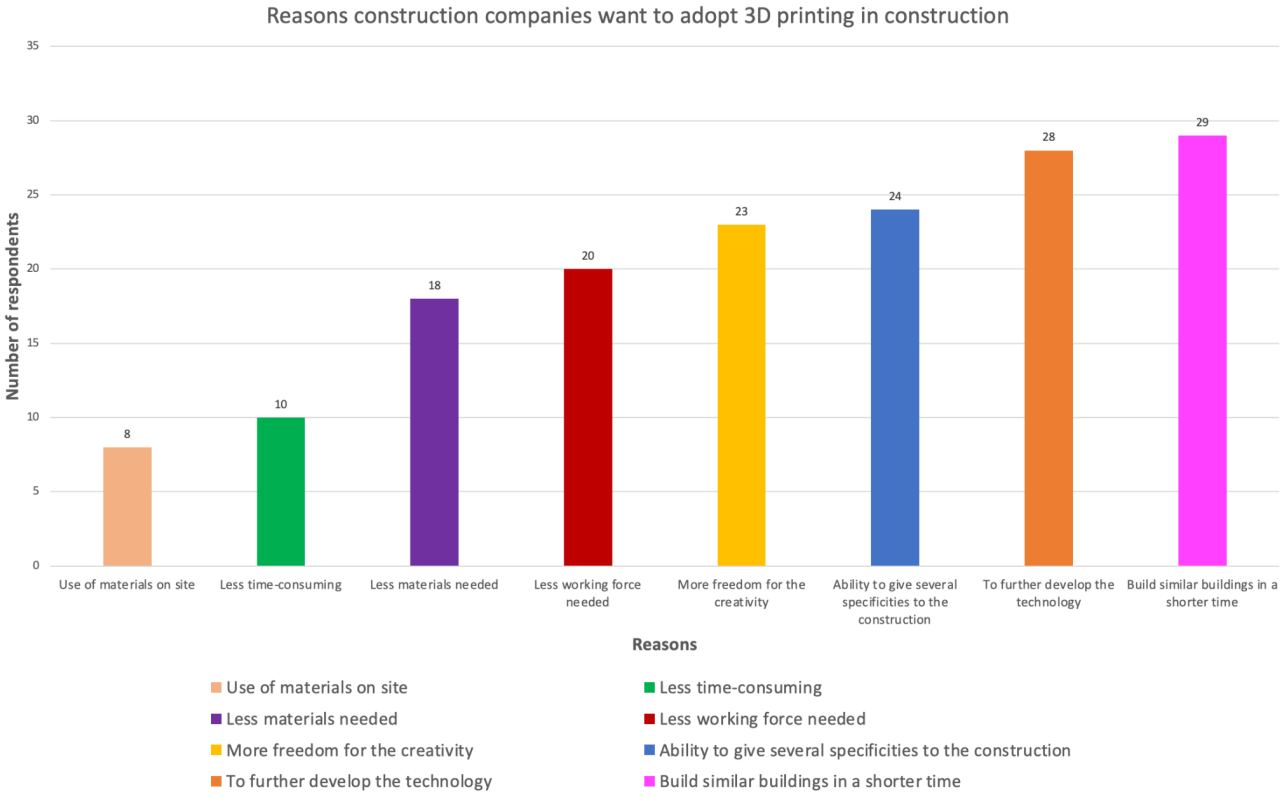
Q3



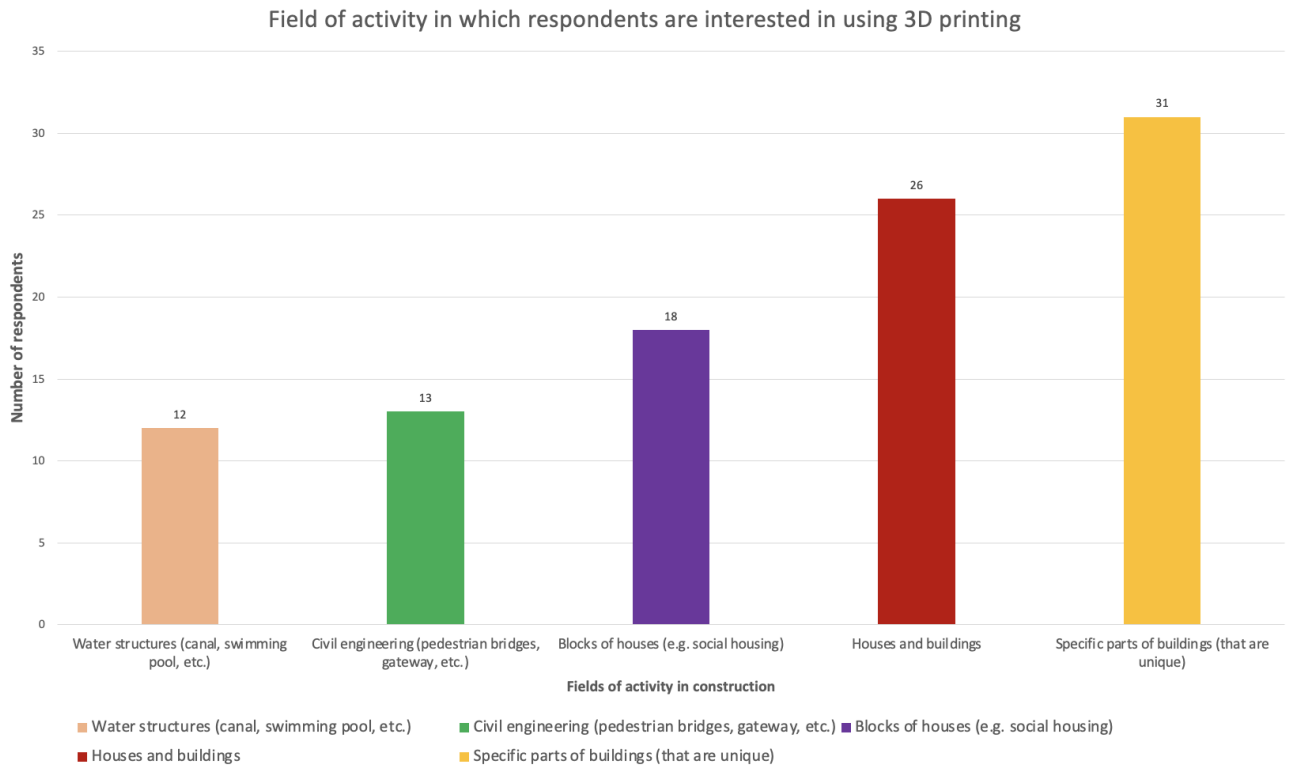
Q4


Position of the respondent in the 3D printing adoption curve
Number of respondents
20
18
16
14
12
10
8
6
4
2
0
12
5
19
10
1
1. Innovators
2. Early adopters
3. Early majority
4. Late majority
5. Laggards
Phase of the adoption curve

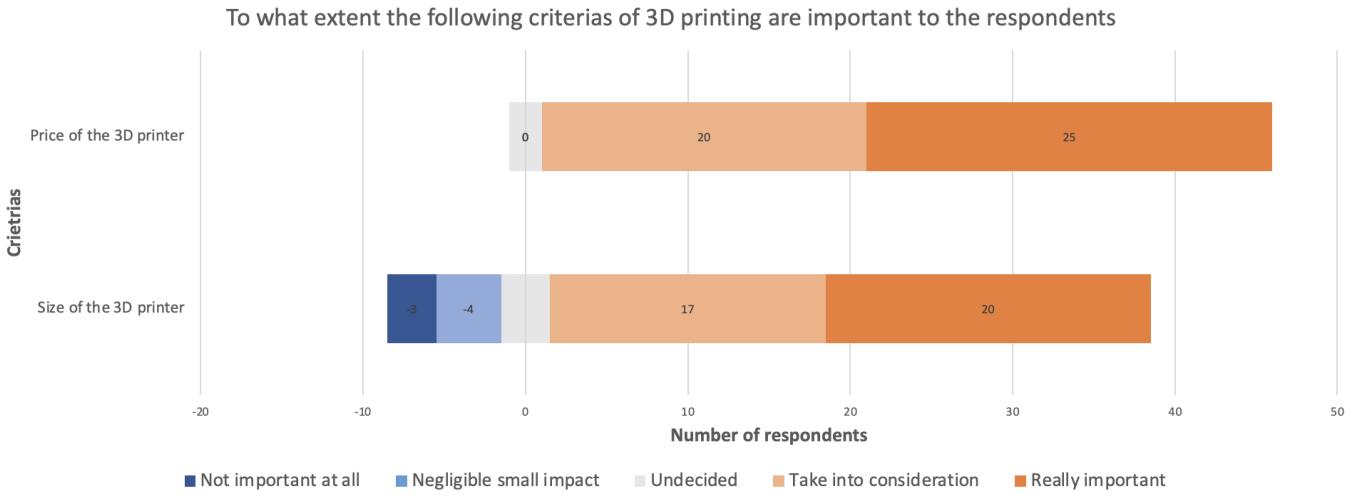
Q5


Reasons construction companies want to adopt 3D printing in construction
Number of respondents
35
30
25
20
15
10
5
0
8
10
18
20
23
24
28
29
Use of materials on site
Less time-consuming
Less materials needed
Less working force needed
More freedom for the creativity
Ability to give several specificities to the construction
To further develop the technology
Build similar buildings in a shorter time
Reasons
Use of materials on site
Less time-consuming
Less materials needed
Less working force needed
More freedom for the creativity
Ability to give several specificities to the construction
To further develop the technology
Build similar buildings in a shorter time

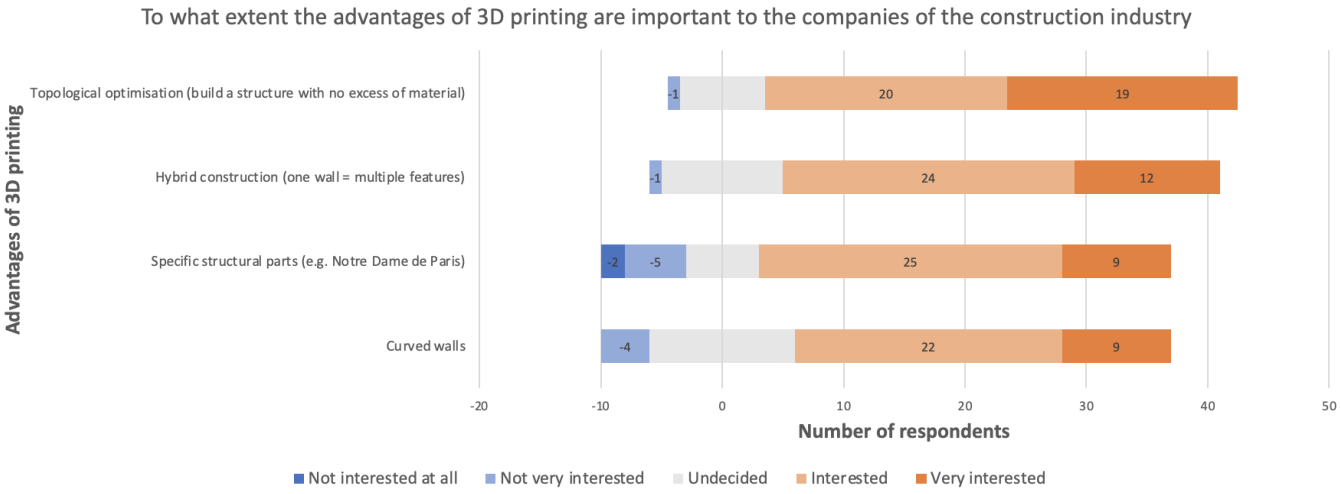
Q6


Field of activity in which respondents are interested in using 3D printing
Number of respondents
35
30
25
20
15
10
5
0
12
13
18
26
31
Water structures (canal, swimming pool, etc.)
Civil engineering (pedestrian bridges, gateway, etc.)
Blocks of houses (e.g. social housing)
Houses and buildings
Specific parts of buildings (that are unique)
Fields of activity in construction
Water structures (canal, swimming pool, etc.)
Civil engineering (pedestrian bridges, gateway, etc.)
Blocks of houses (e.g. social housing)
Houses and buildings
Specific parts of buildings (that are unique)

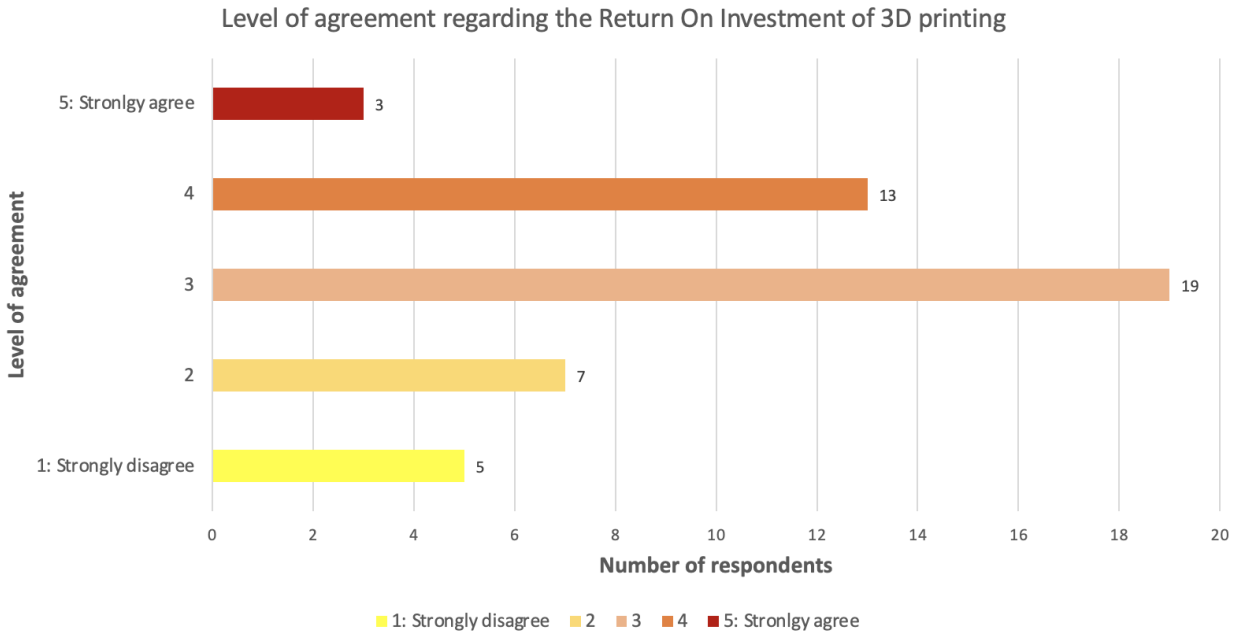
Q7


To what extent the following criterias of 3D printing are important to the respondents
Crietrias
Price of the 3D printer
Size of the 3D printer
0
20
25
-3
-4
17
20
-20
-10
0
10
20
30
40
50
Number of respondents
Not important at all
Negligible small impact
Undecided
Take into consideration
Really important

Q8

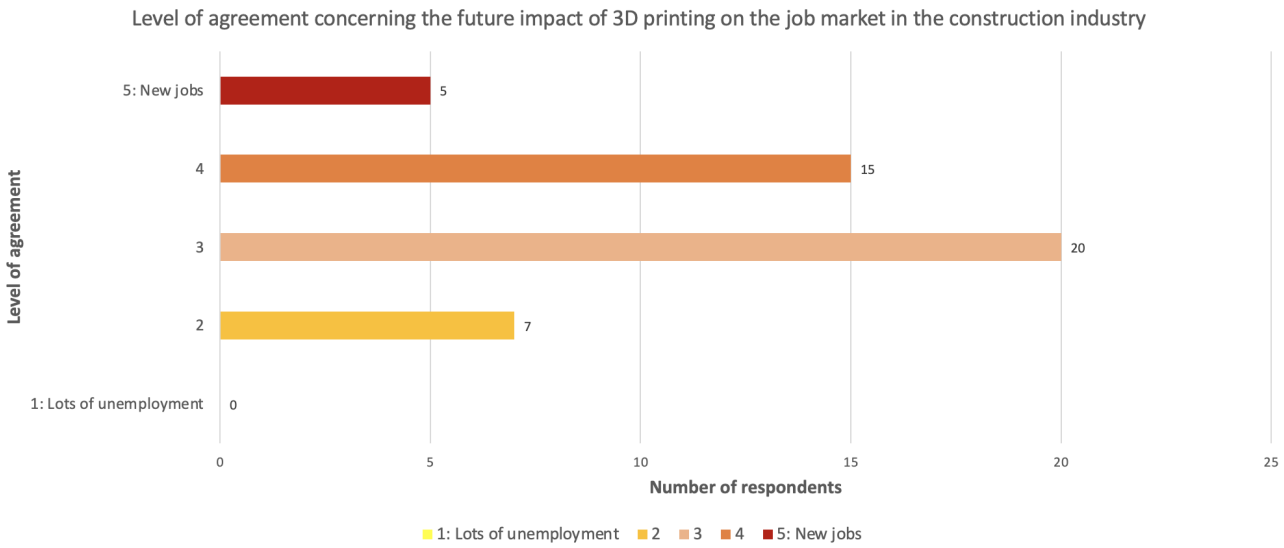


Q9



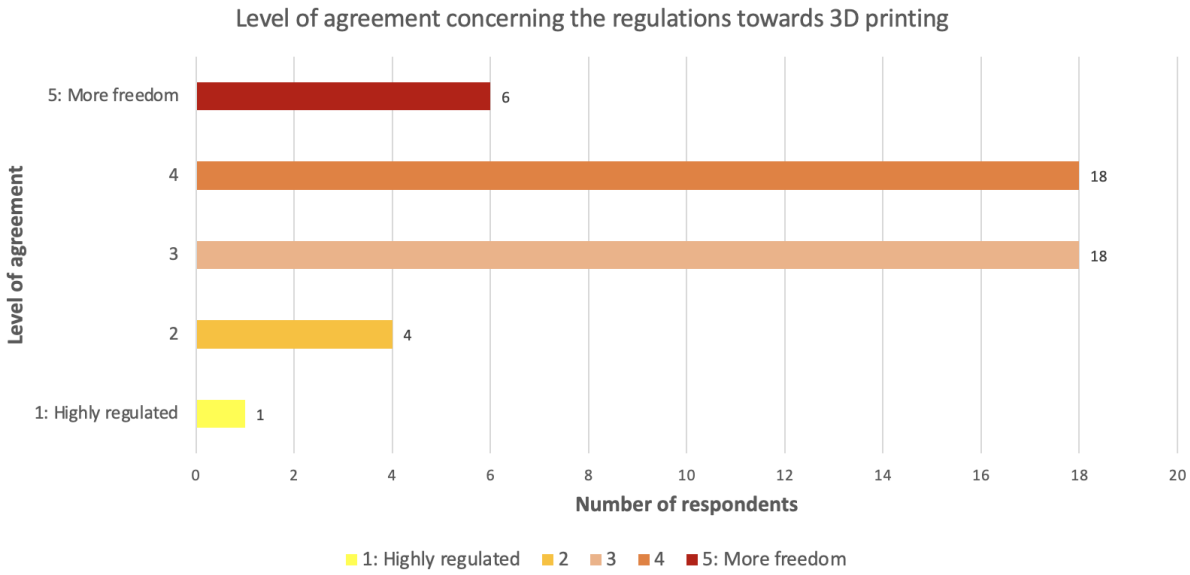
Q10 *Open Question*

Q11



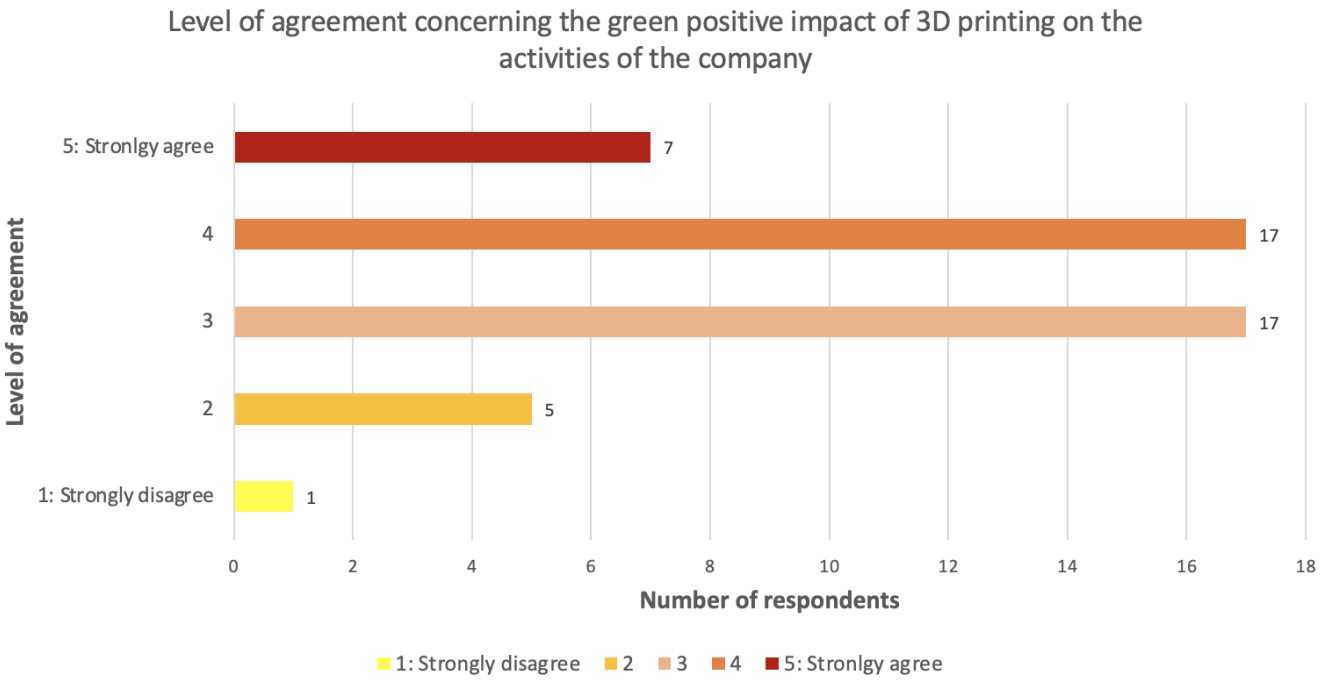
Q12 *Open Question*

Q13



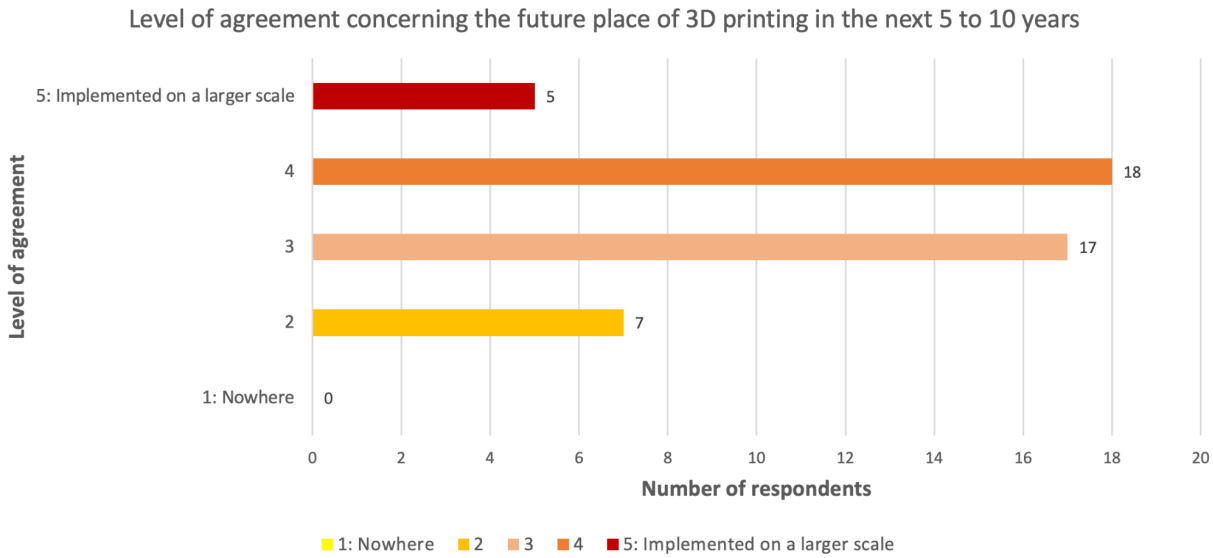
Q14 *Open Question*

Q15

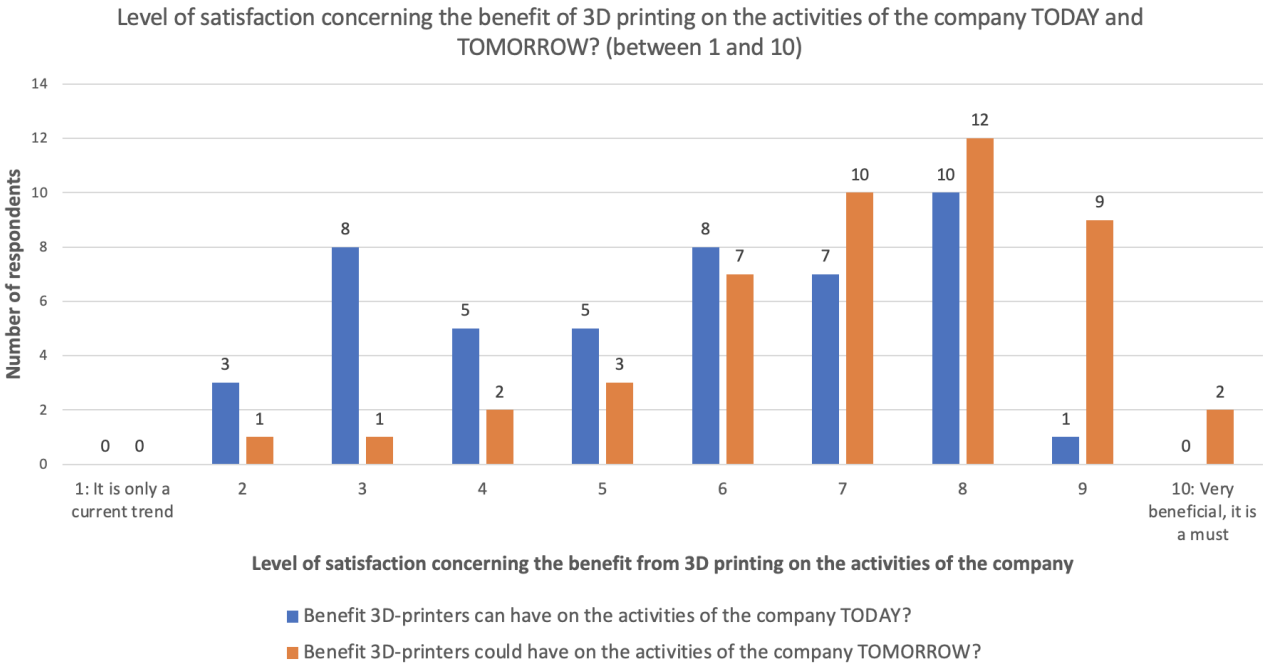


Q16 *Open Question*

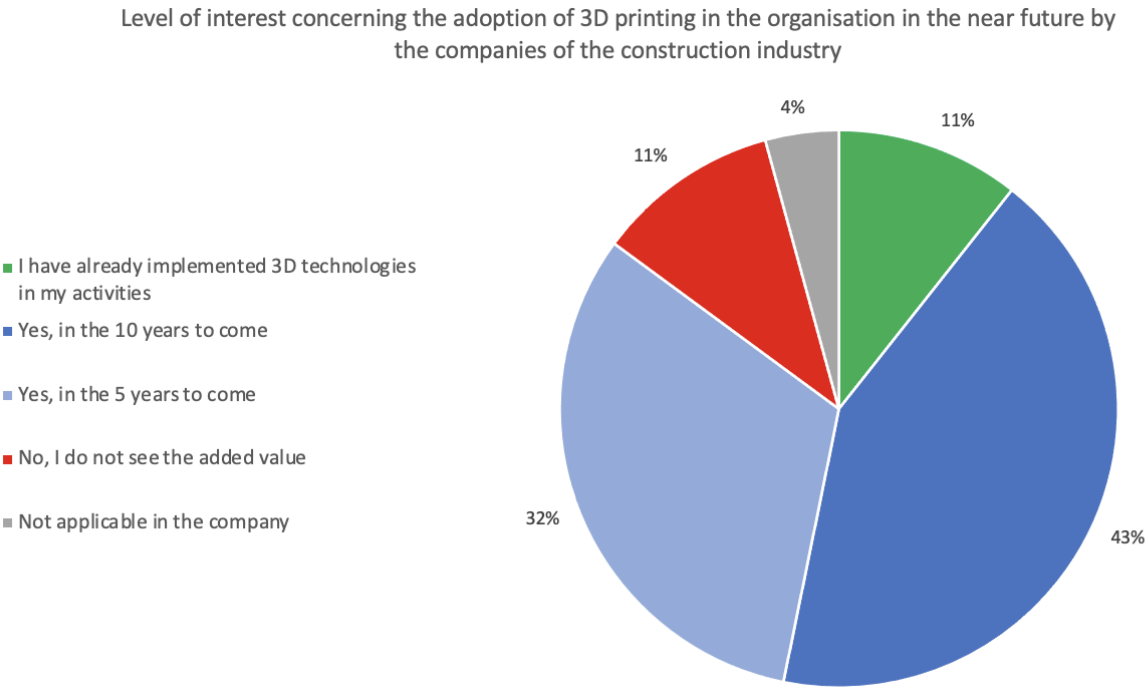
Q17



Q18-19



Q20

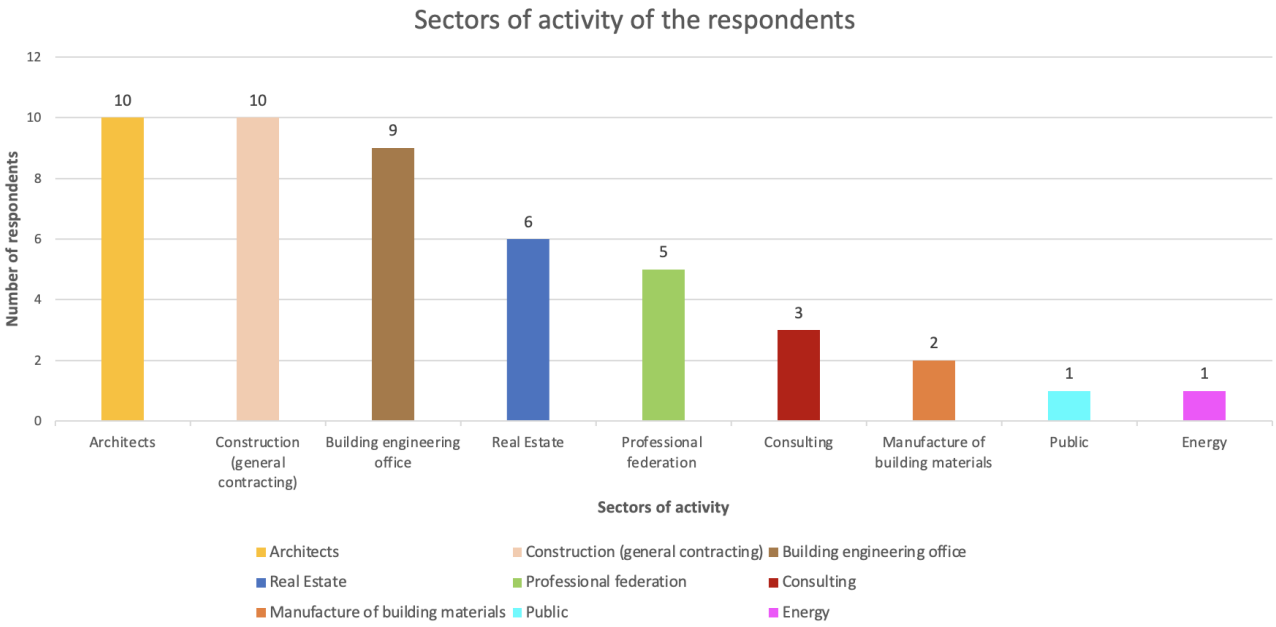


Q21 *Open Question*

Q22 *Personal question about the respondent (location)*

Q23 *Personal question about the respondent (private or public sector of activity)*

Q24 *Personal question about the respondent (sector of activity)*



Q25 *Personal question about the respondent (size of the organisation)*

Appendix 31 **- Online survey "3D-Printing in construction" - regardless of the industry**

Question n°	Link	Question asked	Type of variable	Possible answers
		3D-Printing - Your thoughts		
Q1	Moderator variable	Have you already heard about 3D-printing?	Multiple choice (one answer)	● Yes ● No
Q2	Actual use	Do you own a 3D-printer?	Multiple choice (one answer)	● Yes ● No
Q3	Actual use	Is 3D-printing implemented in your sector of activity today? To what extent is it implemented?	Multiple choice (one answer)	● Not implemented at all ● There are some discussions on 3D-printing ● 3D-printing has been accepted but not implemented on a large scale ● 3D-printing is implemented on a large scale ● I don't know/I am not part of an organisation
Q4	Moderator variable	Have you heard about 3D-printing in the construction industry?	Multiple choice (one answer)	● Yes, I am already interested or involved in it. ● Yes, thanks to my colleagues/company. ● Yes, in the press/media. ● No, only 3D-printing for small objects in polymers. ● No, never.

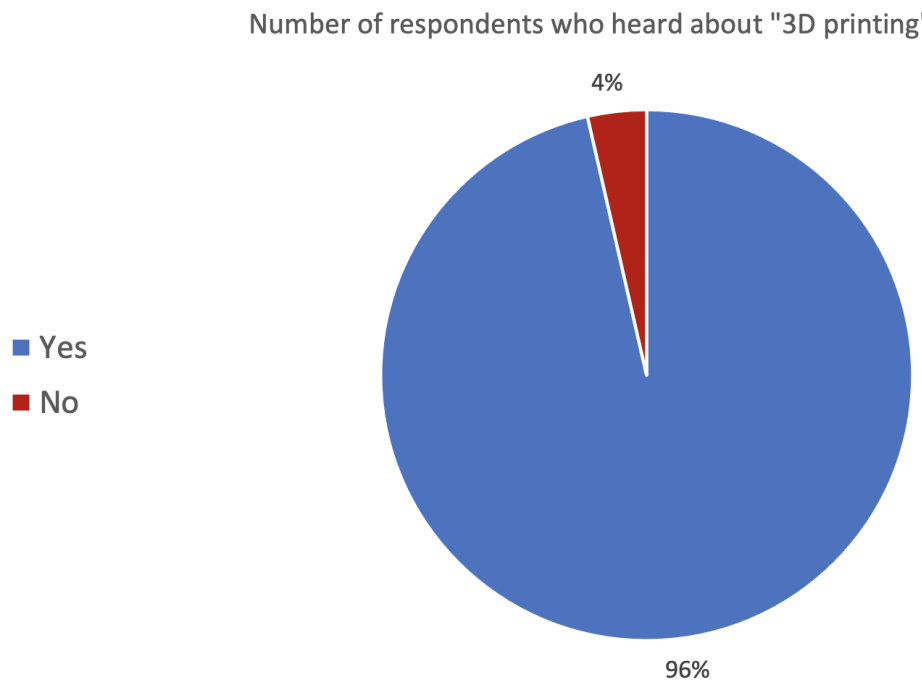
		Technical aspect related to the construction sector		
Q5	Perceived value	3D-printing presents some added values compared to buildings built traditionally. To what extent these added values are important to you? - Shorter construction process - Plus de personnalisation et de liberté de conception (murs incurvés, etc.) - More sustainable (less materials needed = less waste) - Better acoustic and thermal resistance - Use of new technologies = being a precursor	Multiple choice (one answer)	● Not important at all ● No special interest ● Undecided ● Interesting ● Really important
Q6	Intention to use	Based on the added values above, to what extent are you interested to build or live in a 3D-printed house?	Linear scale (between 1 and 5)	1 - Not interested at all 5 - Very interested
		Costs and price		
Q7	Perceived cost	According to you, what is the price of a 3D-printed building compared to one built traditionally?	Multiple choice (one answer)	● A lot cheaper ● Cheaper ● Same price ● More expensive ● A lot more expensive
		3D-Printers = a "disruptive" technology		
Q8	Perceived market acceptation	From a human and consumer perspective, 3D-printed products and buildings will be accepted by the market (private consumers).	Linear scale (between 1 and 5)	1 - Strongly disagree 5 - Strongly agree

		Impact on the environment - A green solution?		
Q9	Perceived environmental impact	The ecological footprint is an important factor to you when renting/buying/building a house or apartment.	Linear scale (between 1 and 5)	1 - Strongly disagree 5 - Strongly agree
Q10	Perceived environmental impact	The use of 3D-printers (for all purposes) will have a green positive impact in the future.	Linear scale (between 1 and 5)	1 - Strongly disagree 5 - Strongly agree
Q11	Perceived environmental impact	Justify, for what reason? (if any)	*Open Question*	*Open Question*
		The Future?		
Q12	Perceived market impact	In what sector does 3D-printing will have a significant positive impact tomorrow? (multiple answers allowed)	Multiple choice (one or more answer(s))	● Construction & Real estate ● Medical & Health ● Engineering & Aerospace ● Automotive ● Energy ● Consumer goods & Retail ● IT & Electronics
		Some information about you		
Q13	Moderator variable	What is your age?	Multiple choice (one answer)	● -18 ● 18-34 ● 35-49 ● 50-65 ● +65

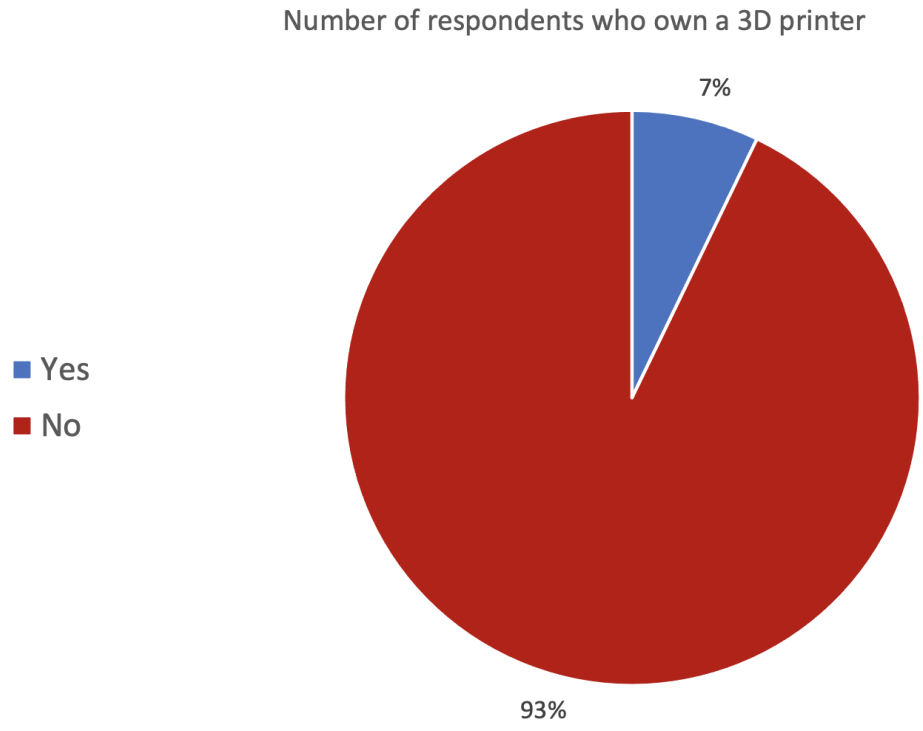
Q14	Moderator variable	Where are you living?	Multiple choice (one answer)	• Belgium • France • Germany • Luxembourg • Netherlands • Switzerland
Q15	Moderator variable	What is your sector of activity?	Multiple choice (one answer)	• Construction & Real estate • Medical & Health • Communication • Public sector • Administration & Politics • Consumer goods & Retail • Energy • Automotive • Horeca • Engineer & Aerospace • Education • Financial services • Consulting • IT • Unemployed • Student

***Appendix 32* - Graphs derived from online survey responses on "3D-Printing in construction" - regardless of the industry**

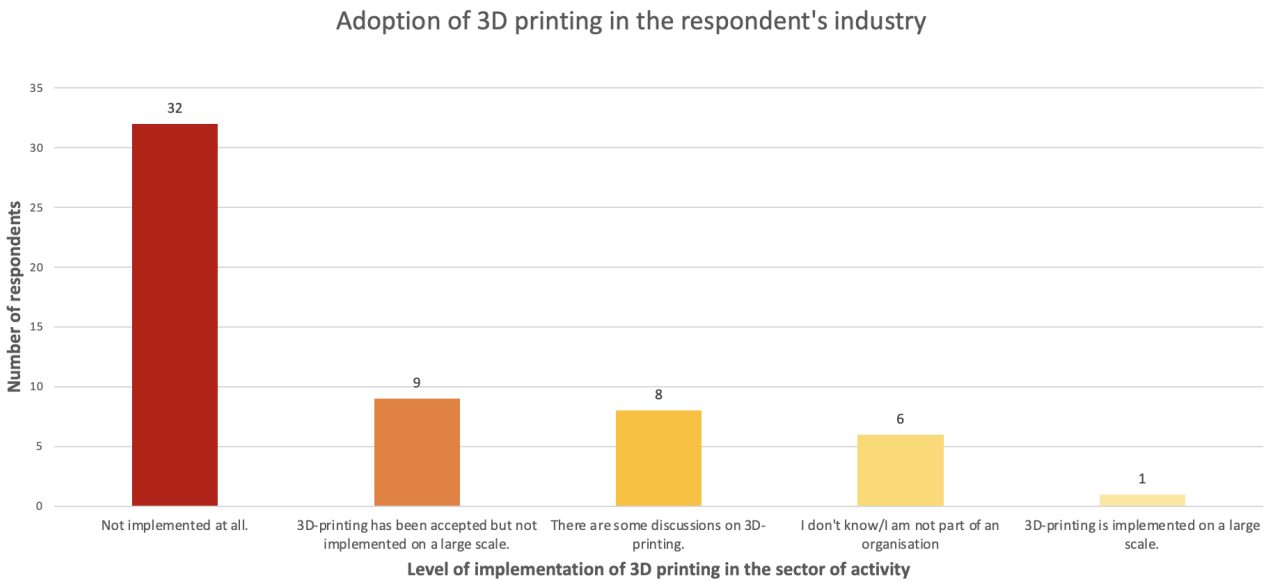
Q1



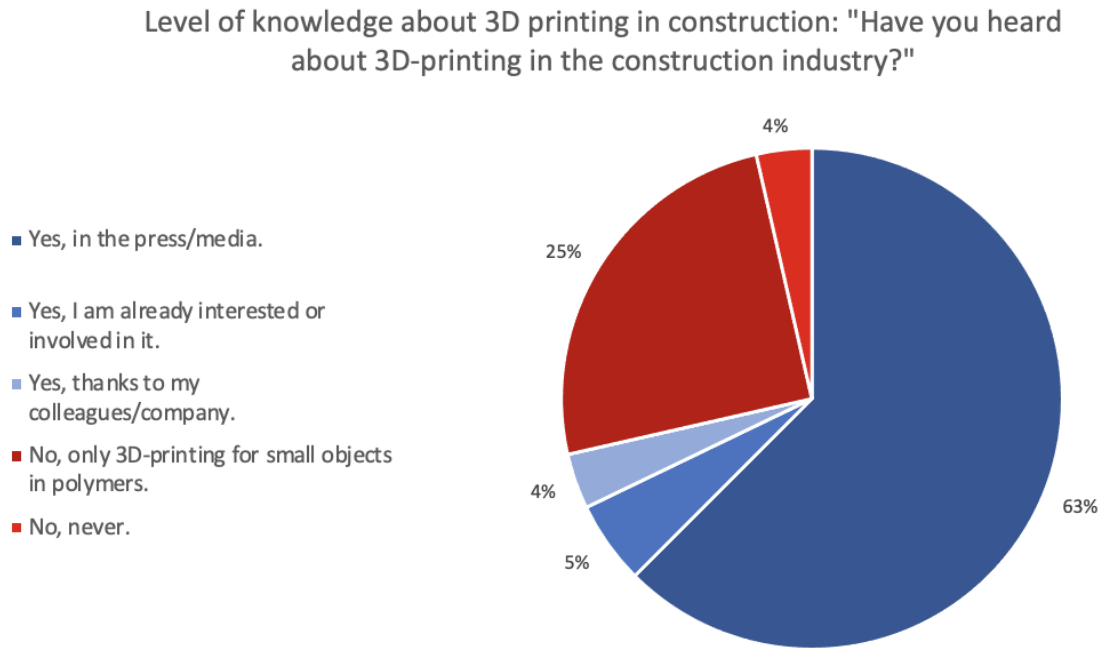
Q2



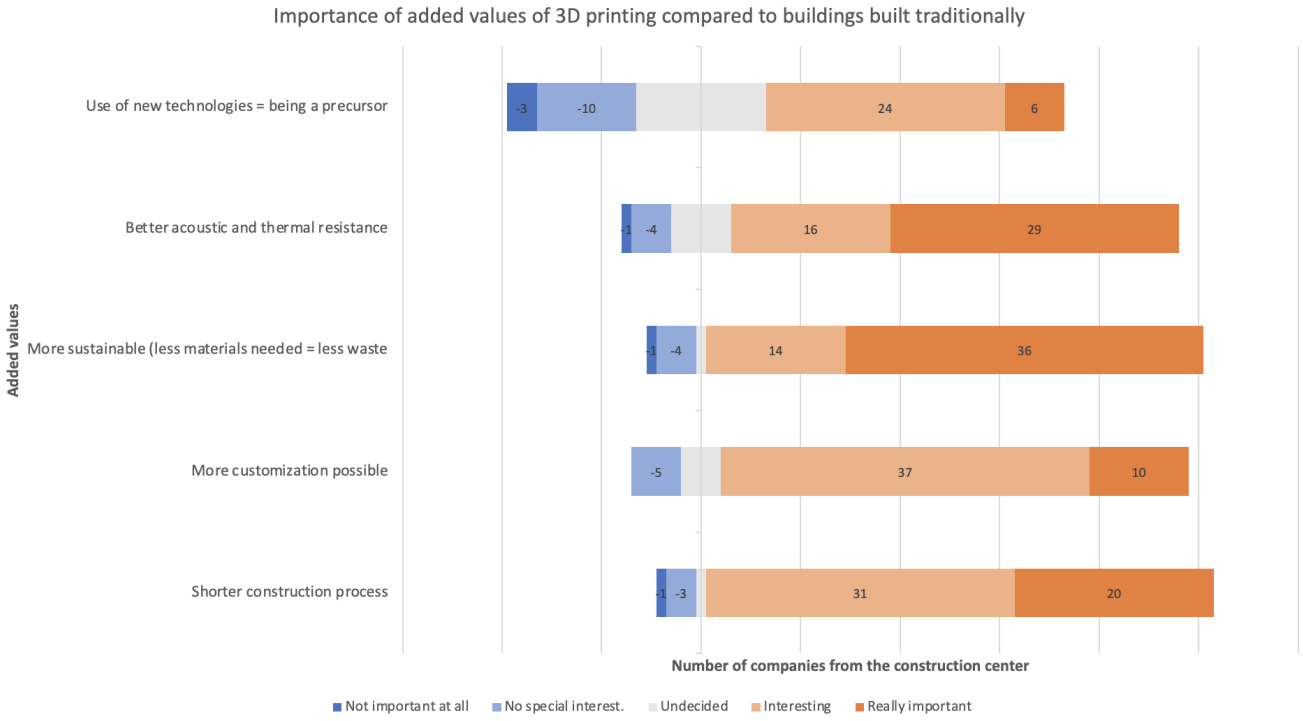
Q3


Adoption of 3D printing in the respondent's industry
Number of respondents
35
30
25
20
15
10
5
0
32
9
8
6
1
Not implemented at all.
3D-printing has been accepted but not implemented on a large scale.
There are some discussions on 3D-printing.
I don't know/I am not part of an organisation
3D-printing is implemented on a large scale.
Level of implementation of 3D printing in the sector of activity

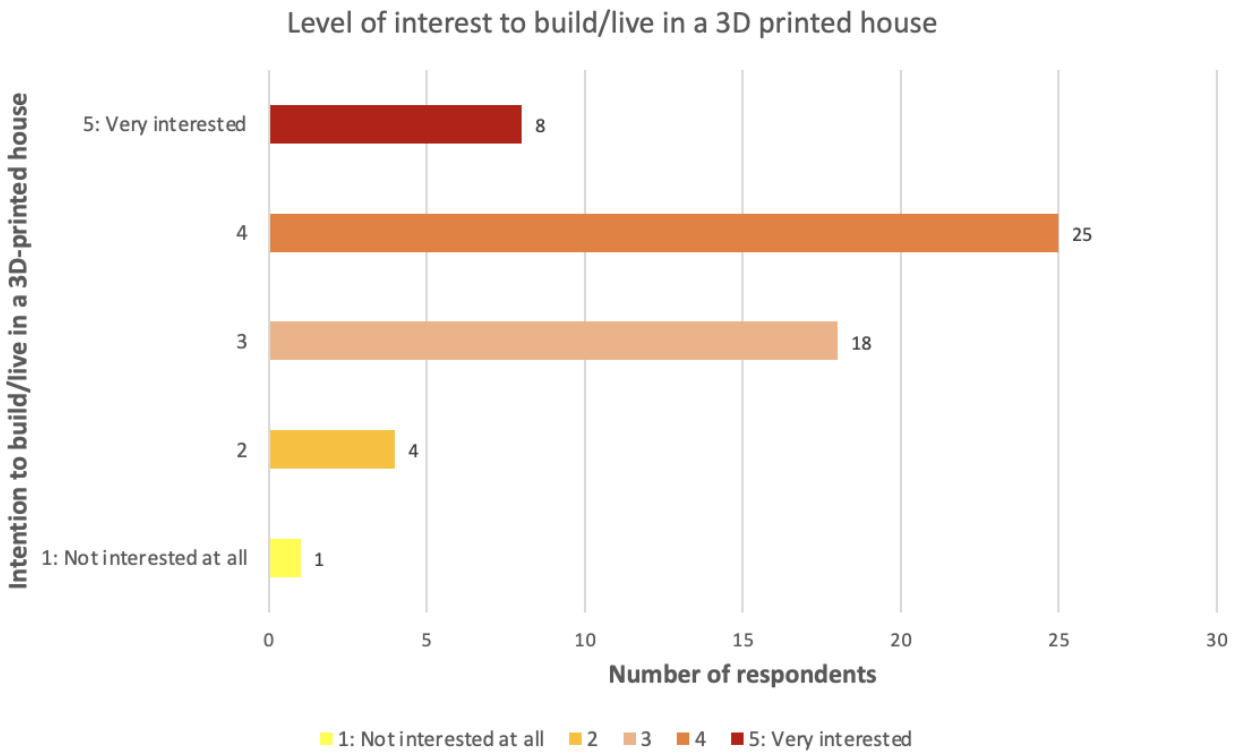
Q4


Level of knowledge about 3D printing in construction: "Have you heard about 3D-printing in the construction industry?"
Yes, in the press/media.
Yes, I am already interested or involved in it.
Yes, thanks to my colleagues/company.
No, only 3D-printing for small objects in polymers.
No, never.
4%
25%
4%
5%
63%

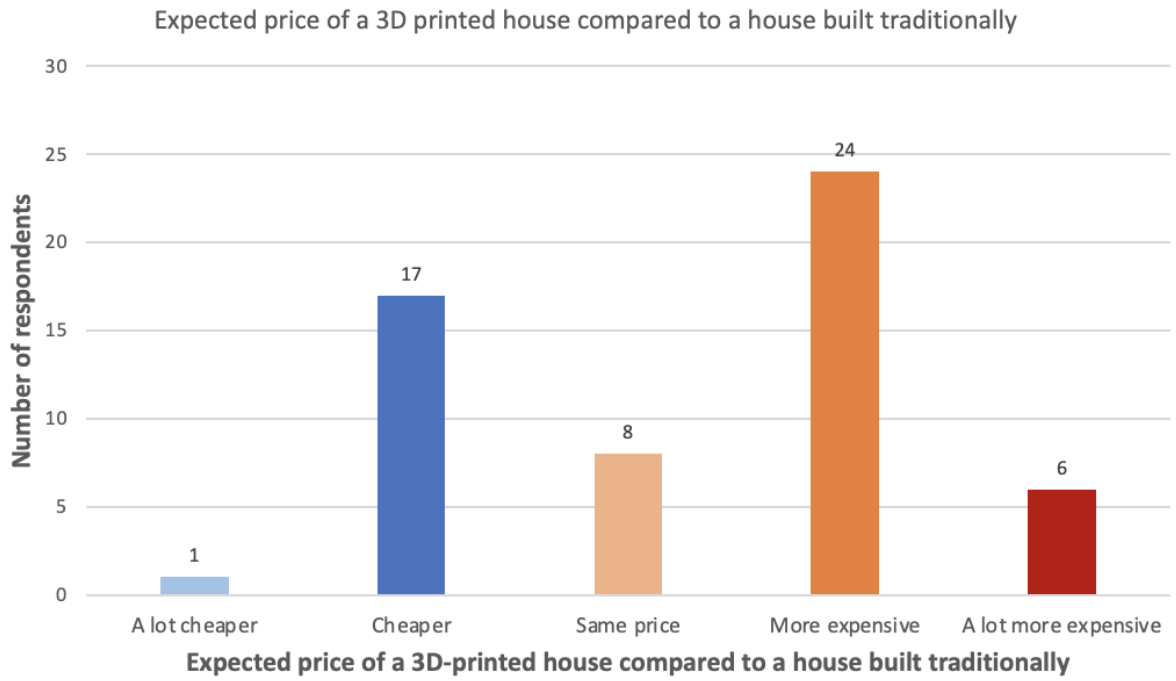
Q5


Importance of added values of 3D printing compared to buildings built traditionally
Added values
Use of new technologies = being a precursor
Better acoustic and thermal resistance
More sustainable (less materials needed = less waste
More customization possible
Shorter construction process
-3
-10
24
6
-1
-4
16
29
-1
-4
14
36
-5
37
10
-1
-3
31
20
Number of companies from the construction center
Not important at all
No special interest.
Undecided
Interesting
Really important

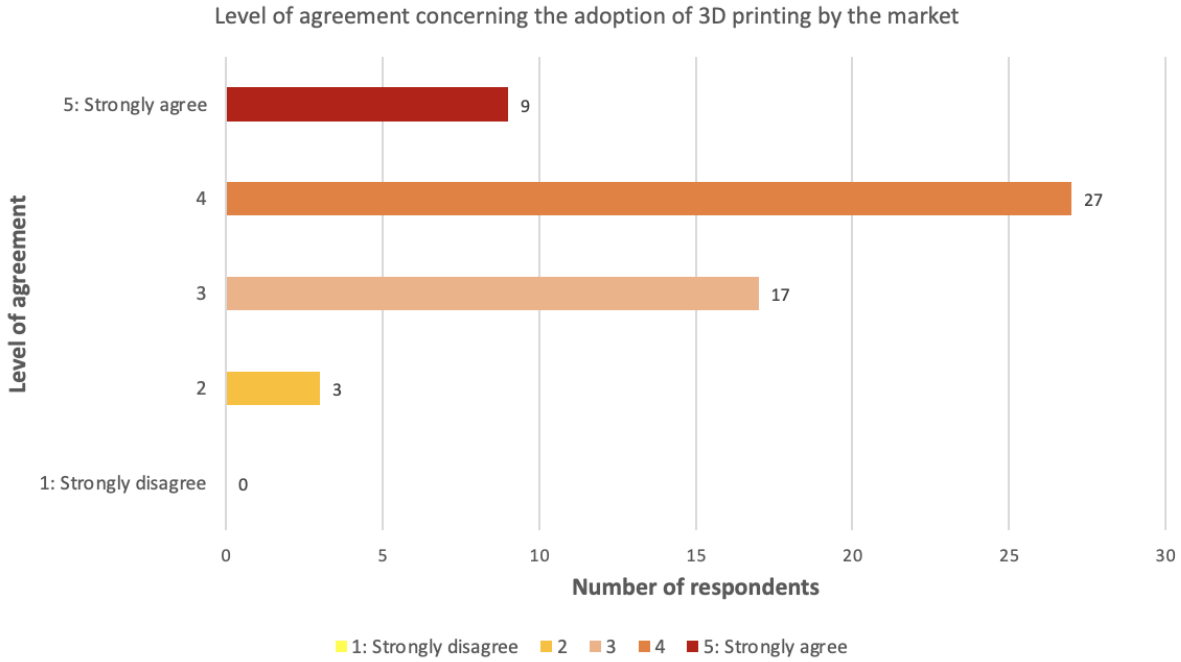
Q6


Level of interest to build/live in a 3D printed house
Intention to build/live in a 3D-printed house
5: Very interested
4
3
2
1: Not interested at all
8
25
18
4
1
0
5
10
15
20
25
30
Number of respondents
1: Not interested at all
2
3
4
5: Very interested

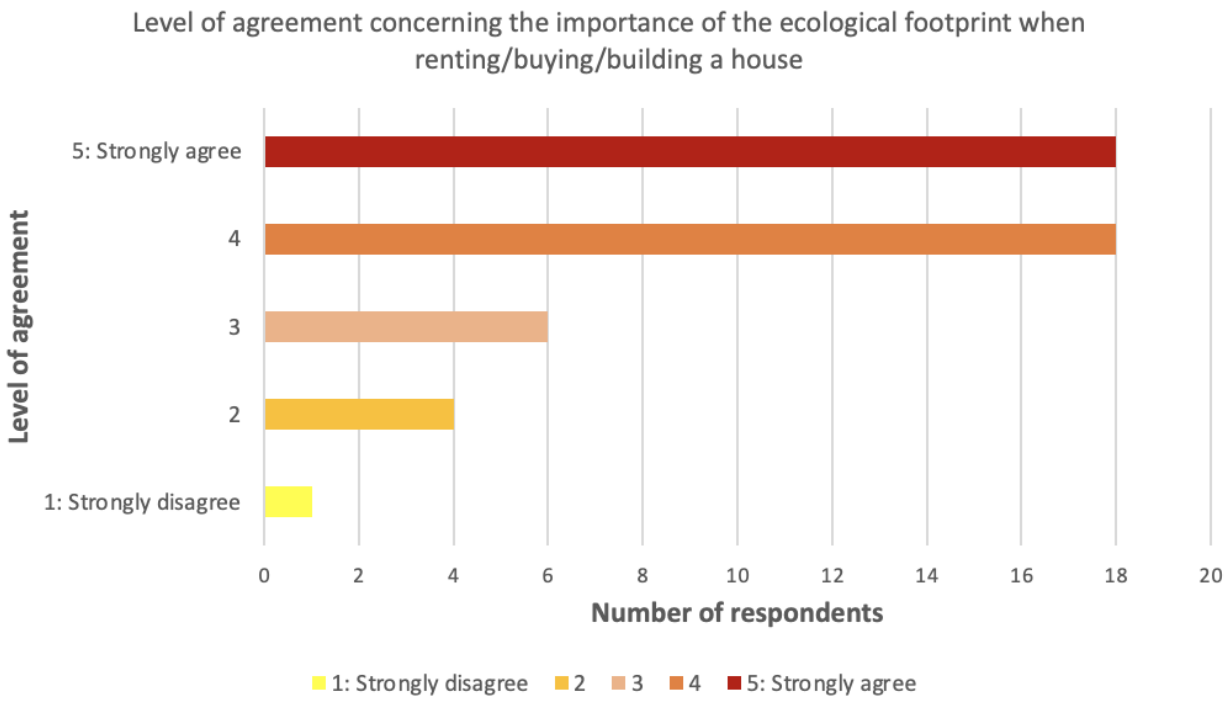
Q7


Expected price of a 3D printed house compared to a house built traditionally
Number of respondents
30
25
20
15
10
5
0
1
17
8
24
6
A lot cheaper
Cheaper
Same price
More expensive
A lot more expensive
Expected price of a 3D-printed house compared to a house built traditionally

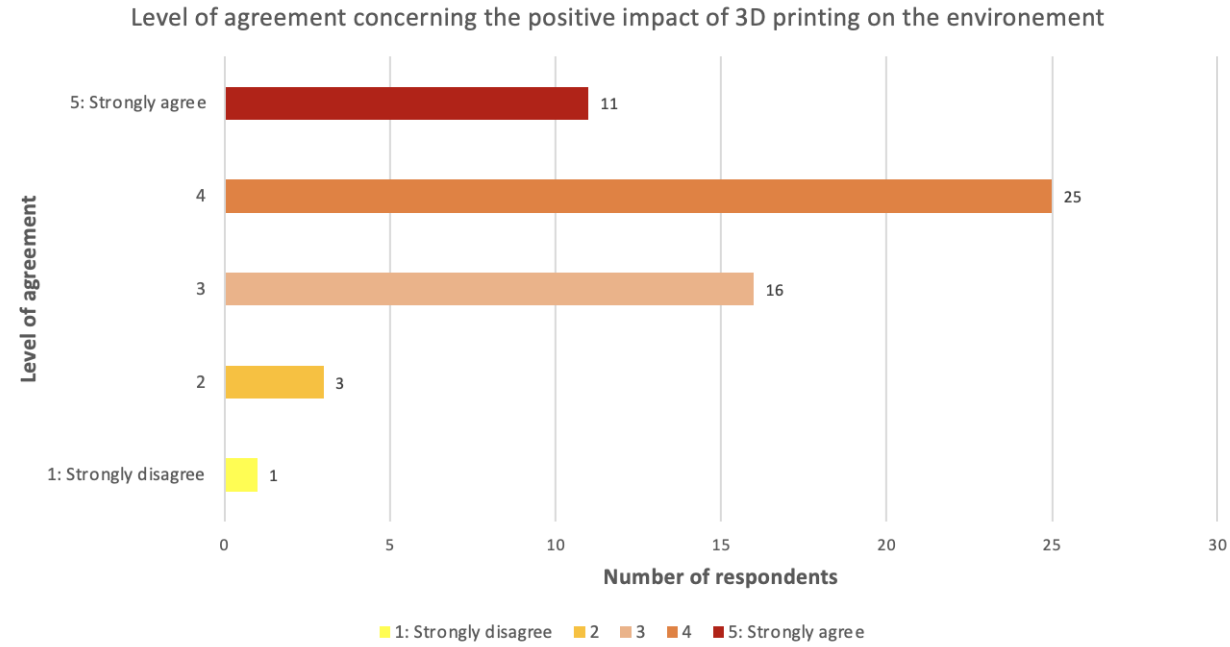
Q8


Level of agreement concerning the adoption of 3D printing by the market
Level of agreement
5: Strongly agree
4
3
2
1: Strongly disagree
9
27
17
3
0
0
5
10
15
20
25
30
Number of respondents
1: Strongly disagree
2
3
4
5: Strongly agree

Q9

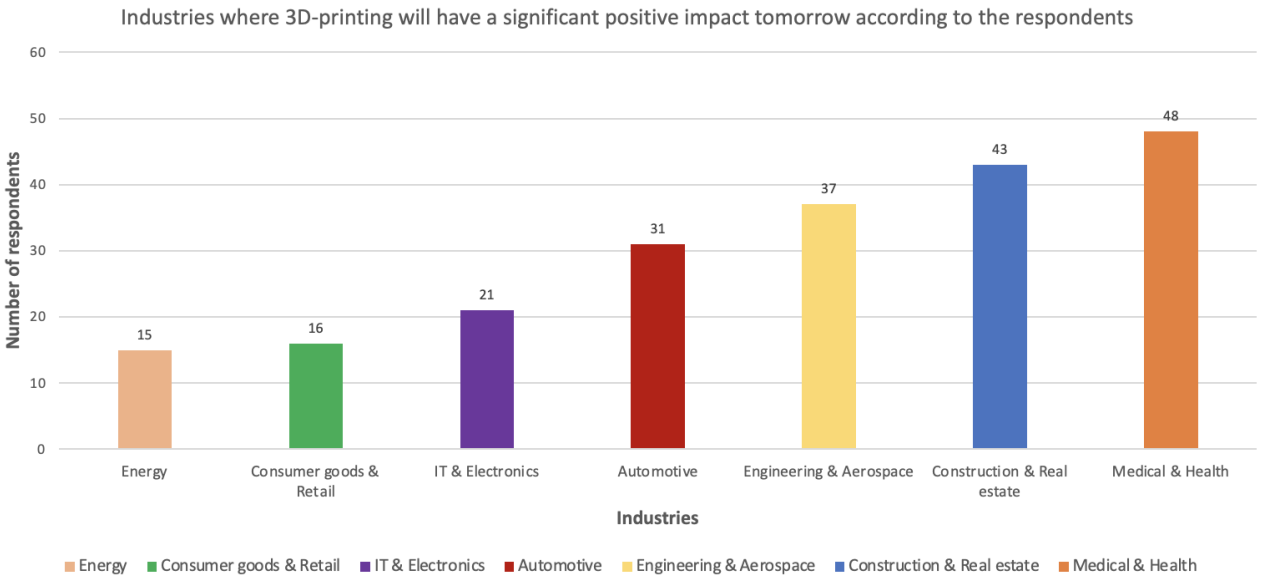


Q10



Q11 *Open question*

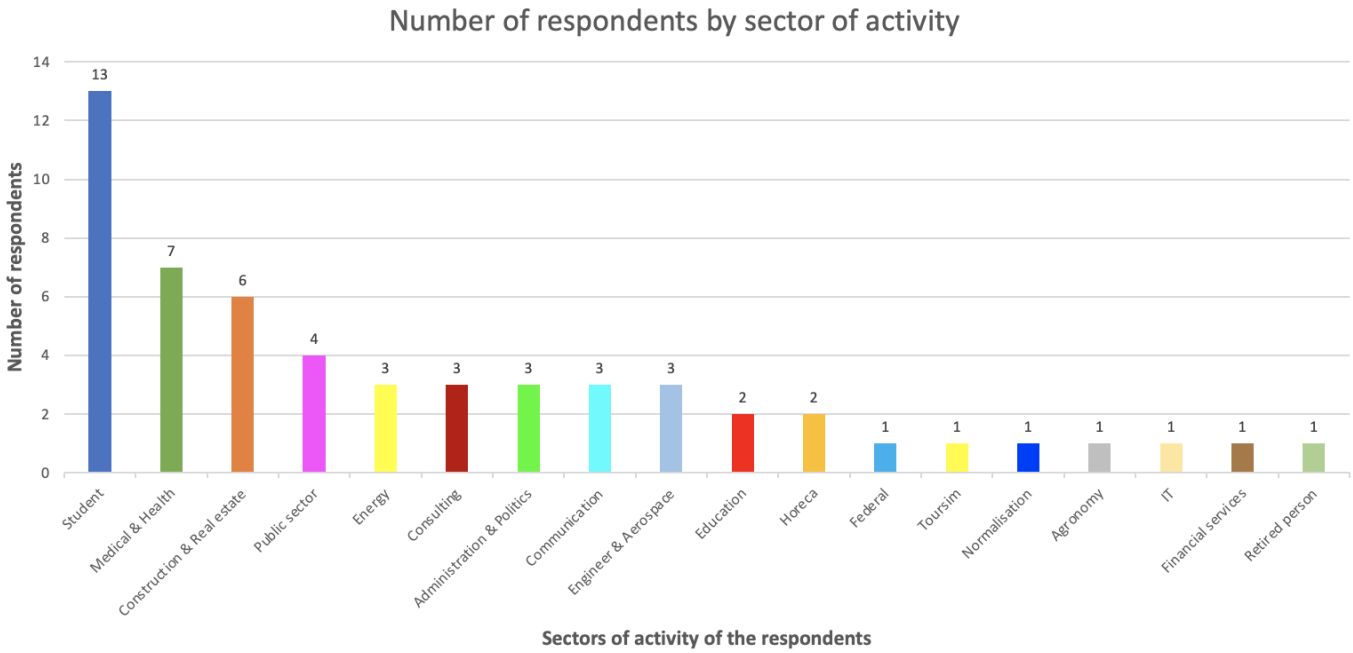
Q12



Q13 *Personal question about the respondent (age)*

Q14 *Personal question about the respondent (location)*

Q15 *Personal question about the respondent (sector of activity)*



3D printing began to revolutionise the market in the late 1980s. Since, 3D printers have evolved and have progressively made their way to various disciplines such as aerospace, medicine, or construction. However, it is only recently that entry-level models, more affordable and accurate, have made their appearance on the market. Their introduction has rapidly gained a lot of success and has emphasized the development of the Do-It-Yourself approaches.

In recent years, the need to automate the construction process for structures and buildings has been constantly propelled by the lack of innovation in the building processes, which has remained almost entirely based on manual labour for years. As a result, organisations around the world have demonstrated a keen interest in 3D printing projects in the construction industry. Compared to traditional methods, the use of 3D printers has revealed social, economic, technical, and environmental benefits and opens the possibility of building structures layer by layer from digital data.

This master's thesis presents a holistic approach to 3D printing technology and its applications in the construction sector through extensive literature review. In recent years, the technology has shown potential in a wide range of fields: the building industry being a new exciting and growing area for 3D printing. This technique can create the opportunity for customisation of large-scale projects since it removes the restrictions of shape in the traditional ways of building.

However, there are still many unsolved issues related to the 3D technological innovation in this sector. One of them is its disruptive aspect on the market, the human being, the regulation, and the environment. Therefore, the purpose of this thesis is to better understand whether 3D printing technologies will have a sustainable future in the construction industry. A content analysis on the state of the art of 3D technologies in construction and interviews with industry experts were conducted to identify their potentially disruptive impact on the market. A questionnaire survey was also adopted to complete the data collection and collect professional's and market's opinions on the use of the technology.

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