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PROJECT MANAGEMENT

ANALYSIS OF CRITICAL SUCCESS FACTORS IN MANAGING CONSTRUCTION PROJECTS UTILIZING 3D PRINTING TECHNOLOGY

ANALIZA KRITIČNIH DEJAVNIKOV USPEHA PRI UPRAVLJANJU GRADBENIH PROJEKTOV Z UPORABO TEHNOLOGIJE 3D TISKANJA

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ABSTRACT

The adoption of 3D printing technology in construction projects has the potential to deliver many advantages, such as reduced on-site labour, more reliable management of project deadlines and budgets, as well as more effective waste management. Nevertheless, the technology's growth is not as dynamic as anticipated due to a lack of standardized processes and methodologies, and challenges associated with the novel technology.

Understanding the benefits of 3D printing projects for prospective investors when choosing a construction method requires standardization of project activities and an in-depth comprehension of the factors that make projects using this technology successful or unsuccessful. This thesis identified the challenges of obtaining a building permit for a 3D printing projects, determining roles and responsibilities of key participants in such projects, and defining the following critical success factors: 1) Relative advantage, 2) Complexity, 3) Trialability, 4) Compatibility, 5) Absorptive capacity, 6) External pressure, 7) Uncertainty, 8) Supply-side benefits and 9) Demand-side benefits. The importance of these factors, together with other contributing issues (legislative and ethical issues) was demonstrated through 11 case studies divided into 4 stages of empirical research.

3D printing technology projects were confirmed to contribute to be objectives of "Construction 5.0", a paradigm that combines the achievements of Construction 4.0 with sustainable development, resilience and human welfare goals. Therefore, 3D printing projects are a viable solution to some of the pervasive problems of the construction sector as well as a solution to the contemporary environmental sustainability problems.

Based on evidence collected from the case studies, it was concluded that 3D printing technology has a specific effect on the roles and responsibilities of stakeholders in construction projects. The key adjustment concerns the role of the project manager, who must acquire and implement new skills, expand his/her competencies, and consider adopting new organizational solutions to accommodate the requirements of this new technology.

Keywords: Construction Project Management, 3D Printing Technology, Critical Success Factors, "Construction 5.0".

IZVLEČEK

Uporaba tehnologije 3D tiskanja v gradbenih projektih lahko prinese številne prednosti, kot so manj dela na samem gradbišču, bolj zanesljivo upravljanje z roki in proračunom na projektih ter učinkovitejše ravnanje z odpadki. Kljub temu pa razširjenost tehnologije ni takšna kot pričakovano, predvsem zaradi pomanjkanja standardiziranih procesov in metodologij ter izzivov, povezanih z uporabo nove tehnologije.

Za razumevanje prednosti projektov 3D tiskanja za potencialne investitorje, kot alternativna izbira načina gradnje, sta potrebni standardizacija projektnih dejavnosti in poglobljeno razumevanje dejavnikov, zaradi katerih so projekti z uporabo te tehnologije uspešni ali neuspešni. V pričujoči doktorski nalogi so bili opredeljeni izzivi pri pridobivanju gradbenega dovoljenja za projekte 3D-tiskanja, določitvi vlog in odgovornosti ključnih deležnikov v takšnih projektih ter opredelitvi naslednjih kritičnih dejavnikov uspeha: 1) Relativna prednost, 2) Kompleksnost, 3) Možnost preizkušanja, 4) Združljivost, 5) Absorpcijska sposobnost, 6) Zunanji pritiski, 7) Negotovost, 8) Koristi na strani ponudbe in 9) Koristi na strani povpraševanja. Pomen teh dejavnikov, je bil skupaj z drugimi obravnavanimi vprašanji (zakonodajna in etična vprašanja), prikazan s pomočjo 11 študij primerov, razdeljenih v 4 faze empirične raziskave.

Potrjeno je bilo, da projekti s tehnologijo 3D-tiskanja prispevajo k ciljem "Gradbeništva 5.0", to je k paradigmi, ki združuje dosežke Gradbeništva 4.0 s cilji trajnostnega razvoja, odpornostjo in blaginjo ljudi. Zato so projekti 3D-tiskanja realna rešitev za nekatere vseprisotne probleme gradbenega sektorja in tudi rešitev sodobnih problemov trajnostnega okoljevarstva.

Na podlagi dokazov, zbranih v študijah primerov, je bilo ugotovljeno, da ima tehnologija 3D tiskanja poseben učinek na vloge in odgovornosti deležnikov v gradbenih projektih. Ključna prilagoditev zadeva vlogo projektnega vodje, ki mora pridobiti in uporabljati nova znanja, kot tudi razširiti svoje kompetence in spodbuditi k sprejemanju novih rešitev v organizaciji, da bi se lahko le-ta prilagodila zahtevam te nove tehnologije.

Ključne besede: upravljanje gradbenih projektov, tehnologija 3D tiskanja, kritični dejavniki uspeha, “Gradbeništvo 5.0“.

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LIST OF ABBREVIATIONS

3DP - 3D Printing

AC - Absorptive Capacity

AEC Industry - Architecture, Engineering and Construction Industry

AIM - Absolute Innovation Management (AIM)

AM - Additive Manufacturing

AMoC – Additive Manufacturing of Concrete

BGB - German Civil Code

BIM - Building Information Modelling

BM - Business Manager

CAD - Computer-Aided Design

CAM - Computer-aided manufacturing

CC - Contour Crafting

CDM Regulations - Construction (Design and Management) Regulations

CDW – Construction and Demolition Waste

CICA – Confederation of International Contractors' Associations

CMSII - Construction method selection, implementation, and improvement

C&D - Construction and Demolition

CP - Compatibility

CS – Case Study

CS - Increased Construction Safety

CS1 - Reduce Biological Hazards

CS2 - Reduce Chemical Hazards

CS3 - Reduce Ergonomic Hazards

CS4 - Reduce Psychosocial Hazards

CS5 - Reduce Physical Hazards

CS6 - Reduce Mental Fatigue of Workers

CSFs - Critical success factors

CT - Contingency Theory

CTI - Increased Compatibility (Technology)

CT1 - Compatibility with IoT

CT2 - Compatibility with Big Data

CT3 - Compatibility with BIM

CT4 - Compatibility with Cloud Computing

CT5 - Compatibility with Artificial Intelligence

CX – Complexity

DS - Demand-Side Benefits

ES - Increased Environmental Sustainability

RE - Increased Resilience

EP - External Pressure

ES1 - Reducing CO2 Emissions

ES2 - Reducing Carbon Footprint

ES3 - Reducing Energy Consumption

ES4 - Reducing Water Use

ES5 - Reduce Construction Time

ES6 - Waste Generation Reduction

ES7 - Using Local Materials

FM Industry - Facility Management Industry

GDP - Gross Domestic Product

IDT - Innovation Diffusion Theory

IR - Number of industrial robots

ISO - International Organization for Standardization

KPIs - Industry's Key Performance Indicators

MES - Modern Manufacturing Execution System

MRQ – Main Research Question

PEOU - Perceived Ease of Use

PM - Project Manager

PM^2 - Project Management Methodology developed by the European Commission

PMBOK - Project Management Body of Knowledge

PU - Perceived Usefulness

RA - Relative Advantage

RE1 - Resilience for natural hazards

RE2 - Resilience by Cyber Security Challenges and Vulnerability

RE3 - Robustness

RE4 – Resourcefulness

RE5 – Rapid Recovery

RE6 - Redundancy

RM - Rapid Manufacturing

SCM - Construction Supply Chain Management

SCT - Social Cognitive Theory

SDGs - Sustainable Development Goals

SRQ2 - Supporting Research Question

SS - Supply-Side Benefits

SSCM - Sustainable Supply Chain Management

TA – Trialability

TAM - Technology Acceptance Model

TMO - Temporary Multi-Organization

TPB - Theory of Planned Behaviour

TR - Technology Readiness

TRA - Theory of Reasoned Action

UC - Uncertainty

VOB/B - German Construction Contract Procedures

WCM - World-Class Manufacturing

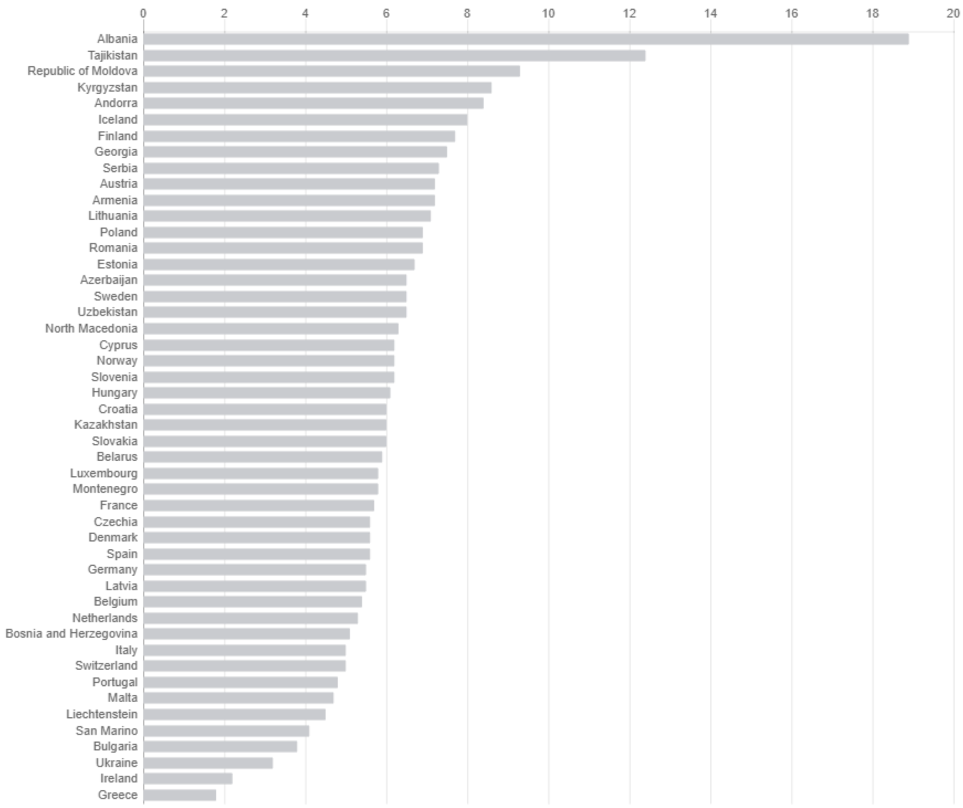
Parts of this Thesis were published in Spicek (2020); Spicek (2022); Spicek et al. (2023).

1 INTRODUCTION

1.1 Business challenges in the construction industry

In any country's economy, the construction sector plays a key role (Craveiro et al. 2019, 251). The construction industry composes 10% of GDP in developed countries, and more than 25% in developing countries on a global scale (Kim et al. 2015, 347). This fact, although not to such an extent, is also visible in the examples of European Union and partner countries (UNECE 2021, 1).

Figure 1: Share of construction in GDP (on a percentage basis)



Source: UNECE 2021, 1.

Also, the construction industry is a vast, dynamic and highly complex business (Behm 2008, 175). For instance, in the EU there are around 2.7 million companies (most of them small and medium companies) involved in this business (Balaguer and Abderrahim 2008, 1). Therefore it is not surprising that there is evidence of the existence of a very strong corelation between construction activity and economic growth (Dlamini 2014, 5).

From the above stated data, it is evident how significant the construction sector is to the welfare of any economy. This leads to the overall conclusion that the progress and enhancement of this industry is a topic worth researching. For this thesis, this was the basic pre-supposition.

1.1.1 Low labor productivity

During the last decade, the shortage in skilled labour remained one of the most important worries for the construction industry. It is very complex phenomenon, and it dynamically reacts to the labour market's behaviour and its impact on construction projects (Kim et al. 2020, 1). In general, the major concern to the construction industry, would be the decreasing quality and productivity of end products, labour shortages, occupational health and safety, and allowing work to be performed where people cannot do (Kamaruddin et al. 2015, 111).

Labour cost includes 30 to 50% of the total project's spending (Guhathakurta and Yates 1993, 15; McTague and Jergeas 2002, 1), and consequently is considered as a true sign of the economic success of the endeavour (Soham and Rajiv 2013, 583).

Since construction is a labour - intensive industry, the significance of this effect not only confirms the concern over its labour productivity, but it can also be claimed that labour power is the only productive resource. Henceforward, construction productivity is principally dependent upon human effort and performance (Soham and Rajiv 2013, 583).

Accordingly, productivity analysis in construction is a hot research topic among various research scholars and academicians throughout the globe. The cost of low productivity in big construction and infrastructure project is too high, and to deal with this, various research have been done to sort out the factors affecting construction productivity (Dixit 2020, 2275).

The analysis of 45 factors considered in a study called "Factors affecting labour productivity in building projects in the Gaza strip" shows that the main factors negatively affecting labour productivity are: material shortage, lack of labour experience, lack of labour surveillance, misunderstandings between labour and superintendent, and drawings and specification alteration during execution (Enshaasi et al 2010, 245).

Analogously, the three items of greatest concern that could affect construction productivity were identified within the study “Construction productivity: Issues encountered by contractors in Singapore” as struggle in the recruitment of supervisors, struggle in the recruitment of workers, and a high rate of labour turnover (Lim and Alum 1995, 51).

As a potential solution to the increasing demands of the workforce, use of foreign workers has been a common practice for a country to increase workers from nearby less-developed countries. While it can contribute to reducing the labour deficiency, foreign workers are typically less productive and often involve diverse risks due to cultural differences, communication difficulties, and different work ethics and customs (Han and al 2008, 1).

Therefore, potential solutions need to be sought through other alternatives as well. Rapid innovations in artificial intelligence (AI) and automation technologies have the potential to drastically disrupt labour markets. While AI and automation can increase the productivity of certain workers, they can also substitute the work done by others and will probably transform almost all professions at least to some degree (Frank et al. 2019, 15).

For the above-mentioned problem, the use of robotization and new technologies (including 3D printing) are suggested in this thesis as possible acceptable options.

1.1.2 Inefficient waste management

Construction and demolition actions produce enormous quantities of waste materials (Menegaki and Domingos 2018, 8). Waste occurring from construction and demolition activities in civil and structural engineering, so-called C&D waste, represents a major share of total waste production, showing its high consequence from both a waste management and a resource efficiency standpoint (Hiete 2013, 53) and it is given great attention by all stakeholders (investors, contractors, authorities, etc.) (Spisakova 2022, 1).

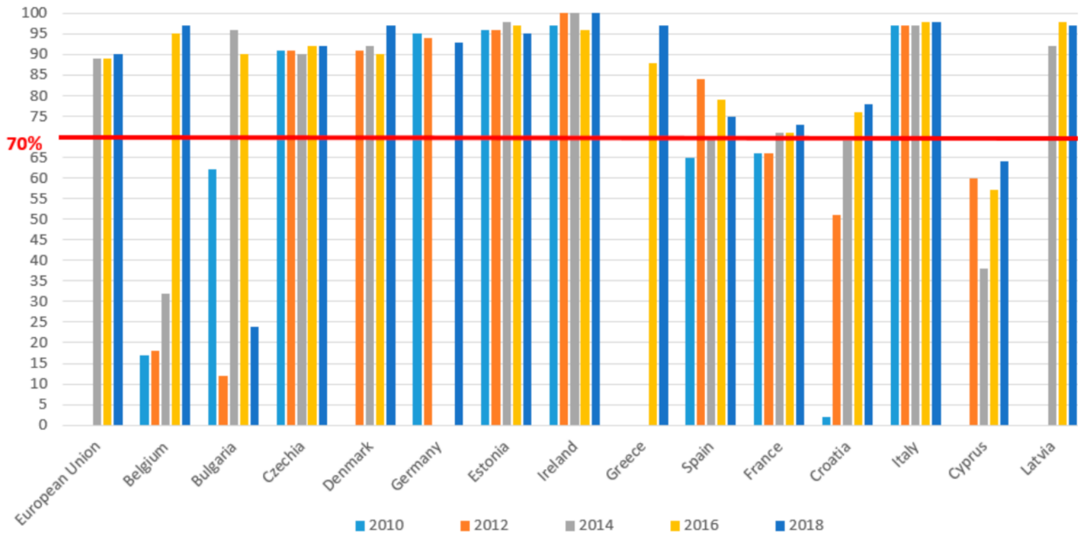
Therefore, the efficient construction and demolition (C&D) waste management is indispensable for the achievement of sustainable construction. So far, many attempts have been made to assess C&D waste management. Still, the majority of efforts have been attempted to explore C&D waste management from an economic point of view, while very limited studies have been focused on the environmental and social aspects, which are essential to encourage effective C&D waste management (Yuan 2013, 1).

Nevertheless, researchers from developed economies have contributed noticeably to the progress of the research in the discipline. It is projected that more future studies on C&D waste management will be conducted by researchers from developing economies, where construction works will remain their major economic activities (Yuan and Shen 2011, 670).

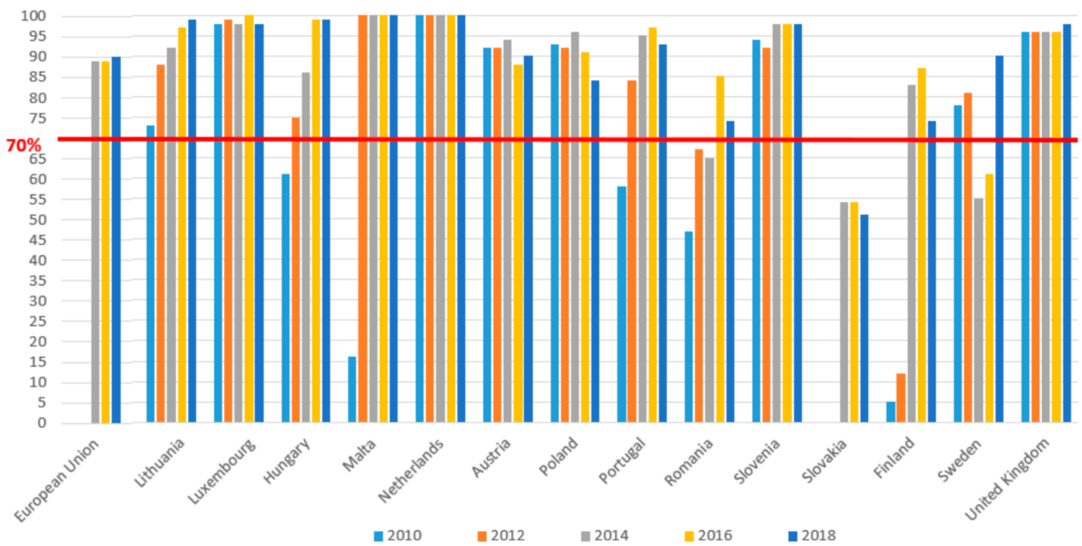
Based on analyses of C&D waste production, waste regulations, and major waste management practices in Shenzhen, within the study “Barriers and countermeasures for managing construction and demolition waste: A case of Shenzhen in China”, five weaknesses were revealed, which are “undeveloped regulatory environment for managing C&D waste”, “multiple government departments are separately involved in different C&D waste management processes but no one takes the leading role”, “non-existence of fundamental data in C&D waste”, “insufficient attention is paid to waste management in construction projects”, and “C&D waste recycling factories march toward growth (Yuan 2017, 84).

Research studies also show that one of the main barriers to insufficient CDW recovery is inadequate policies and legal frameworks to manage CDW. This topic is also one of European Union’s (EU) environmental priorities (Spisakova 2022, 1).

Figure 2: Recovery rate of construction and demolition waste in EU member states in the period 2010-2018



(a)



(b)

Source: Eurostat 2020, 1.

The construction segment has an enormous potential for reducing waste. Majority of construction and demolition waste is not hazardous and is consequently suitable for recovery (Spisakova 2022, 1).

Accordingly, there is a potential demand for advanced solutions and innovative technologies to accomplish this objective. Among the possible alternatives to the traditional building approach, 3D printing technology might have the potential to bring advancements in waste reduction and that premise is advocated in this thesis, specifically in the part devoted to the concept of “Construction 5.0”.

1.1.3 Management of a risk within construction projects

PMI (Project Management Institute) acknowledge the project as a temporary undertaking, exceptional, in line with the organization’s strategy and envisioned to create a product that has never been carried through before. As the goal of a project is to generate an unknown product, it usually involves risk because the steps to achieve the proposed targets are not known by the people in charge of project development (PMI 2004, 36).

Uncertainty is present in everyday life, in organizations and projects (Olsson 2007, 745), indicating a strong risk to the business, but also in itself is an important opportunity that must be taken (Hillson 2011, 1). It is self-evident that projects are risky, and that risk should be managed proactively in order to optimise project performance (Hillson 2011, 1).

Risk may also correspond to opportunities, but the fact that most of the risk usually has negative results has led individuals to only think about the negative side of risk (Baloi and Price 2003, 33; Hillson 2011, 1). There is a connection between uncertainty and risk as Hillson (2004, 2) suggests: “The risk is the uncertainty measured, and uncertainty is a risk that cannot be measured” (Serpella et al. 2014, 653). Risk is a complex concept (Wang et al. 2004, 237), which is described as the probability of a damaging event occurring in the project, affecting its goals (Yu 2002, 1251; Baloi and Price 2003, 261), but not always associated with negative outcomes.

The conception of project risk is related to all events or conditions that can produce positive or negative effects in at least one project objective. Risks can be categorized as internal, when the project team can influence or control them, and external when the project team are powerless to control and influence them (PMI 2004, 274; Dos Santos and Cabral 2008, 1).

Nowadays, risk management is a vital part of project management (Olsson 2007, 745; del Caño and de la Cruz 2002, 473), where one of the most difficult activities is determining what are the project’s risks and how should they be prioritized (Anderson and Anderson 2009, 25). This is a key process and most of project managers know that risk management is essential for good project management (Baloi and Price 2003, 263; Perera and Holsomback 2005, 129; Alali and Pinto 2009, 1). Therefore, the management of the risk of a project is one of the major roles undertaken by a project manager (Serpella et al. 2014, 653). Risk management is described as the process of identifying and assessing risk, and to apply methods to reduce it to an acceptable extent (Tohidi 2011, 881). Also, the main purpose of project's risk management is to identify, evaluate, and control the risk for project success (Lee et al. 2009, 5880). Overall, risk management process includes the following main steps: (1) Risk planning; (2) Risk identification; (3) Risk assessment (qualitative and quantitative); (4) Risk analysis; (5) Risk response; (6) Risk monitoring, and (7) Recording the risk management process (ISO 31000 2009, 2; Baloi and Price 2003, 261).

Nevertheless, this duty is particularly complex and unproductive if good risk management has not been done from the beginning of the project. An effective and efficient risk management approach necessitates a proper and systematic methodology and, more significantly, knowledge and experience (Serpella et al. 2014, 653).

Risk management is also a crucial field of construction industry and has gained more significance globally due to the latest research conducted on a large scale. Nonetheless, this relatively new field requires more attention to bring some benefit. Construction projects are confronting a number of risks which have negative effects on project objects such as time, cost, and quality (Iqbal and Shah 2014, 1).

However, many of the projects fail at an amazing rate (Matta and Ashkenas 2003, 1), i.e., they run behind schedule or incur unanticipated costs. Subsequently, the risk management in construction projects is still very unproductive and that the main reason of this situation is the lack of knowledge (Serpella et al. 2014, 653). In order to prevent such scenarios, it is crucial to establish risk management strategies (Olsson 2007, 745). The risk management methodology of the Project Management Institute (PMI) presented in the Project Management Body of Knowledge – PMBOK – is possibly one of the most used technical developments for controlling risks (Dos Santos and Cabral 2008, 1).

PMBOK's Risk Response Planning involves taking action to maximize the opportunities and to minimize the threats, which could endanger the objectives and goals of the project. Besides the risk response plan itself, "Risk Response Planning" involves the assessment of residual risks, secondary risks. It also must consider contractual agreements, the inputs for other processes and inputs for a revised project planning (PMI 2004, 302).

As for individual rolls, the contractor is answerable for management of most risks occurring at sites during the implementation phase, such as problems related to subcontractors, labour, machinery, availability of materials and quality, while the client is responsible for the risks such as financial issues, issues related to design documents, changes in codes and regulations, and scope of work (Iqbal and Shah 2014, 1).

Acquiring and implementing new technologies is the process that usually requires considerable effort on the part of the organizations, as it involves factors such as complexity, scarce resources (both financial and human), and normally tight schedules. With aim to cope with such obstacles, the process of new technology deployment is generally addressed through projects (Dooley et al. 2005, 466).

Consequently, the development and implementation of successful project management methodologies, risk management processes in particular, are keystones of successful new technology projects (Dos Santos and Cabral 2008, 1).

One of the new technologies where the assumption about the importance of risk management would be applicable is most certainly 3D printing. The risk management segments of construction projects using 3D printing technology are continuously being considered in this thesis. The aforementioned role of the various stakeholders in the construction project in shaping risk management is also covered in detail in the part that focuses on the project's organization structure.

1.1.4 Expensive construction costs, demand for housing

Construction costs represent the largest portion of the price of new homes in most markets, but their investigation has been relatively neglected (Gyourko and Saiz 2006, 661).

Reliable estimates of construction costs and schedules provided by modern contractors, their consultants, and suppliers at the time of project approval are important to economically justify a project and plan its financing. The economic impact of a construction cost overrun is the potential loss of economic justification for the project. A cost overrun can also be critical in developing sustainable development measures based on economic costs. The financial implications of a cost overrun also lead to a demand for loans for construction investments (Stasiak and Potkányb 2015, 35).

Likewise, for owners with a mortgage, the average cost of housing increased significantly. Interest rates, investment demand, the economic climate, deregulation and innovation in the financial sector, land supply and the land-use planning system, government taxes, levies and fees, demographics, economic growth, and the wealth effect all play an important role in influencing housing prices (Rahman 2010, 577).

Since 1950, housing prices have regularly increased by almost two percent per year. Between 1950 and 1970, this increase reflected rising housing quality and construction costs (Glaeser et al. 2005, 329).

Pursuant to the price rise, it also reflects the progressive difficulty in obtaining regulatory approval for the construction of new dwellings. Too often, analysts try to understand real estate prices by looking only at demand-side factors such as interest rates or per capita income, while ignoring the supply side of the market. Rising prices require not only rising demand, but also supply constraints. Housing supply includes three elements: land, building construction, and government permission to construct the building on the land. Therefore, rising prices must reflect rising physical construction costs, rising land prices, or regulatory barriers to new construction, consequently making the acquisition of suitable housing a great challenge for individuals at various stages of their lives (Glaeser et al. 2014, 701).

Many phases - moving out of the parental home, partnership, raising children - have historically accumulated in the 20s and early 30s. Increasingly, these phases extend into the late 30s and early 40s (Flynn 2016, 374).

Construction method selection, implementation, and improvement (CMSII) is an important and difficult task in construction projects, especially large and complex projects that often confront constraints such as a complex project environment, lack of information, and uncertainties due to new technologies (Ren et al. 2013, 1).

In this challenging process of choosing a construction method, reliable factors that determine the success or failure of projects are required, and awareness of these factors definitely provides guidance in selecting the prospective method. Also, one of the essential assumptions of this thesis is that choosing 3D printing technology, after meeting the necessary prerequisites, could be the answer to the above problems.

1.1.5 Supply chain management

The sizeable number of supply chain partners and the significant level of fragmentation limit the levels of integration that are feasible. The interplay of environmental and procurement related factors renders the realization of truly integrated supply chains extremely problematic and challenging to achieve (Briscoe and Dainty 2005, 319).

Although it seems that Construction Supply Chain Management (SCM) is still in its infancy, a certain awareness of the philosophy is obvious. Contractors identified improved production planning and purchasing as crucial targets for the application of SCM in construction (Akintoye et al. 2000). Impediments to success consist of workplace culture, lack of senior management commitment, unsuitable support structures and a lack of knowledge of SCM philosophy (Akintoye et al. 2000, 159).

Sustainable construction and supply chain management (SCM) have, in latest years, become two of the extremely important performance-related issues within the construction industry. To accomplish corporate sustainability within any organization, it is vital that sustainability issues are tackled throughout the organization's whole supply chain, a process referred to as sustainable supply chain management (SSCM). The implementation of SCM and sustainability is, nonetheless, an extremely complex responsibility (Adetunji 2008, 161).

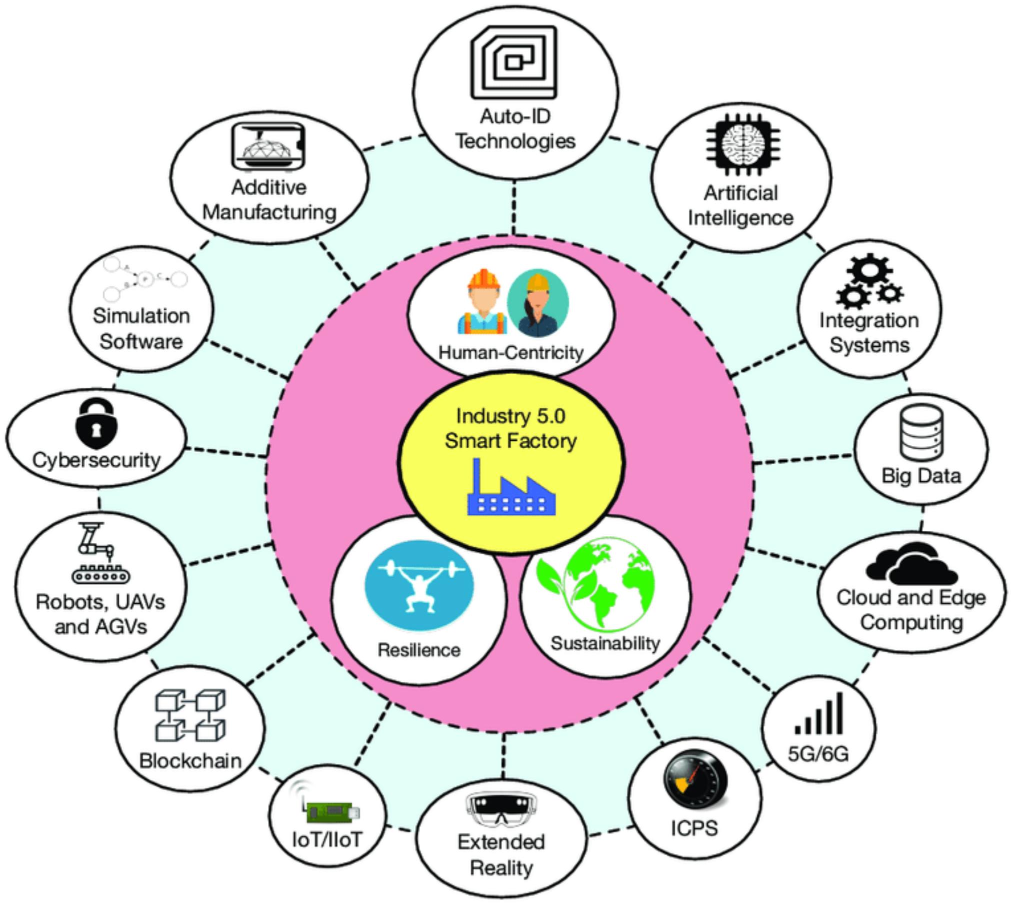
One of the potential advantages of 3D printing technology is precisely in this segment, which is specially thematized and checked in Chapters 6 and 7 of this dissertation.

1.2 Industry 5.0 & "Construction 5.0"

Industry 5.0 adheres to the paradigm of Industry 4.0 and aims to transform the way industry works. Effectively, Industry 5.0 focuses on research and innovation to promote the sustainability of industrial production and to put the well-being of industrial workers at the forefront of the manufacturing process. Therefore, Industry 5.0 is founded on three main pillars: it is human-centred, it promotes sustainability, and it aims to develop resilience to disruption (Grabowska et al. 2022, 3117).

To accomplish this, Industry 5.0 uses new technologies to generate wealth beyond jobs and growth and simultaneously consider sustainability issues. Altogether, Industry 5.0 references humans working side by side with robots and smart machines, with human labour efficiency enhanced by advanced technologies The adoption of Industry 5.0 has ignited the discussion on the smart and sustainable built environment and associated areas such as construction management and smart cities. Among some of the technologies in the spotlight are digital twins, green technologies, lean practices, artificial intelligence, the Internet of Things, unmanned aerial vehicles, building data modelling, infrastructure data modelling, Big Data, 3D scanning, virtual and augmented reality, robotics, blockchain networks, 3D printing, digital literacy, and next-generation education technologies (Reddy et al. 2021, 1).

Figure 3: Key enabling technologies for Industry 5.0



Source: Fraga-Lamas et al. 2021, 1.

The venture named "Construction 5.0" is aimed at promoting the alignment of technological and digital innovations for the construction sector alongside societal dimensions in harmony with the 17 Sustainable Development Goals (SDGs) of the United Nations and the Paris Agreement (CICA 2022, 1).

The very fact that technologies could help put people back at the centre of the universe in terms of manufacturing and enable them to focus on their creativity is the basis on which 3D printing technology in construction projects ought to fit into the concepts of “Construction 5.0”.

1.3 3D printing as the solution to business challenges

In recent years, 3D printing, which is an automated production process with layer-by-layer control, has experienced a rapid ascent. The technology had already been utilized in the manufacturing industry for decades and has recently been adopted in the construction industry to print houses and villas. After years of development, a systematic review shows that 3D printing technology can be utilized to print large-scale architectural models and buildings. The capacity of the technology, nonetheless, is constrained by the lack of large-scale implementation, the development of building data models, the need for mass customization, and the life-cycle cost of printed projects (Wu et al. 2016, 21).

While 3D printing technology has significant potential, the speed of its adoption is not quite what the market anticipated (Yeh and Chen 2018, 209).

A large body of research has defined a variety of process (e.g., material, design, printer) and product-related issues of 3D printing that are impeding the adoption of this technology in the construction sector. In the way construction is currently organized, there is still the fact that most structures are made from a combination of different materials. Then again, the use of inhomogeneous or multiple materials is still a challenge for the 3D printing design process (Labonnote and al 2016, 347; Camacho and al 2018, 110; Marchment and Sanjayan 2020, 1).

Although the idea is scaling, the processes and materials are improbable due to a multitude of factors, including material properties, cost, and availability. Such challenging factors can be grouped into the following areas: Layered manufacturing and construction, design implications, data issues, process, and control (Buswell et al. 2008, 224).

In addition to technical solutions, innovations in construction and project management are also necessary to meet the new stakes. 3D printing enables a reduced construction time and cost, as well as a reduction in waste. The project managers should adequately modify their style of designing and scheduling. Certainly, 3D printing will be a portion of the construction industry's future. There are, nevertheless, a number of remaining challenges that need to be addressed before 3D printing can be a viable solution. Some risks connected to this emerging technology have been already identified and classified based on their sources. Such risks need to be evaluated so for them to be incorporated in the design phase of such construction projects (El-Sayegh 2020, 1).

As already stated, the biggest issues for the construction industry in general are declining quality and productivity of end products, labour shortages, occupational health and safety, and the ability to perform work that people cannot. The paper "Barriers and Impact of Mechanisation and Automation in Construction to Achieve Better Quality Products " discusses ways to increase the quality of life by removing the barriers and their impact on this initiative that could improve the industry in terms of productivity, safety, and quality. Also, this effort should ensure the balance between environmental and energy management with the increase in productivity for better quality products which might result in an improved quality of life for end-users (Kamaruddin et al. 2016, 111).

3D printing technology could offer several benefits compared to traditional processes, among them lower material and energy consumption (Berman 2012, 155; Khajavi et al. 2014, 50; Labonnote et al. 2016, 347; Walter et al. 2004, 9), on-site manufacturing with less resource requirements and lower CO_2 emissions throughout the product life cycle (Gebler et al. 2014, 158). It is also driving changes in working patterns, including safer working environments, and a shift towards more digitalised and more localised supply chains (Ghaffar et al. 2018, 1).

Seen from an architect's point of view, 3D printing technology can reduce design and development cycles; it allows clients to co-design products that are perfectly adapted to their needs and goals; it enables the realisation of complex designs and the rapid implementation of design modifications (Berman 2012, 155; Ghaffar et al. 2018, 1; Khajavi et al. 2014, 50; Labonnote et al. 2016, 347; Walter et al. 2004, 9).

1.4 Scientific research perspective

1.4.1 Research objective and research questions

3D printing is emerging as a viable option for addressing some of today's construction industry issues (Wu et al. 2016, 21). However, compared to other branches of industry and theoretical possibilities, the technology's momentum is still limited (Yeh and Chen, 2018, 209).

It seems that without standardization of the process, as well as an answer to the question of what are the factors that make construction projects that utilize 3D printing technology successful or fail, this forward motion is unlikely to take place. Without the certainty of future investors about the potential success factors of such projects, they are unlikely to choose 3D printing technology as a construction method for their projects (Spicek 2020, 220).

With the goal of filling this research gap, the following research questions in lieu of research hypotheses are addressed through the analysis of the key success / failure factors in managing construction projects utilizing 3D printing technology through a prism of: (1) Relative advantage; (2) Complexity; (3) Trialability; (4) Compatibility; (5) Absorptive capacity; (6) External pressure; (7) Uncertainty; (8) Supply – side benefits; (9) Demand – side benefits.

Therefore, the main research question (abbreviation in this thesis = MRQ) is:

MRQ: ***"What are the critical factors in ensuring success (or causing failure) of 3D printing technology in construction project applications?"***

In addition, the first two supporting research questions (abbreviation in this thesis = SRQ) were formulated as:

SRQ1: *"What are the impacts on construction project management by such disruptive technology as 3D printing?"*

SRQ2: *"How can these impacts be addressed / investigated with the purpose of achieving the economic profitability, quality, and safety of construction projects?"*

In the course of researching these topics, the following new sub-questions crystallized in the process of developing the research guidelines, which are always assigned to the respective research topic in this thesis:

Project organization structure:

SRQ3: *"What has been discovered to date about the roles, responsibilities and interactions of key participants in construction projects utilizing 3D printing technology?"*

SRQ4: *"What conclusions can be substantiated about the roles, responsibilities, and interactions of key participants in projects involving 3D printing technology linked to the conventional construction model?"*

SRQ5: *"Do existing project management methods/project organization structures need to be modified to this comparatively innovative technology?"*

"Construction 5.0":

SRQ6: *"Is 3D printing technology in line with the characteristics of the "Construction 5.0" paradigm?"*

SRQ7: *"What are the implications of 3D printing technology that meet the criteria of "Construction 5.0"?"*

Benchmarking critical success factors:

SRQ8: *"How are this success factors applicable through case studies of 3D printing projects and how these same factors behave in the context of conventional construction projects?"*

1.4.2 Scientific research approach

A multi-stage research concept is designed in order to address the specific research questions. Initially, the importance of the construction sector in today's economy and the problems that the construction industry is facing in practice and academic research have been examined (Chapter 1.1. -1.2.). As a possible solution to some of the previously identified problems, the idea of 3D printing was explored in terms of an interesting alternative technology compared to more traditional methods (Chapter 1.3.). To begin with, a literature review was conducted on what the success of the project means (Chapter 2.1.) and what are the possibilities as well as the state of the art of the several topics related to robotics and automation (Chapter 2.1.). Then, the core of this dissertation was conducted in the area of literature review regarding the topics: Ethics (Chapter 2.2.), Project Organization Structure (Chapter 2.3.), Critical Success Factors (Chapter 3.7.), "Construction 5.0" (Chapter 2.4.) and several other subjects.

Within the conceptual part, using methodological tools for defining 3D printing success factors, the most important theories and terms are explained (Chapter 3.). This is followed by the main research segment, which is divided into "Challenges in the introduction of 3D printing technology in construction projects" (Chapter 4), with topics such as Prerequisites for implementation (Chapter 4.1.), Legislation (Chapter 4.2.), Changes in Project Organization Structure (Chapter 5.), the Concept of "Construction 5.0" in connection with 3D printing technology implementation (Chapter 6.), and Analysis of critical factors in comparison with conventional construction techniques (Chapter 7.).

The research part finishes with the Feedback from the practice on 3D printing success factors (Chapter 8). Following these chapters, the end of the dissertation includes Discussion (Chapter 9.), Assumptions and limitations / restrictions of the presented research (Chapter 10.) as wells as Conclusion (Chapter 11.), which is additionally clarified by the contributions of the dissertation and recommendations for further research (Chapter 12.).

1.4.3 Research philosophy

Philosophical perspectives, a system of general worldviews that form action-guiding beliefs, emerge from ontology (what people can know) and epistemology (how knowledge is formed and what can be known). These perspectives matter because, when made explicit, they reveal researchers' assumptions about their research and lead to decisions that are applied to the purpose, design, methodology, and methods of research, as well as to data analysis and interpretation. On the most basic level, the mere decision of what to study in the sciences establishes values on one's subject (Moon and Blackman 2017, 1).

There are assumptions about the sources and nature of knowledge at each stage of the research process. The research philosophy represents the key assumptions of the author, and these assumptions serve as the basis for the research strategy. More generally, research philosophy has many branches associated with a multitude of fields of disciplines. Particularly, in management studies, there are four important research philosophies: 1) pragmatism, 2) positivism, 3) realism, and 4) interpretivism (interpretivist) (Dudovskiy 2022,1).

Table 1: Research philosophies and data collection methods

Research philosophy	**Pragmatism**	**Positivism**	**Realism**	**Interpretivism**
Popular data collection method	Mixed or multiple method designs, quantitative and qualitative	Highly structured, large samples, measurement, quantitative, but can use qualitative	Methods chosen must fit the subject matter, quantitative or qualitative	Small samples, in-depth investigations, qualitative

Source: Spicek 2022, based on Saunders et al. 2009, 106.

1.4.4 Explanation of quantitative, qualitative, and mixed methods of research

Research methods are the strategies, processes, or techniques utilized in collecting data or evidence for analysis to reveal some novel information or to provide a deeper comprehension of a given subject. Qualitative research accumulates data about lived experiences, emotions, or behaviours and the meanings individuals connect to them, thus helping researchers acquire a better comprehension of complex concepts, social interactions, or cultural phenomena. Quantitative research involves collecting numerical data that are able to be classified, measured, or categorized using statistical analysis. Mixed-methods research combines both qualitative and quantitative research, providing a holistic approach in which statistical data with deeper contextual insights are combined and analysed (Newcastle 2023, 1).

Typically, a management case study contains a description of real-life management issues and recommended solutions. Students, practitioners, and professionals alike use case studies to think critically about problems and to design and implement corrective actions for challenging management situations. Commonly, a case study includes facts, theories, assumptions, analysis, and prioritized solutions (WikiHow 2023, 1).

Table 2: Selecting the case study strategy

Researcher's position (in relation with the research target)	Understanding, describing, or illustrating a phenomenon	Driving or supporting transformation in the phenomenon
Internal	Interpretive case studies	Interventionist case studies
External	Exploratory, descriptive and explanatory case studies	Constructive case studies
	Nature of the research task	

Source: Martinsuo and Huemann 2021, 417.

Generating novel contributions should be accomplished through the following: 1) Avoiding generalization, making context important, 2) Expanding on existing body of knowledge, 3) Focusing reflection on similar types of cases at the right level of analysis as well as the phenomenon in its context, 4) Providing validation through transparency of data and traceability of the data process (collection and analysis), 5) Strategically recommending further research (Martinsuo and Huemann 2021, 417).

Case study is an ideal method when a holistic, in-depth research is required (Feagin and al 1991, 1).

No individual source has a total advantage compared to the others; rather, they are complementary and may be used in conjunction with each other. Consequently, a case study should use as many sources as are relevant for the study (Tellis 1997, 1). The strengths and weaknesses of each type of source can be seen in the Table 3:

Table 3: Types of evidence

Source of evidence	Strengths	Weakness
Documentation	Stable – repeated review Unobtrustive – exist prior to case study Exact – names etc. Broad coverage – extended time span	Retrievability – difficult Biased selectivity Reporting bias – reflects author bias Access – may be blocked
Archival records	Same as above Precise and quantitative	Same as above Privacy may inhibit access
Interviews	Targeted – focuses on case study topic Insightful – provides perceived casual interferences	Bias due to poor questions Response bias Incomplete recollection Reflexivity - interviewee expresses what interviewer wants to hear
Direct Observation	Reality – covers events in real time	Time consuming Selectivity – might miss facts

Source: Spicek 2022, based on Tellis 1997, 1.

1.4.5 Research methods applied in this thesis

To respond to the main research question formulated as: "What are the critical factors in ensuring success (or causing failure) of 3D printing technology in construction project applications?", 8 different supporting research questions were defined, based on the literature review. They were divided into 4 stages of empirical research, with a total of 11 case studies. Based on personal professional preferences, the journey began with researching literature. The literature research is a systematic and well-organized search of the already published data to find a large number of high-quality references on a specific topic.

The research problem is usually a topic that the researcher is interested in and familiar with. Therefore, it needs to be channelled by focusing on information that still needs to be researched. Having narrowed down the problem, the search and analysis of the existing literature allows the research approach to be narrowed further (Grewal et al. 2016, 635).

The literature review is an essential ingredient for any evidence-based project. It will help in understanding the complexity of a given problem, give insight into the scope of a problem, and provide best management approaches as well as the best available supporting evidence on the topic. Without this step, the evidence-based practice project cannot move forward (Accelerate Learning Community 2023, 1).

First of all, the database was determined, and the decision was primarily made to use Scopus and Web of Science.

The Google Scholar database was also used extensively. Google Scholar is an easy way to search extensively for scholarly literature. Starting from one place, one can search across many disciplines and sources: Articles, dissertations, books, abstracts, and court decisions from academic publishers, professional organizations, online repositories, universities, and other websites (Google Scholar 2023, 1).

Keywords pertinent to the topic were utilized and after finding an article that seems relevant to the topic, use the "snowballing" technique in order to find more related articles. Snowballing implies leveraging an article's reference list or the article's citations to help identify additional articles (Wohlin 2014, 1). From the very beginning of the search for literature and collecting articles, it was important to store all the relevant research results in an organized manner. A personal database of the most relevant articles was maintained, and a web-based reference manager called "EndNote Basic" was also used. The following Table 4 shows the partial literature review accountable for shaping the research questions of each paper, as well as the general context of this dissertation.

Table 4: Literature review for shaping research questions

	Research area				
	Integration of new technologies in the management of construction projects	**Ethics in construction projects utilizing 3D printing technology**	**Construction project organization for 3D printing technology**	**"Construction 5.0" Paradigm**	**Methodological tools for defining 3D printing success factors**
Literature research component	Construction automation as enabler of 3D printing technology adoption	Ethics in traditional construction projects	Construction projects using 3D printing technology (strengths, weaknesses, challenges, critical success factors)	Industry 4.0 overall - A suitable foundation for identifying impact dimensions	Research model development
		Ethics in construction projects utilizing 3D printing technology	Collaboration between construction project key participant	Industry 5.0 – Concept and patterns	Innovation Diffusion Theory
			Roles, responsibilities, and interactions of key participants in project organization structure	Construction 4.0 - A suitable foundation for identifying impact dimensions "Construction 5.0" - Concept and patterns	Technology Readiness
				Project Management in Industry 4.0 and Industry 5.0 - Concept and patterns	Technology Acceptance Model
				The concept of sustainability in project management	Contingency Theory
				Increased Environmental Sustainability	Additional factors

				Increased Compatibility (Technology)	Relative advantage, Complexity, Trialability, Compatibility, Absorptive capacity, External pressure, Uncertainty, Supply-side benefits, Demand-side benefits
				Increased Compatibility (Technology)	
				Increased Resilience	
				3D Printing Technology – In scope of Industry 4.0, Industry 5.0 and PM context	

Source: Spicek 2022.

After the literature review and the definition of the research questions, the quest for answers to these questions started. As a method to explain these phenomena, different case studies were selected for each topic separately. As is also evident in the example of this thesis, a case study provides an in-depth examination of a person, group, or an event (Crowe and al 2011, 1). In a case study, virtually every aspect of the person's life and narrative is analyzed to find patterns and causes of action (Kitchenham et al. 1995, 52).

The main features of each case study are explained individually in the following Table 5. A more detailed description of the case study can be found in the sections predicted for that throughout the core of this thesis.

Table 5: Case studies details

Ordinal number	Case Study working title	Description of the nature of the case study	Case study location	Forecasted/executed project
1	"Project Cabana: Augsburg"	In-depth, multi-faceted understanding of a complex issue in its real-life context	Augsburg, Germany	Cottage of 50 m2, in the documentation phase
2	"Project Cabana: Zagreb"	In-depth, multi-faceted understanding of a complex issue in its real-life context	Zagreb, Croatia	Cottage of 50 m2, in the documentation phase
3	"Staircase Leipzig"	In-depth, multi-faceted understanding of a complex issue in its real-life context	Leipzig, Germany	Formwork for stairs of irregular shape, implemented project
4	"3D printed panels and columns"	In-depth, multi-faceted understanding of a complex issue in its real-life context	England, UK	Columns and panels for wall sections, in planning phase
5	"3D printed housing"	In-depth, multi-faceted understanding of a complex issue in its real-life context	Arizona, US	Family house, finished project
6	"Leipzig-Stairs (Formwork)"	In-depth, multi-faceted understanding of a complex issue in its real-life context	Leipzig, Germany	Formwork for stairs of irregular shape, implemented project

7	“3D printed bridge”	In-depth, multi-faceted understanding of a complex issue in its real-life context	Tianjin-Zhaozhou, China	Complete reconstruction of the ancient bridge, completed project
8	“Smart Slab”	In-depth, multi-faceted understanding of a complex issue in its real-life context	Zurich, Switzerland	Load-bearing concrete slab produced with 3D-printed formwork, implemented project
9	“Integrated Funicular”	In-depth, multi-faceted understanding of a complex issue in its real-life context	Zurich, Switzerland	Customized formwork from fully recyclable materials for a functional concrete slab, implemented project
10	“3D printed house – Beckum”	In-depth, multi-faceted understanding of a complex issue in its real-life context	Beckum, Germany	Family house, completed project
11	“Traditional house – Berlin”	In-depth, multi-faceted understanding of a complex issue in its real-life context	Berlin, Germany	Family house, completed project

Source: Spicek 2022.

Empirical research is research that is founded on the observation and measurement of phenomena that the researcher directly experiences. The data gathered in this manner can be compared to a theory or hypothesis, however, the results are still based on real life experiences. All data collected is primary data, although secondary data from a literature review may provide the theoretical background (Emerald Publishing 2023, 1).

Table 6: Overview of the empirical part of the research

General method / sampling	Research question	Key result
MAIN RESEARCH QUESTION Accumulated conclusion of the results of the entire research (all case studies)	**MRQ:** "What are the critical factors in ensuring success (or causing failure) of 3D printing technology in construction project applications?"	Relative advantage, Ease of use (complexity), Trialability (divisibility), Compatibility, Absorptive capacity, External pressure, Uncertainties, Supply-side benefits and Demand-side benefits were affirmed as most relevant success factors of construction projects utilizing 3D printing technology. As some other drivers that may affect the feasibility of 3DP construction projects, matters of ethical issues and the process of obtaining a building permit were also considered. In meeting "Construction 5.0" criteria, defined impact dimensions include Increased Environmental Sustainability, Increased Construction Safety, Increased Compatibility (Technology) and Increased Resilience).
STAGE 1 **Challenges in introduction of 3D printing technology to construction projects** 2 In-depth case studies	**SRQ1:** "What are the impacts on construction project management by such disruptive technology as 3D printing?" **SRQ2:** "How can these impacts be addressed / investigated with the purpose of achieving the economic profitability, quality, and safety of construction projects?"	The impact of 3D printing technology on project management in the construction sector is multifaceted and complex, and it will have a definite influence on the role of the project manager in the coming future. Only by being aware of these factors and their implications is it possible to determine the construction method in advance and create a trustworthy decision-making tool in the case of a dilemma regarding the best construction technique.

STAGE 2 **Project organization structure** 3 In-depth case studies	**SRQ3:** "What has been discovered to date about the roles, responsibilities and interactions of key participants in construction projects utilizing 3D printing technology?" **SRQ4:** "What conclusions can be substantiated about the roles, responsibilities, and interactions of key participants in projects involving 3D printing technology linked to the conventional construction model?" **SRQ5:** "Do existing project management methods/project organization structures need to be modified to this comparatively innovative technology?"	There is a lack of existing body of research on the impact of 3D printing technology on the roles and responsibilities within the organizational structure of a construction project. Evidence from the relevant case studies demonstrates that the primary impact of the new technology will be on design, supply chain, and quality, which means that project management will be required to coordinate integration, scope, procurement, risk, and stakeholder management responsibilities and processes. project management professionals will be confronted with new set of challenges, specifically in the fields of integration, scope, risk and stakeholder management. Particular focus should be given to the competency model and its actualization for all key roles during the preparation and building processes.
STAGE 3 **"Construction 5.0":** 4 In-depth case studies	**SRQ6:** "Is 3D printing technology in line with the characteristics of the "Construction 5.0" paradigm?" **SRQ7:** "What are the implications of 3D printing technology that meet the criteria of "Construction 5.0"?"	3D printing technology was acknowledged to be at least moderately superior in meeting "Construction 5.0" criteria to that of more common construction methods in practically all regards, which is particularly evident in the impact dimension entitled "Increased Environmental Sustainability (ES)." Through the prism of the human-centred approach and human-robot collaboration, humans will be able to maximize their creative and inventive potential, while

		robots will perform dry, repetitive, and even very complicated tasks by means of automation.
STAGE 4 **Analysis of critical success factors** 2 In-depth case studies	**SRQ8:** “How are this success factors applicable through case studies of 3D printing projects and how these same factors behave in the context of conventional construction projects?”	In both cases, the factors mentioned were identified as being tangible, relevant, applicable, and research worthy.

Source: Spicek 2023.

1.4.6 Scope of the research

The focal point of this research lies in construction projects performed using 3D printing technology. As mentioned on several occasions in this thesis, 3D technology has the potential to solve some of the challenges of the modern construction sector (Berman 2012, 155; Khajavi et al. 2014, 50; Labonnote et al. 2016, 347; Walter et al. 2004, 9).

Nevertheless, the full momentum of the technology is still to come (Yeh et Chen 2018, 209), and this vitality is unlikely to be realistic without process standardization and the resolution of problematic circumstances, both in theory and in practice (Spicek 2020, 220).

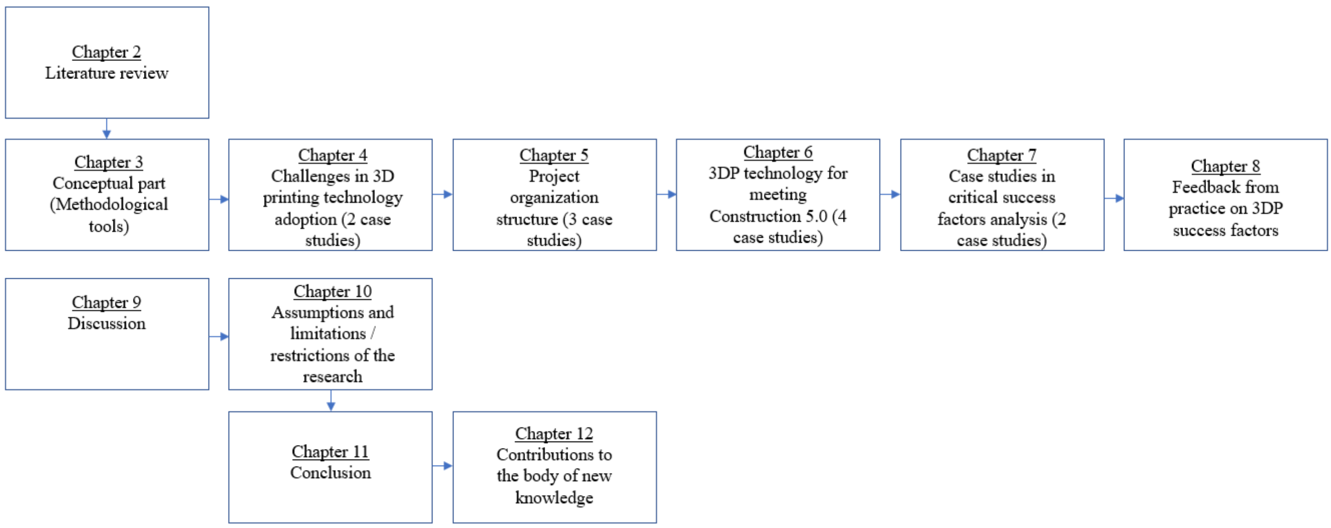
From a more theoretical perspective, several theories have been observed which could define critical success factors for construction projects using 3D printing technology, whereas from a more practical side of the research, the focus has been on case studies which attempt to answer how these factors work in the "real world" and upon what the success is dependent. Also, these topics could provide a clearer picture of the level of adaptation of this relatively new technology. Given that the research was part of a PhD study, no specific budget or grant funding was envisaged.

All research related to this thesis was conducted between the beginning of 2018 and the end of 2022. Representative examples of construction projects using 3D printing technology were targeted. In a sense, these are pioneering projects that are considered to be beyond the scope of everyday construction and reach outside the parameters of traditional building methods. Case studies in the U.S., China, the U.K. and Germany were selected based on their leading role in this emerging trend (Chun et al. 2018, 397), as well as countries that are not yet as prominent on the global scene of 3D printing technology applied within construction projects (e.g., Croatia and Switzerland). For the projects studied, 3D printing technology was allowed to be partially combined with traditional construction methods, with the rule being that the structural design (particularly the shell) was done via 3D printing, and conventional methods were allowed to be used for the finishing works (e.g., installations and suchlike). In terms of projects, it did not necessarily have to be the entire building / structure, as the example of the case studies on formwork or slabs shows. All other assumptions and limitations as well as any expected controlling, extraneous, or confounding variables that might potentially distort this research if not correctly addressed, will be explained in detail (based on each individual case study) in Chapter 10.

1.4.7 Thesis structure

The different chapters of this thesis are illustrated and interconnected through Figure 4.

Figure 4: Thesis structure



Source: Spicek 2023.

2 LITERATURE REVIEW

2.1 Integration of new technologies in the management of construction projects

Despite the fact that there is no unified definition of what determines project success, authors agree that project success can be reached through good measures taken by the project manager (Radujkovic and Sjekavica 2017, 1). The main driver of any project is people, and competent project managers are critical even for megaproject success (Misic and Radujkovic 2015, 71). Managing the risk of a project is one of the most significant responsibilities of a project manager. Risk management in construction projects is full of deficiencies that have an impact on both its effectiveness as a project management function and eventually on project delivery performance (Serpella et al. 2014, 653).

Risk management is delineated as the process of identification and evaluation of risks and the use of methods to reduce them to an acceptable degree (Tohidi 2011, 881). Hence, the main objective of risk management within a project is to identify, assess, and control the risk to the project execution (Lee et al. 2009, 5880). For almost every project, the goal is project success. Nevertheless, this implies dissimilar matters to various individuals. Whereas some authors view time, cost, and quality as the most dominant criteria, others suggest that success is slightly more complicated than that (Chan and Chan 2004, 1). It seems that the idea that a project is successful if it only meets the goals of time, cost, and quality is presently obsolete. This may be corroborated by (Collins and Baccarini 2004, 211) who argue that time, cost, and quality are not the only criteria for project success and that it is mandatory to instruct project managers to consider criteria other than this triad (Shokri-Ghasabeh and Kavousi-Chabok 2009, 1). Proper distribution of reduced resources is promoted by recognizing the key factors for construction project success (Chua et al. 1999, 1). Yet, one of the continuing problems with projects is the realization that implementation is poor, and the primary desired goals are not achieved, particularly with respect to project schedules and costs (Radujkovic and Sjekavica 2017, 1).

As mentioned, the labour productivity in construction has become a major constraint in the construction industry. For most countries, labor costs account for 30% to 50% of total project expenditures (Yates and Guhathakurta 1993, 15; McTague and Jergeas 2002, 1) and are thus regarded as a true indicator of the economic success of the project (Soham and Rajiv 2013, 583).

As construction is a labour-intensive industry, this impact not only validates the concerns about labour productivity, but it can also be reasoned that labour is the sole productive resource and consequently construction productivity mainly relies on human effort and performance (Soham and Rajiv 2013).

In order to achieve sustainable construction, efficient management of construction and demolition waste is imperative. So far, many attempts have been made to benchmark the management of construction and demolition waste. Most efforts, nonetheless, have been made to study the management of construction and demolition waste from an economical point of view, while very few studies have concentrated on the environmental and social aspects that are vital to the effective management of construction and demolition waste (Yuan 2013, 1).

Incorporating new technologies and solutions into the management of construction projects is the possible answer. Technology Readiness (TR) reflects the consumer's desire to adopt and utilize innovative technologies to meet their daily/business goals (Parasuraman 2000, 307). In addition, it is a measure of positive or negative attitude about technology (Başgöze 2015, 26). The TAM (Technology Acceptance Model), which is derived from the Theory of Reasoned Action (Ajzen 1991, 93) and originally proposed by Davis (1985, 1), suggests that the acceptance of information systems is determined by two main variates: (1) Perceived Usefulness (PU) and (2) Perceived Ease of Use (PEOU) (Lee et al. 2003, 1).

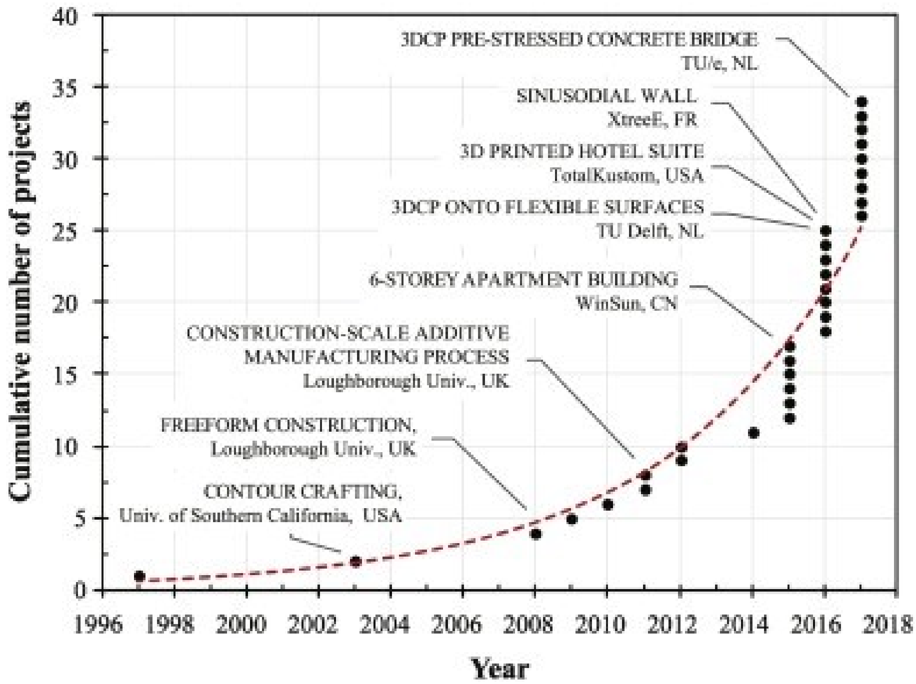
On the basis of the abbreviated conclusions of IDT (Rogers 1962, 1), TAM (Davis 1989, 319) and other prominent studies in the field of innovation adoption (Cohen and Levinthal 1990, 128; Moore and Benbasat 1991, 192), it is possible to highlight three groups of variables that appear to be pertinent to AM technology adoption: (1) technology-related factors (relative advantage and ease of use (complexity)), (2) firm-related factors (absorptive capacity and compatibility), and (3) market structure-related factors (external pressure and perceived external support) (Oettmeier and Hofmann 2017, 97).

2.1.1 Construction automation as enabler of 3D printing technology adoption

Despite the fact that automation in manufacturing has advanced, automation in construction has been slow to develop, probably due to the fact that the conventional methods of manufacturing automation are not applicable to the building of large-scale structures with indoor finishing (Khoshnevis 2004, 5).

Equivalently, the use of automated technology and processes control, commonly seen in the automobile and aerospace industries, finds no parallel in the modern construction sector. The sector also battles to upgrade health and safety aspects and still uses more traditional procurement practices. These issues are aggravated by the disappearing skills of the workforce and production methods need to evolve if these problems are to be resolved (Buswell and al 2018, 37).

Figure 5: The rise in large-scale additive manufacturing for construction applications since the concept inception in 1997



Source: Buswell et al. 2018, 37.

Despite this obviously negative fact, there are efforts by experts and researchers around the world to compensate for this lag in construction robotics and automation compared to other industries.

Even in 1988 in a study called "Analysis of Robotic Surface Finishing Work on Construction Site" Authors Skibniewski and Hendrickson discussed how a multifunction surface finishing robot that performs a variety of construction operations may be technically and economically feasible, potentially offering greater variety and flexibility in building surface design. They also concluded that the use of a robotic machine for a series of comparative, repetitive surface application operations is likely to be both technically and economically reasonable (Skibniewski and Hendrickson 1988, 1).

Similarly, the same authors in the study named "Automation and robotics for road construction and maintenance" debated how with rising road construction and maintenance expenses and a shortage of productivity improvements, automated road construction and maintenance equipment will be an attractive alternate for completing future routine tasks. They also indicated that road construction and maintenance tasks have considerable promise for progressive automation because of the repeatability and relatively low level of sensory requirements of many of the tasks and that eventually, once single-purpose automated devices prove successful, integrated multitasking systems should be feasible (Skibniewski and Hendrickson 1990, 261).

Using a similar logic, it can be appended that with the developing trend of automation and robotic technologies in construction engineering and civil engineering, new schematics, components and tools will be invented to facilitate the process of integration and to obtain the maximized utility (Kim et al. 2015, 347).

The application of such robots in real-time constructions enables the improvement of multiple parameters such as time, cost and quality (Kumar et al. 2016, 1).

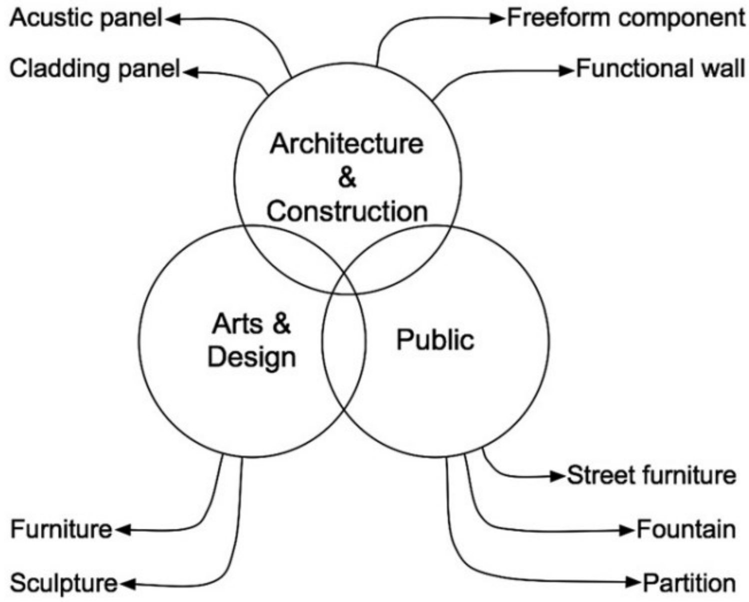
Figure 6: Robotics in construction industry

Automated machinery	Value estimation (per year in Rs)	Payback period(years)	Return on investment (%)	Final suggestion
Reinforcement mat placing robot	14,79,558	3.19	31.32	Recommended
Interior/floor finishing robot	7,21,531	11.8	8.47	Not Recommended for small and medium scale projects.
Quality Inspection robot	2,27,250	3.88	25.70	Recommended
Drones to carry loads	1,19,788	1.66	60.24	Recommended
Sensors to prevent accidents	-	-	95	Recommended

Source: Kumar et al. 2016, 1.

As a result of the efforts of researchers and other experts, the additive manufacturing in construction, however, is starting to develop from a modelling tool for architects into a tool that can be used to manufacture full-size architectural elements and building components such as walls and façades (Lim et al. 2012, 262).

Figure 7: Practical Applications of Concrete Printing Process



Source: Lim et al. 2012, 267.

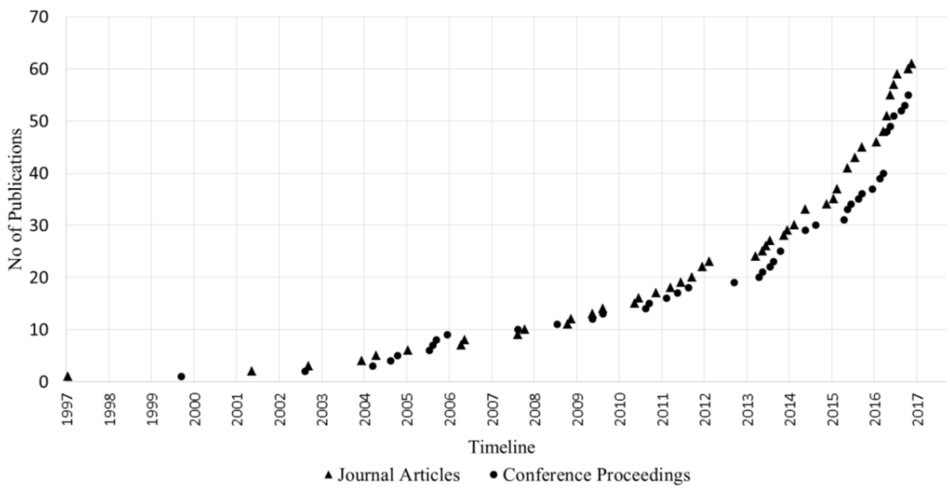
In a study called "Additive construction: State-of-the-art, challenges and opportunities" was concluded that additive construction has the capability to transform the construction industry, though its success depends on the willingness of the entire construction community to overcome three main challenges: the need for an architectural shift in paradigm, the necessity of a holistic design process, and the need for more rational designs (Labonnote et al. 2016, 347).

Methodical research indicates that after years of development, 3-D printing technology can be applied to large-scale printing of architectural models and buildings. Nevertheless, the full scope of the technology's potential is constrained by the lack of large-scale implementations, the development of building data modelling, the requirements of mass customization, and the lifecycle expenses of the printed projects. It is therefore expected that future studies will be conducted in these areas to consolidate the stability and broaden the applicability of 3D printing in the construction sector (Wu et al. 2016, 21).

Another study states that additive manufacturing provides design optimization and on-demand production of customer-specific components, supporting a wealth of evidence found to underpin the promise of additive manufacturing in the fields of (1) customized healthcare products to enhance public health and quality of life, (2) reduced impact on the environment for manufacturing sustainability, and (3) more simplified supply chains to increase efficiency and responsiveness in fulfilling demands (Huang et al. 2012).

In another study called "3D printing trends in building and construction industry: a review" a similar conclusion about the advantages of this technology was drawn stating that a novel application of this technology to the built environment seems to enhance both our traditional construction strategies as well as reduce the need for manpower, high capital investments, and additional formwork. Also, the same study testifies to the more massive emergence of 3D printing technologies of relevant scientific works. Figure 8 shows the number of conference proceedings and journal articles published on 3D printing for B&C from 1997 to 2016. There were 42 publications in the first 16 years of the study period from 1997 to 2012. Between 2013 and 2016, there were 73 publications, which is almost double the number of publications in the first 16 years, demonstrating that the level of interest in 3D printing for B&C application has significantly expanded over this period (Tay et al. 2017, 261).

Figure 8: Trend of publication output over the years



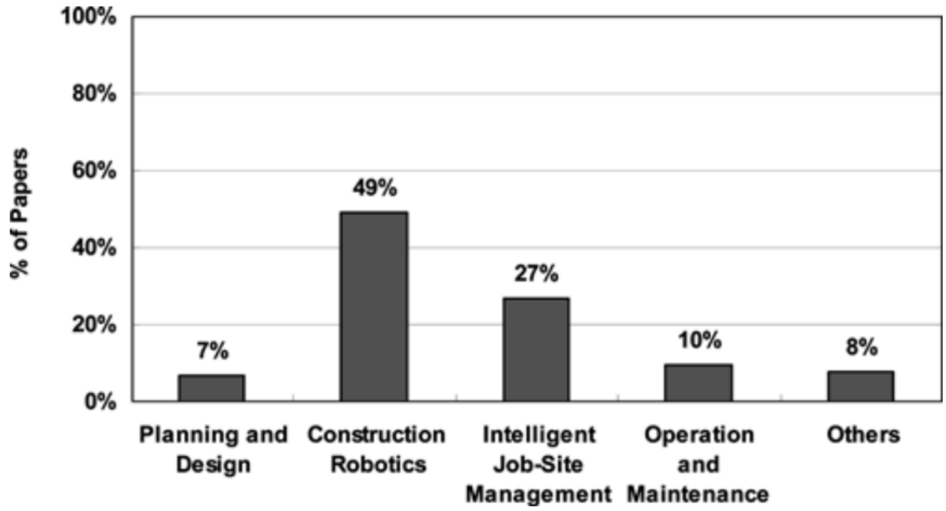
Source: Tay et al. 2017, 261.

Freedom of design, mass customisation, waste minimisation and the ability to manufacture complex structures, as well as fast prototyping, were stated as the main benefits of additive manufacturing (AM) or 3D printing (Tuan et al. 2018, 172).

The paper "State-of-the-art of 3D printing technology of cementitious material"—An emerging technique for construction summarizes the facts that Significant progress has been made in the last few years in the development of large-scale 3D printers to satisfy the demand for 3D printing on an industrial scale. Materials containing cement that are compatible with 3D printing are encouraging the rapid adoption of this cutting-edge technology in the construction industry, with the benefits of cost effectiveness, high efficiency, flexibility of design, as well as being eco-friendly (Ma et al. 2017, 1).

Attention to the development of automation and robotics in the construction industry seems to be growing, and awareness of the potential benefits of developing automation and robotics technologies is increasing as well (Figure 9 below). Although research and development (R&D) may facilitate advancement of the state of the art and provide considerable savings in time and money over the long term to the companies that use it, the cost of R&D is expensive in the short term and resources are constrained. The analysis of trends in existing research is helpful in identifying where further R&D is needed and in proposing directions for research in the future (Hyojoo 2010, 133).

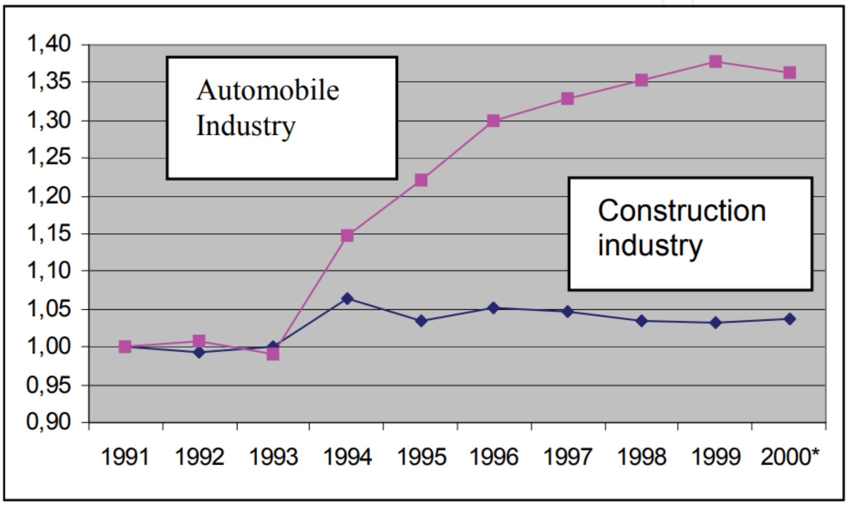
Figure 9: Distribution of Research and Development by a Category



Source: Hyojoo 2010, 133.

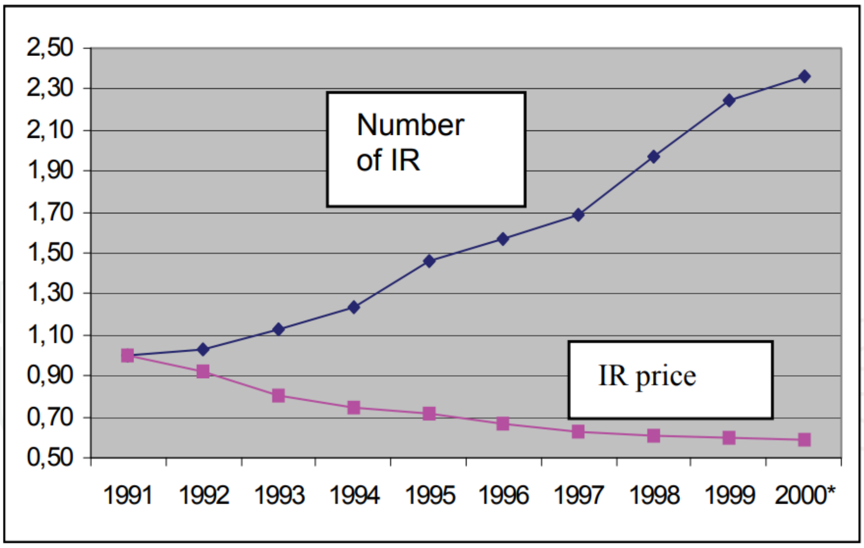
The study “Trends in Robotics and Automation in Construction”, among other things, Shows the gap between the construction and automotive sector in terms of productivity and the number of industrial robots, demonstrating the necessity of further development of all aspects of robotization in the construction industry (Balaguer and Abderrahim 2008, 1).

Figure 10: Productivity of the construction and automobile industries in EU



Source: Balaguer and Abderrahim 2008, 3, based on Euroconstruct, Eurostat, ACEA.

Figure 11: Number of industrial robots (IR) in EU and its price in US$



Source: Balaguer and Abderrahim 2008, 3, based on IFR.

Many of the first applications of AM technologies were in aviation, automotive, and health services. Expanding on the advances of AM in these sectors, there are several as yet experimental implementations of AM in the construction industry (Camacho and al 2018, 110).

Currently, one of these methods being explored both in academia and in construction practice is additive manufacturing of concrete (AMoC). However, despite a steadily growing number of scientists and private enterprises involved in this field, AMoC is still in its early stages. Nevertheless, the different permutations of these manufacturing techniques are continuously being refined and optimize. Underlying scientific comprehension of the links among design, materials, process, and product is being explored. In a study called "Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing" many successful examples of 3D printing projects are mentioned (Bos et al. 2016, 209).

Table 7: Examples of noteworthy 3D construction printing projects

Noteworthy 3D printing projects with short description
1. Two-storey house in China, measuring 400 m2, built by Beijing-based HuaShang Tengda in 2016
2. Interior of a hotel Suite measuring 12.5 × 10.5 × 4 m, in the Philippines, completed 20 September 2015, by Total Kustom
3. Five-storey apartment building in Suzhou, China, completed in January 2015 by Winsun
4. Suzhou, China, a 1100 m2 villa, by Winsun, completed early 2015.
5. Series of 10 houses, in Suzhou, China, by Winsun, 2014. Printed with a massive 150 × 10 × 6.6 m printer
6. Children's Castle, Minnesota, USA, completed August 2014, by Total Kustom
7. Office building in Dubai, UAE, measuring 250 m2, 2016, by Chinese construction company Winsun. The building was printed using a 120 × 40 × 20 feet 3D printer (approximately 36.6 × 12.2 × 6.1 m), featuring an automated robotic arm

Source: Bos et al. 2016, 214.

Combination of three-dimensional (3D) scanning and cement mortar-based 3D printing technology is being used to create a new approach to replicating a historical architectural component that is conventionally labour-intensive and expensive to manufacture (Xu et al. 2017, 85).

In the article entitled "Economic Implications of 3D printing: Market structure Models in light of additive manufacturing Revisited" it was stated that additive manufacturing is currently being touted as the spark for a new industrial revolution, where the technology enables the manufacturing of tailored goods without adding costs in production, as neither tooling nor moulds are needed. In addition, AM facilitates the realization of more complex and integrated functional layouts in a one-step procedure, thereby reducing the requirement on assembly operations. In addition, this article discusses the impact of AM technology at the enterprise and industry levels. Using an analysis of established economic patterns, the economic (Figure 12 below) and technological (Figure 13 below) characteristics of AM have been determined and four key principles of relevance to enterprise-level producers are highlighted (Weller et al. 2015, 21).

Figure 12: AM technology's opportunities and limitations from a technological perspective

Technological characteristics of AM	
Opportunities	Limitations
+ Direct digital manufacturing of 3D product designs without the need for tools or moulds	- Solution space limited to 'printable' materials (e.g., no combined materials) and by size of build space
+ Change of product designs without cost penalty in manufacturing	- Quality issues of produced parts: limited reproducibility of parts, missing resistance to environmental influences
+ Increase of design complexity (e.g., lightweight designs or integrated cooling chambers) without cost penalty in manufacturing	- Significant efforts are still needed for surface finishing
+ High manufacturing flexibility: objects can be produced in any random order without cost penalty	- Lacking design tools and guidelines to fully exploit possibilities of AM
+ Production of functionally integrated designs in one-step	- Low production throughput speed
+ Less scrap and fewer raw materials required	- Skilled labour and strong experience needed

Source: Weller et al. 2015, 30.

Figure 13: AM technology's opportunities and limitations from an economic perspective

Economic characteristics of AM	
Opportunities	**Limitations**
+ Acceleration & simplification of product innovation: iterations are not costly and end products are rapidly available	- High marginal cost of production (raw material costs & energy intensity)
+ Price premiums can be achieved through customization or functional improvement (e.g., lightweight) of products	- No economies of scale
+ Customer co-design of products without incurring cost penalty in manufacturing	- Missing quality standards
+ Resolving "scale-scope dilemma": no cost penalties in manufacturing for higher product variety	- Product offering limited to technological feasibility (solution space, reproducibility, quality, speed)
+ Inventories can become obsolete when supported by make-to-order processes	- Intellectual property rights & warranty related limitations
+ Reduction of assembly work with one-step production of functional products	- Training efforts required
+ Lowering barriers to market entry	- Skilled labour and strong experience needed
+ Local production enabled	
+ Cost advantages of low-wage countries might diminish in the long run	

Source: Weller et al. 2015, 44.

Figure 14: Key principles of production with AM technology

Versatile manufacturing machine	- On-demand direct digital manufacturing of 3D product models enabled - End products are rapidly available at constant marginal cost (no economies of scale) - Local availability of versatile manufacturing resources with standardized interface
Customization and flexibility for free	- Product designs can be customized without cost or time penalties in manufacturing - Volume and product flexibility without cost or time penalties for machine setup or changeover - No tools or moulds needed
Complexity for free	- Higher design complexity without cost penalty in manufacturing - Little design constraints for products - No cost penalties for higher product variety
Reduction of assembly work	- Direct production of functionally integrated parts (e.g., moving parts, cooling system) possible - Fewer production steps involved - Lower manual intervention throughout production processes

Source: Weller et al. 2015, 46.

The factors listed in Figure 12 and Figure 13 served as the starting ground for labelling the critical success factors in construction projects using 3D printing technology, as there such research trends are missing in the construction sector. Nevertheless, their limitations were considered due to the specifics of the manufacturing sector.

The paper called “Framework for decision-making on implementing robotics in construction” introduces a framework for a computerized decision aid in the form of an expert system that analyses possible robotic applications in construction. The knowledge base for such a tool should contain the robotic work performance characteristics and a detailed economic analysis, and it should reflect company's technical and business long-term goals (Skibniewski 1988, 188). This was one of the preparatory principles for specifying the decision-making tools characteristics in this thesis.

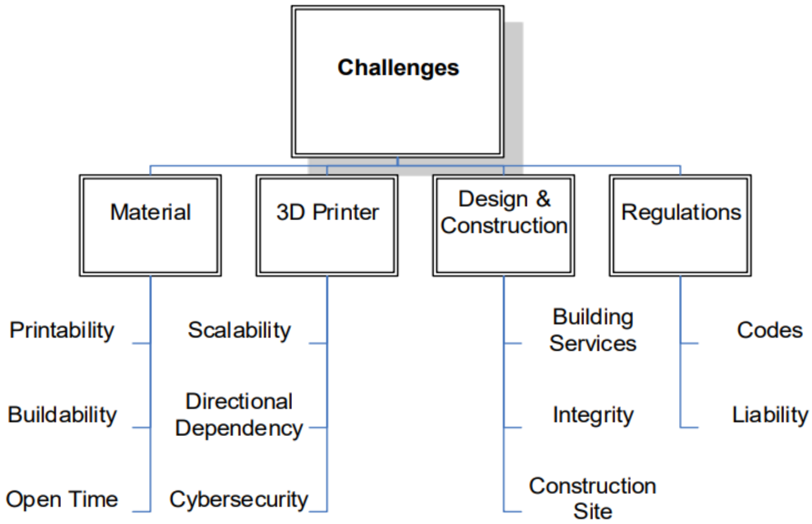
From the point of view of the material used, the basic concept that makes rapid manufacturing feasible is the capacity to selectively control either the material deposition or the material phase change activation. Additionally, rapid manufacturing is reliant on a complete digital rendering of the geometry of the items to be produced (Buswell et al. 2008, 224).

Compatibility of currently available materials, however, has been a barrier to widespread adoption and market penetration (Panda et al. 2018, 666).

The requirements are also very different in the United States than in Japan, for example. The disparities in cultural, economic, and business conventions help explain why construction automation and robotics is sparking so much action and investment in Japan, but so few in the United States (Everett and Saito 1996, 122). This discrepancy in trends between certain countries is also visible in the case study section that deals with the project organization structure, presented in this thesis. Also, the difference is visible in the comparison of target construction standards between, for example, the USA and Germany (Chapter 7.3.).

According to Romdhane and El-Sayegh, there are four categories of challenges: Material, Printer, Design and Construction, and Regulations. Figure 15 illustrates the key categories and the accompanying challenges (Romdhane 2020 and El-Sayegh, 314).

Figure 15: Challenges of 3D printing



Source: Romdhane 2020 and El-Sayegh, 316.

In terms of future prospects, Contour Crafting (CC) was recognized back in 2004 as a technology for layer-by-layer fabrication that has significant promise for the automated construction of entire structures as well as subcomponents. Using this method, a singular house or a colony of houses, each potentially with a different design, can be automatically constructed in a single run, with all wiring for electrical, plumbing, and air conditioning being embedded in each home. There has also been research on the application of CC in the construction of habitats on other planets. Most likely, CC will be one of the few viable approaches to construct structures on other planets, such as the Moon and Mars, for human habitation before the end of this century. This field is also a good indicator of how far behind the construction sector is compared to other sectors (e.g., manufacturing) (Khoshnevis 2004, 5).

The paper, titled "Cable Robotic 3D-printing: additive manufacturing on the construction site", details an important step in the characterization of a new field of research in robotic design that uses a cable-driven parallel robot to extrude cementitious material in three-dimensional space. This will offer a comprehensive new approach to computer-aided design and construction, as well as robotic manufacturing on a larger scale. Developed by the Faculty of Art and Design at Bauhaus University Weimar, the Faculty of Architecture at Dortmund University of Applied Sciences and Arts, and the Chair of Mechatronics at the University of Duisburg-Essen, that approach provides unique advantages over existing additive manufacturing methods. It is easily transportable and scalable, it eliminates the need for additional formwork or scaffolding, and it provides digital integration and information control across the entire design and construction process (Hahlbrock et al. 2022, 305).

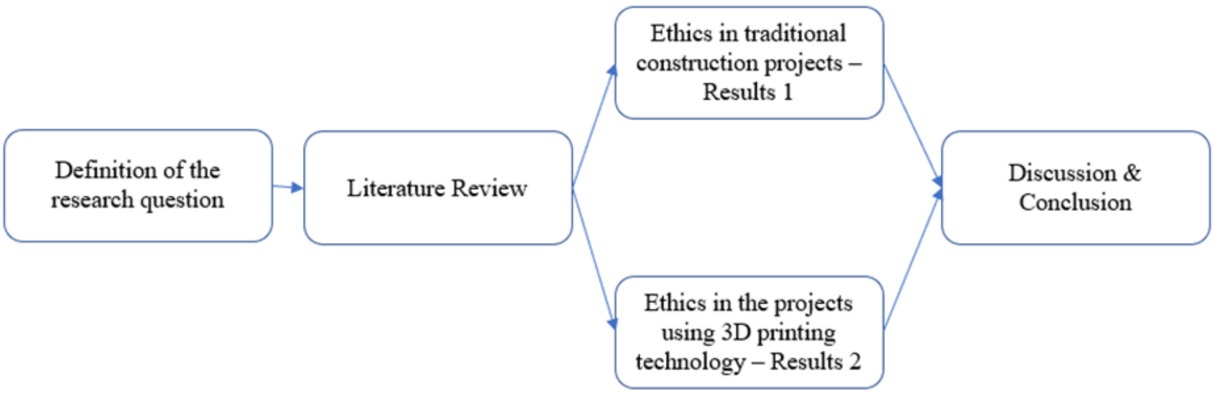
2.2 Ethics in construction projects utilizing 3D printing technology

Some of the following fragments that could be challenging in the standardization and automation of construction projects that use 3D printing technology is the ethics of such projects. According to Cambridge Dictionary, ethic is a system of accepted beliefs that control behaviour, particularly such a system that is based on morals (Cambridge Dictionary 2022, 1). Ethics management, business ethics, and corporate social responsibility are latest ethics-related issues for all corporations globally, and there is not enough proof that the same level of attention is being paid to ethics management in the construction industry and construction projects (Kang et al. 2004, 1).

If this is the situation with conventional construction, it can be presumed that in projects that use 3D printing technology, the matter of ethics is even more overlooked (due to the fact that 3D printing technology in construction is a comparatively innovative expertise). The goal of this article was to explore that assumption and to draw conclusions from conventional construction as a foundation for upcoming research into ethical concerns in projects that utilize 3D printing technology.

In this literature review article, the "Google Scholar Database" was examined for scientific articles that discuss ethics in construction projects in overall, and they were categorised by significance and publication date. Afterwards, further articles on the "Google Search Engine" with the same subject were sought and ordered in the same manner. The complete process was then duplicated for construction projects using 3D printing technology. This process is visible in the graphic below (Figure 16). The results for traditional construction and 3D printing technology were separately offered. Finally, in the discussion and conclusion section, the recommendations for further research on this issue are given.

Figure 16: Ethics in construction projects utilizing 3D printing technology – Research methodology



Source: Spicek 2022, 486.

Literature review findings

Literature review – Ethics in traditional construction projects

The most frequently quoted study on this topic is called "How professional ethics impact construction quality: Perception and evidence in a fast developing economy" and it clarifies how professional ethics plays an important role in quality-correlated difficulties in a construction project with the deduction that professional ethics is a pre-condition for reaching constant and acceptable quality in construction and proposes various tactics to boost professionalism among construction experts to advance excellence in construction (Hamzah 2010, 3742).

Research called "Ethics in construction project briefing" states that diverse project participants are known to follow personal objectives to differing levels and having different viewpoints/insights as well as operating/behaving alternatively in various situations. Consequently, determination of the proper structure and content of a project is, expectedly, a question of applying value verdicts and compromises. In that sense it indicates ethical considerations (Fellows 2004, 289).

Additional germane studies are occupied with topics such as “Developing a systems approach for managing ethics in construction project environments” (Kang et al. 2004, 1), “Ethics in construction law” (Uff 2003, 2), “Ethics training on multi-cultural construction projects” (Kang et al. 2014, 1) on top of “Professional ethics in construction industry of Pakistan” (Ehsan et al. 2009, 1).

Apropos of non-scientific articles, the CHAS portal describes through an article known as “Promoting Good Ethical Practice in Construction” exactly how ethics are a factor of our choices in both everyday life and business — and that involves the construction industry as well. It also presumes that a construction-company code of behaviour will typically centre around a basic set of “good ethics” or values. This set frequently consist of honesty, integrity, kindness, fairness, and respectfulness. Those five characteristics relate to the unanimity of comparable articles that can be observed on the “Google Search Engine” (Minett 2022, 1).

Literature review – Ethics in construction projects utilizing 3D printing technology

The utmost suitable study, in the field ethics of construction projects that use 3D printing technology, is entitled “The Problem with Printing Palmyra: Exploring the Ethics of Using 3D Printing Technology to Reconstruct Heritage” and indicates that the usage of 3D printing technology to remake the Arch of Triumph in Palmyra has unlocked a “Pandora’s Box” of ethical problems regarding the use of digital technology to preserve inheritance embodied by historic objects and sites (Khunti 2018, 1).

Nevertheless, it is only fraction of the formerly said five aspects of ethics in construction projects (Minett 2022, 1). From other subdivisions of science, for instance medicine, few conclusions may be reached about the ethics of 3D printing where three ethical matters are spoken: fairness in access to health care, testing for safety and efficacy, and whether these technologies should be applied to augment the capability of persons outside what is 'normal' for people (Dodds 2015, 1).

Analogously, for the construction sector it can theoretically become an ethical question when building cheaper houses using 3D printing technology. Likewise, a report named "Top 3 legal issues of 3D Printing!" records 3 big legal-ethical quandaries that rise with 3D printing, explicitly: Is "3D Printing the new piracy", "Who is liable for products manufactured through 3D printers" and "Are replicas privacy threats"? It was deducted that there are still a plenty of open doubts on 3D printing and, as often occurred related to slightly new sort of technology, legislators and courts may possibly not be entirely prepared for them (Coraggio 2015, 1).

While it is quite obvious that ethical matters have a great influence on challenges regarding the quality of construction projects, ethical issues of such projects are still a pretty unexplored subject. Nonetheless, there are, yet scarce, some findings that describe, clarify and support through various examples the most crucial sections of ethical concerns in conventional construction projects. Alas, 3D printing, as a fairly new technology, is even less exemplified in studies on ethical matters, which is partially plausible given the only recent growth of the technology. Probable conclusions from some other sectors that use 3D printing technology, for example medicine, would be viable completion of this gap.

Ethical queries of construction projects that utilize 3D printing technology should be an imperative unit of standardization process and responses to such queries could possibly help to generate trust among the participants of this projects, for an improved and more consistent transmission of information. Accordingly, it could seriously contribute to the automation of such ventures.

For the future research, it would be thought-provoking to understand through case studies and the several roles and responsibilities of participants of construction projects that utilize 3D printing technology, how certain projects have demonstrated themselves in the field of the above-mentioned topics of honesty, integrity, kindness, fairness, and respectfulness. Those conclusions could be extremely beneficial when analysing the critical factors of success (or failure) of such projects. More could be then told regarding the fact whether the expertise of ethics from conventional construction projects is satisfactory or whether it is required to create new theories and/or to modify them to this new technology.

2.3 Construction project organization for 3D printing technology

2.3.1 Construction projects using 3D printing technology (strengths, weaknesses, challenges, critical success factors)

In the course of the development of construction technology, the application of prefabrication was marked as one of the milestones that brought significant improvements. However, it was determined that appropriate criteria for evaluating applicability to a particular building were not satisfactorily offered. Making decisions about the application of prefabrication is for the most part still based on anecdotal evidence or a purely cost-based evaluation when comparing different construction methods (Chen et al. 2010, 848).

It could nevertheless be an important source of lessons learned about today's 3D printing technology, which lacks standardization, fundamentals, and benchmark examples of successful construction projects using 3D printing technology. Three-dimensional (3D) printing in construction engineering has evolved quickly in recent years and is being prototypically used for rather small-scale building and bridge construction projects. Several 3D printing-based solutions, nevertheless, are still at the stage of laboratory experiments, so the question of how to successfully use 3D printing continues to be one of the biggest challenges for the construction industry (Besklubova et al. 2021, 1).

The same authors suggested nine potential factors and thirty-two of their measurements that govern the decision to adapt 3D printing technology into construction projects, where the most important factors for the success of 3D printing technology in construction were "technology compatibility", "supply-side advantages", and "complexity" (Besklubova et al. 2021, 1).

In addition, the theoretically near field of "additive manufacturing" refers to technologies in which three-dimensional objects are built up layer by layer, with each successive layer bonding to the preceding layer of molten or partially molten material. The pertinent studies on this topic have focused on the additive manufacturing implementation process and are being driven by the lack of socio-technical studies in this area. The emphasis is on the need for existing and potential future additive manufacturing project managers to have an implementation framework to assist their efforts in implementing this emerging and potentially ground-breaking technology (Mellor et al. 2014, 194).

Also, the research of Sonar et al contributes to identifying the factors of additive manufacturing from a general viewpoint, while context-specific factors require further exploration (Sonar et al. 2020, 1837).

The two studies mentioned above (Mellor et al. 2014, 194; Sonar et al. 2020, 1837) also confirmed that the issue of roles, responsibilities, and interactions of key stakeholders in construction projects using 3D printing technology is still a relatively new topic that should be studied more in the future.

2.3.2 Collaboration between construction project key participants

Within the field of conventional construction, there are notable models of collaboration between project participants, the conclusions of which can conceivably be extrapolated to projects that utilize 3D printing technology. One such example is the study undertaken as part of Paper named:" A systematic review of 'enablers of collaboration' among the participants in construction projects" seeks to identify the enablers, i.e., governing factors of collaboration (Deep et al. 2019, 919).

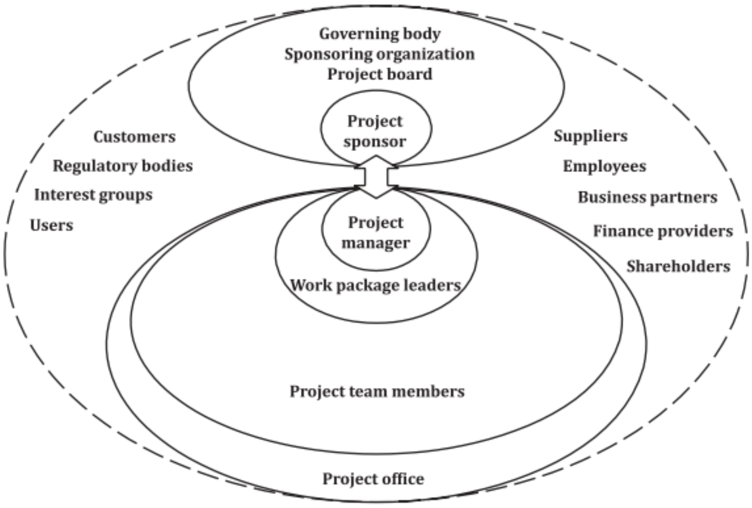
The study "Impact of participants' values on construction sustainability" examines the methods by which values are determined and operationalized in the context of construction projects, especially with regard to sustainability. The TMO (the project temporary multi-organization) is an everchanging, multi-objective, power-based alliance that raises oscillations in the values used to govern the project as it progresses, making performance evaluation extremely problematic. As values are people-defined, they are rooted in culture. Understanding culture as an operational concept in the project's value system encourages the knowledge and development of ideas and practices related to construction project sustainability for the reason already mentioned, namely that values are defined by people (Fellows and Liu 2008, 219).

While this is a potentially intriguing approach, the effect of the progressive membership and power structure of the temporary multi-organization (TMO) should be further evaluated in projects utilizing 3D printing technology, with the strong suggestion that the cultural factor should be incorporated as a vital factor in the sustainability of construction projects other than temporary multi-organization (TMO), the impact of participant values on construction sustainability is a segment that is worth investigating in projects using 3D printing technology. It is evident that technology is one of the core ingredients for the success of construction projects. Nevertheless, even the most advanced high-tech alone cannot necessarily guarantee success. Evidence from the field is plentiful that various users are achieving different results, even despite the fact that they are using the same technology. This is linked to the people' role and the manner in which they are skilled and organized in a project. Therefore, the only scenario that will lead to high-level success is one in which advanced technology is paired with appropriate organization and management.

2.3.3 Roles, responsibilities, and interactions of key participants in project organization structure

Various project management standards or/and methodologies (e.g., ISO and PM²), laws and regulations of the countries where the case studies took place, and several aspects of the literature (scientific papers) were examined in order to outline the roles, responsibilities and interactions of the key players within the organisational structure of construction projects. In accordance with ISO (International Organization for Standardization), an individual can only undertake one role, while their responsibilities are detailed in the ISO document (ISO 21502:2020 2020, 15). It describes the roles and responsibilities of, among others, project sponsors, project managers, project officers and project participants in general, as illustrated in Figure 17 below.

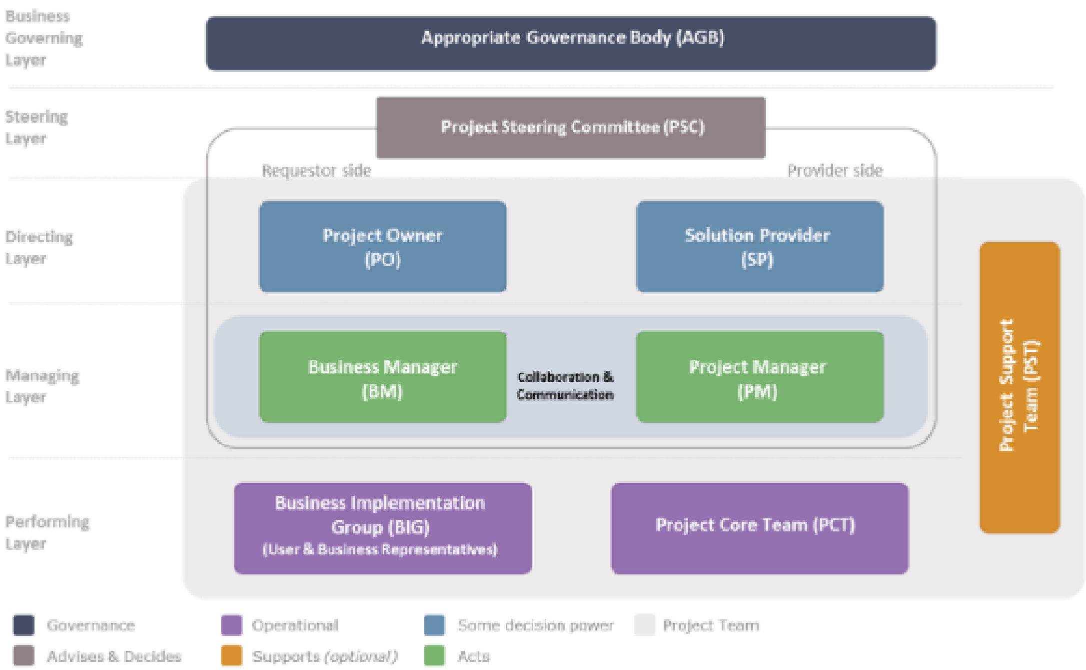
Figure 17: An example of potential project stakeholders



Source: ISO 21502:2020 2020, 15.

PM² (the official project management methodology published by the European Commission) indicates that there is a project team composed of the people assuming the roles defined in the Performing, Managing and Directing Layers, and in order to make the project successful, these individuals must work together as a team. Having strong cooperation and communication between the Business Manager (BM) and the Project Manager (PM) is vital to the success of the project (PM² 2018, 23).

Figure 18: Project Organisation: Layers and Roles



Source: PM² 2018, 23.

The above examples verify that the organisational structure and key roles and responsibilities are acknowledged as crucial components of successful project management.

Despite the variations in the organisational chart, a more detailed analysis could validate the stability of the key concepts and attitudes, while the details could be adapted to the project characteristics and project ecosystem.

Looking at the laws of individual countries, German law, for instance, can be split into two broad areas of law characterised by different legal principles and jurisdictions: private law and public law, where law regulates legal relations between equal legal entities and has the duty of shielding the legal interests of individuals. In particular, the German Civil Code (BGB) states that there are many other parties involved in the construction process in addition to architects and engineers. These include, among other parties, the client, the architect and the various specialist engineers involved: structural engineers, building services engineers, acoustic engineers, engineers for traffic installations, geotechnical engineers, surveyors, etc. Contrary to Germany, where the law is codified and thus a unified and generic construction contract law applies, legally regulated in the BGB (German Civil Code) and further specified by the VOB/B

(German Construction Contract Procedures), a comparable legal framework for construction industry contracts is virtually absent in England (Wirth et al. 2004, 329).

Notwithstanding this, clients, designers, contractors and others engaged in construction activities have obligations under the Construction (Design and Management) Regulations 2015. The parties referred to in the CDM Regulations are the client - the person for whom a project is being undertaken, the principal designer - who has control of the pre-construction phase of the project (appointed by the client), the designer - the organization or person who prepares or modifies a design for a construction project or who instructs or guides another to do so, the main contractor - the organization or person who is responsible for coordinating the work in the construction phase of the project involving more than one contractor so that it is performed in a manner that assures safety and health, and the contractor - any person who directly employs or hires construction workers or manages the construction (CDM 2015, 1).

Three branches of government are known in the US: the judiciary, the legislature and the executive. Each of the branches mentioned is contributing to the laws that regulate planning and building contracts. Different laws may apply to a construction project depending on, amongst other factors, whether the project is private or public, the country in which the project is sited, and the sort of project concerned (DLA Piper 2022, 1).

The construction law in the US is the field of law that addresses the regulations, guidelines and requirements in the construction industry and encompasses components of contract law, property law, commercial law, labour law and many other subjects. It is essentially a collection of regulations that regulate the way in which a construction project should be executed and who is liable if something fails (Budde 2022, 1).

Based on the interpretation of the construction contract, one could conclude that the parties involved in a construction project have the following roles: Owners, Architects/Engineers, Construction Managers, Contractors, Subcontractors and Suppliers (Caravella 2022, 1), which have responsibilities and scope of work not too dissimilar from the roles and responsibilities outlined in the previous said countries. In all selected countries, the main stakeholders and their roles and responsibilities are broadly defined in the regulations, with only minor variations.

2.4 "Construction 5.0" Paradigm

2.4.1 Industry 4.0 overall - A suitable foundation for identifying impact dimensions

According to the authors of the paper, entitled " Industry 4.0 technologies: Implementation patterns in manufacturing companies," Industry 4.0 is considered a newly emerging industrial era where several upcoming technologies converge to deliver digital based solutions. There is, nonetheless, a shortage of comprehension on the way in which companies are adopting and implementing those technologies. Thus, the goal of the above-mentioned paper is to provide an explanation of the adoption models of Industry 4.0 technologies in manufacturing organizations, with several limitations opening up new directions for potential future studies (Frank et al. 2019, 15).

Another question is the extent to which the models from this example can be applied in the Industry 5.0 environment, as they focus only on the digital facets of the transformation and ignore the human-centric perspective as a basic principle of the Industry 5.0 approach. Additionally, it is questionable to what degree this manufacturing model is usable in the adjustment in the project setting. Nevertheless, some implications could be applicable and, in the absence of similar research, could serve as a basis for designing premises within the project organization.

The Maturity Assessment Framework has been proposed in a different study as a way to understand the process of transformation in manufacturing organizations that are moving to Industry 4.0 while also struggling with embedded business challenges that demand the creation of new organizational and technological skills. This was then adapted to 10 in-depth industry case studies in Canada and Italy. Based on a comparative case study assessment, four different standards or archetypes for Industry 4.0 adoption were identified and debated, demonstrating a correlation between a company's manufacturing setup and its journey towards Industry 4.0 implementation (Scremin et al. 2018, 224), whilst stating again that the project's context and particularities were neglected.

The initialization of Industry 4.0 procedures might be a way to address current market turbulence and to safeguard the sustainability of the German industrial sector, which is confronted with strong competition from Chinese and North American businesses, as well as other market vulnerabilities such as volatile customer demand and shortage of resources. The critical factors that have an influence on the adoption of Industry 4.0 related operations were therefore gathered and explored. There are two factors that are positively correlated with the adoption process, the findings indicated, specifically: IT infrastructure and company size. The negative correlates are 4 factors, which can be further described as: Lack of financial resources, inappropriate employee skills, reluctance to change, and maturity level (Balasingham 2016, 1).

Similarly, the fit of Industry 4.0 applications in various production settings is not evident. Purpose of the research "The fit of Industry 4.0 applications in manufacturing logistics: a multiple case study" is to explore and determine the Industry 4.0 technologies that are usable in production logistics and how the production setting affects the adoptability of these technologies. It is done through a multiple case study in four Norwegian production organizations. The findings of the study indicate that the usability of Industry 4.0 in production logistics is dependent on the production setting. Organizations with a lower grade of repetitiveness in production perceive less opportunity for the adoption of Industry 4.0 technologies in production logistics, while organizations with highly repeatable production see a greater potential (Strandhagen et al. 2017, 359). This might be a useful implication for a potentially more troublesome adoption in the project rather than in the production context.

A paper called 'A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises' suggested an experimentally grounded innovative model and its application for evaluating the Industry 4.0 readiness of industrial companies in the discrete manufacturing sector. Among them, it defined 9 dimensions and allocated 62 items to evaluate the Industry 4.0 readiness level. The dimensions "Products", "Customers", "Operations" and "Technology" have been established to evaluate the fundamental enablers. Furthermore, the dimensions "Strategy", "Leadership", Governance, "Culture" and "People" allowed the incorporation of organizational dimensions into the evaluation. Preliminary validations of the model's structure and content demonstrate that the model is both transparent and straightforward to apply, and has proven its usefulness in real-world manufacturing settings (Schumacher et al. 2016, 161).

Another paper entitled "A conceptual approach to analysing manufacturing companies' profiles concerning Industry 4.0 in emerging economies" introduces a broad conceptual framework for systematically assessing and tracking the preparedness of manufacturing organizations for Industry 4.0 in developing economies. Beyond an exclusively technology focus, this approach includes different organizational, managerial, employee, and systemic interaction dimensions.

Framed within a conceptual framework, the approach suggests that producing organizations can be typified by different " levels of readiness for Industry 4.0" (Horvat et al. 2018, 419).

Gauging the adoption of Industry 4.0 in the manufacturing sector is somewhat problematic given the absence of a single definition of the term as well as the lack of information specifically gathered on Industry 4.0 concepts. The study presented in the paper "Assessing Industry 4.0 readiness in manufacturing: evidence for the European Union" is measuring the existence of the factors that are characterizing Industry 4.0 in manufacturing across EU countries. Their analysis reveals that the existence of a digital infrastructure coupled with analytical skills to handle Big Data are the two dimensions that show readiness for Industry 4.0 in any country (Castelo-Branco 2019, 22). The paradigm of Industry 4.0 was then applied as a basis for possible conclusions for Industry 5.0.

2.4.2 Industry 5.0 – Concept and patterns

A decade following the introduction of Industry 4.0, the European Commission has declared Industry 5.0. Industry 4.0 is seen as technology-driven, while Industry 5.0 is value-driven. The co-existence of two industry revolutions poses some questions and consequently requires further debate and explanation (Xu and al 2021, 530).

Nowadays, we are looking beyond Industry 5.0, that is about personalizing of products. Industry 5.0 demonstrates enhanced cooperation between humans and intelligent systems via high-precision industry automation empowered by critical thinking (Haleem and Javaid 2018, 807).

While technology develops expeditiously in the era of digitalization, Industry 4.0 has emerged as a reference term for R&D in the fields of technology in several sectors. This makes everybody to create technologies that can simplify people's lives and make them more beneficial. Therefore, the concept that is introduced is a society revolution that utilizes both technology and considers the human aspects. Certain fields of work and requirements commence with digitalization that uses artificial intelligence, Big Data, robotics, automation, machine learning, and the Internet of Things (Faruqi 2019, 67).

As a result of fast-growing and evolving digital technologies and AI-based solutions, it is getting harder and more challenging to remain at the forefront. The technology, mass customization, and advanced manufacturing world is rapidly transforming. Need to boost productivity while not removing human workforce from the production sector presents great challenge to the global economy, for which a solution has been attempted through the concept of Industry 5.0. In the paper, "Industry 5.0 - A Human-Centered Solution," a set of key characteristics and worries that any producer may have related to Industry 5.0 are also highlighted, with the argument that Industry 5.0 is expected to generate more jobs than it will annihilate (Nahavandi 2019, 1).

"On the road from Industry 4.0 to Industry 5.0: from digital manufacturing to digital society" paper sketches modern technologies - from the Internet of Things to emergent intelligence - that get engineered in the organizations where the authors work. According to them, the convergence of such technologies will facilitate the transformation from Industry 4.0 to Industry 5.0 (Skobelev and Borovik 2017, 307).

There are a range of visions for Industry 5.0, as stated in the paper "Industry 5.0 and Human-Robot Co-working", and one upcoming topic is human-robot collaboration. Over the past few years, robotics and artificial intelligence (AI) research has made considerable advancements. But while there are many studies on human-robot cooperation in straightforward tasks that concentrate on the development of robots, there is a shortage of studies that address organizational concerns that may arise from human-robot collaboration. Regardless of whether Industry 5.0 will be predominantly about human-robot collaboration or not, human-robot collaboration is going to be a game changer for companies. In fact, robotics in our lives is expected to be a momentous game changer for mankind (Demir 2019, 688).

The paper "Innovation in the Era of IoT and Industry 5.0: Absolute Innovation Management (AIM) Framework" notes that in the modern business setting of rapid technological advancements and globalization, fostered by the Internet of Things and Industry 5.0 phenomenon, innovation is imperative for both competitive advantage and economic prosperity. A new framework for innovation management called "Absolute Innovation Management (AIM)" has been proposed in this research to make innovation more comprehensible, implementable, and imbedded in daily business by synergistically bringing together the innovation ecosystem, design thinking, and business strategy to achieve both competitive advantage and economic growth. To summarize, innovation, design thinking, and strategy are combined to make organizations future-ready for the Internet of Things and the Industry 5.0 revolution (Aslam and 2020, 1).

Not only knowledge and digital life, but also robots that behave like humans will take up a large space in the near future. It is due to the fact that people are starting to collaborate with Industry 4.0, which in other words means that Industry 5.0 is arriving (Özkeser 2018, 1).

2.4.3 Construction 4.0 - A suitable foundation for identifying impact dimensions

The Construction 4.0 technologies provide the ability to enhance the planning, management, operation, and decision-making of construction projects (Osunsanmi and 2020, 547).

Over the past few years, the use of 4.0 technology in the construction industry, referred to as "Construction 4.0," has grown, largely due to the immense potential of Industry 4.0 to enhance the execution of construction projects and structure the accompanying management processes. Altogether, the analysis in the paper "Construction 4.0: a survey of research trends" reveals that research on Construction 4.0 is strongly linked to the construction phase (Perrier et al. 2020, 416).

Nevertheless, as the definition of Construction 4.0 continued to be unclear, it was considered essential to undertake a survey of publications in this field. According to the results of the study "Construction 4.0: A Literature Review", the amount of publications is exponentially increasing, with the US, UK and China leading the way. This deduction is also clearly visible in the case studies as part of the project organization structure of this thesis. Additionally, four technologies are essential to understanding Construction 4.0 at this time: 3D printing, Big Data, virtual reality, and the Internet of Things (Forcael et al. 2020, 1).

Echoing the concept of Industry 4.0, the idea of Construction 4.0 is based on a confluence of trends and technologies that promise to transform the way buildings are designed, built, and operated. With the pervasive use of building information modeling (BIM), lean principles, digital technologies, and offsite construction, the industry is on the cutting edge of this evolution. The purpose of the Construction 4.0 - An Innovation Platform for the Built Environment handbook" is to outline the Construction 4.0 framework and identify the resulting processes and practices that will allow us to plan, design, deliver, and operate built environment assets in a more effective and efficient manner by concentrating on the transformation from the physical world to the digital world and then back from the digital world to the physical world (Sawhney and 2020, 1).

Construction 4.0 stands for the investigation of new technologies by the architecture, engineering, construction, and operations industries and is the equivalent of Industry 4.0 in the manufacturing sector. These concepts are not just referring to technological aspects, but also to management and processes. The findings of the study "Quantitative Review of Construction 4.0 Technology Presence in Construction Project Research" indicate that new technologies are addressed separately, while synergy research is rare. Additionally, it is evident that there is a major research gap regarding Construction 4.0 technologies in the construction project context (Schönbeck and 2021, 129).

The equivalent of Industry 4.0 in the AEC/FM industry, also known as Construction 4.0, fundamentally centers around the digitization and automation of the AEC/FM industry. With robotics and other technologies entering the various phases of the construction project lifecycle, worries about the future of both jobs and wages are expected to rise. Although the use of robots has the capacity to boost productivity and safety, it is not necessarily likely to lead to a decrease of overall employment in the construction sector in the long term. It is expected that current professions will evolve and new professions will be generated (e.g., workers with digital skills will be required in tandem with construction workers). Based on the study "Implications of Construction 4.0 to the workforce and organizational structures," it seems that there will be a time when conventional construction and robotic technologies will coexist, leading to increased job flexibility as well as new roles at both management and operations/execution levels (Garcia de Soto et al. 2019, 205).

Traditionally, the construction industry has been marked by a high diversity of stakeholders and processes, a high resistance to change, and a limited use of technology in comparison to the manufacturing industry. Nevertheless, the construction industry is presently undergoing a vigorous process of renewal in terms of methodology and tools as a result of the incorporation of Building Information Modeling, Lean Construction, and Integrated Project Delivery. For example, the research "Methodological-Technological Framework for Construction 4.0" shows a methodological-technological framework adjusted to the architecture, engineering, construction and operation industries. It demonstrates the effects on this industry by reacting to its complexity and specific challenges, like the unique spaces for each work that are hard to standardize, random cost overruns and productivity that is far below the average of other sectors, increasing competitiveness and globalization in contrast to its traditionally local distribution, and the growing requirement to decrease the carbon footprint for all its operations (La Rivera et al. 2020, 689).

The adoption of Industry 4.0 is a serious issue for the construction industry (Construction 4.0). This challenge is even bigger given the low culture of innovation in the construction industry and the demographic structure of the industry - a few executives and a large majority of small and medium-sized companies with very diverse levels of technological maturity. There is also a significant challenge in transforming the industry from business models where the product is "physical in nature" to information and digital products, data, and intellectual business models (Klinc and Turk 2019, 1).

2.4.4 “Construction 5.0” - Concept and patterns

The “Construction 5.0” project seeks to encourage the alignment of technological and digital innovations for the construction industry along societal dimensions in the coherence of the 17

Sustainable Development Goals (SDGs) of the United Nations and the Paris Agreement (CICA 2022, 1).

Figure 19: 17 Sustainable Development Goals (SDGs)

Source: UN Global Compact 2022, 1.

"Construction 5.0" is the fusion of the preceding Construction 4.0 and Sustainable Construction working groups. Construction 4.0 covered technologies such as BIM, drones, robotics, and artificial intelligence, inclusive Big Data and augmented reality. The 5.0 dimension is adding the social angle to digitization, which also includes commitment to the Sustainable Development Goals (SDGs), for example, by targeting the industry's key performance indicators (KPIs) to the UN's 2030 Agenda for Sustainable Development. The Construction 4.0 perspective is complementary to sustainable construction and vice versa, as emerging and digital technologies are expected to facilitate the realization of the Sustainable Construction Goals. It is also expected that the application of robots, artificial intelligence, including Big Data and augmented reality, will enhance the capacity to supervise construction projects and improve the construction industry's performance in terms of providing sustainable and smart buildings/infrastructure (CICA 2022, 1).

2.4.5 Project Management in Industry 4.0 and Industry 5.0 - Concept and patterns

The implementation of Industry 4.0 in a production organization is a very demanding process that consists of many different activities. Such activities must be planned and managed, and it is viable to describe this process as a project. The main objective of project management is to effectively achieve the desired goal, and this is possible in the instance of the Industry 4.0 implementation project (Hirman et al. 2019, 1181).

Industry 4.0 has a complexity beyond the modern manufacturing execution system (MES) and world-class manufacturing (WCM). The purpose of the study "Interaction in Project Management Approach within Industry 4.0" was to demonstrate that the concept of project management within the Industry 4.0 approach, which seeks to combine large-scale physical and virtual worlds, is especially impacted by this transformation in the manufacturing sector. Through this study, it is determined that a shift in the project management approach is an imperative (Cakmakci 2019, 176).

Industry 4.0 is also a multi-dimensional concept that addresses the current trends of automation, digitization, and data sharing in advanced technologies and manufacturing processes. Within this context, project managers are attempting to comprehend the technological changes and their impact on project management practices (Lopez-Robles 2020, 1).

The 4th Industrial Revolution is questioning the very nature of how we work on all fronts. In fact, its impacts are evident in families, organizations, and communities. One part of the work environment concerns the way project teams should be managed. To implement the various technologies that form the foundation of the fourth industrial revolution, speed and flexibility will be necessary. As such, this requires project teams and project managers to modify their practices (Marnewick and Marnewick 2019, 314).

Since manufacturing IT and Industry 4.0 projects differentiate from conventional technical projects, other strategies, e.g., agile project management, are required to guarantee success (Gentner 2016, 628).

2.4.6 The concept of sustainability in project management

Sustainability is one of the most significant global challenges of modern society, which is specifically explaining how can we develop prosperity while not endangering the lives of future generations. Organizations are incorporating sustainability thinking into their marketing, corporate communications, annual reports, and operations. It is acknowledged that projects play a central role in achieving more sustainable business practices, and an emerging theme in project management research is the relation between projects and sustainability. On the basis of a content analysis of the sampled articles, it is concluded that sustainability forms a new, distinct, and emerging school of thought in project management. Defining features of this sustainability school are: Viewing projects from a societal perspective, managing for stakeholders, applying triple bottom line criteria, and a values-based approach to projects and project management (Silivus 2017, 1479).

The content and understanding of corporate sustainability varies depending on the context (van Marrewijk 2003, 95).

The concept of sustainability in project management is expected to gain prominence in the coming years. Questions of sustainability and how sustainability aspects can be incorporated into project management are already well documented in the scientific literature. There is, nevertheless, still a gap between what is suggested in the literature and what is actually applied in practice (Okland 2015, 103).

In the present day, the conditions (socioeconomic, environmental, and technological) in which both organizations operate and projects are implemented are continuously transforming. As a result, sustainability is emerging as one of the most significant driving forces in organizations and projects, making the relationship between project management and sustainability a crucial factor (Tufinio et al. 2013, 91).

Project management and sustainability topics have been covered in numerous studies, but there is still a need for more research concentrating on the overlap of these topics. The study "Key factors of sustainability in project management context: A survey exploring the project managers' perspective" considers sustainability from the triple bottom line standpoint: economic, social, and environmental. The findings reveal that four factors stand out: Sustainable Innovation Business Model, Stakeholder Management, Economic and Competitive Advantage, and Environmental Policy and Resource Conservation (Martens and Carvalho 2017, 1084).

The integration of sustainability into project management demands the incorporation of a holistic set of sustainability principles and not just a set of indicators (Silivus 2017, 1479).

In recent times, sustainability has become a growing trend; small and medium-sized enterprises (SMEs) are emphasizing sustainability principles more and more in their business management. The outcomes of the research "Critical Success Factors of Project Management in Relation to Industry 4.0 for Project Sustainability" indicate that organizations perceive leadership and experience, as well as people and flexibility, as the key factors for the project management success. The main critical factor for the sustainability of projects with a focus on Industry 4.0 is funding, which determines the execution of projects (Vrchota et al. 2021, 281).

In this thesis, the dimensions of the impact of 3D printing on the "Construction 5.0" criteria are also determined in accordance with the concept of sustainability in project management.

2.4.7 Increased Environmental Sustainability

Taking into account the quantity of concrete manufactured and the number of concrete structures built, the problem of associated environmental impacts presents a major part of the overall sustainable development problem globally. As such, the utilization of ecologically optimized concrete structures offers the promise of increasing construction quality and, as a result, decreasing environmental impacts. A life cycle analysis is a complex, multiparametric assessment of the environmental impact of a structure over its entire life cycle and it includes all the environmental factors of the structure, while addressing all major environmental issues in a singular assessment process, including CO2 emissions, energy consumption, water use, waste generation, etc. For concrete, the selected criteria should support the design and construction of high quality concrete structures that are at the same time environmentally friendly. However, the basic problem is to gather relevant environmental input data for specific concrete types and transport and production processes that can be used in the LCA process (Hajek et al. 2011, 13).

The article "Building houses with local materials: means to drastically reduce the environmental impact of construction" details the process of material selection, design and construction of a series of residential small houses in southern France. Materials were sourced locally whenever feasible to minimize the environmental impact of the new buildings. The energy consumption to construct a house is compared to that of a more traditional concrete house. Utilizing local materials significantly decreased energy consumption during construction by up to 215% and reduced transportation impacts by 453% (Morel and 2001, 1119).

The results of the study "Environmental consideration in procurement of construction contracts: current practice, problems and opportunities in green procurement in the Swedish construction industry" indicate that both public and private clients in the Swedish construction industry incorporate environmental considerations in their purchases. Preferences for the environment are frequently expressed as environmental requirements. Nonetheless, environmental criteria in bid evaluation are less prevalent and only seldom affect purchasing decisions. Environmental assessment criteria more often relate to the contractors' ability to manage environmental activities within the scope of the project (Varnas et al. 2009, 1214).

The findings of the study "Influence of construction and demolition waste management on the environmental impact of buildings," which were based on measurements of real buildings and the activities of demolition contractors, found that not all types of selective demolition have benefits for the environment (Coelho and de Brito 2012, 532).

2.4.8 Increased Construction Safety

While the concept of safety culture is fairly new to the construction industry, it is gaining popularity as it incorporates all perceptual, psychological, behavioural, and management factors (Choudhry et al. 2007, 207).

Many types of hazards occur in the workplace. Among them are ergonomic, chemical, biological, physical, psychological, etc., which may cause damage or impairment in the workplace (Tamrin and Yussof 2014, 55).

With the increased application of digital technologies in the design of buildings and infrastructures, the question of their effects on construction safety arises. As such, the study named "Construction safety and digital design: A review," investigates the connections between construction safety and digital design practices with the goal of encouraging and leading further research on this topic (Zhou et al. 2012, 102).

2.4.9 Increased Compatibility (Technology)

The paper "A Study on Research Trends of Technologies for Industry 4.0; 3D Printing, Artificial Intelligence, Big Data, Cloud Computing, and Internet of Things" provides an analysis of the latest emerging trends of five technologies. Specific technologies covered are 3D printing, artificial intelligence, Big Data, cloud computing, and Internet of Things, all of which are of importance to Industry 4.0 (Chun et al. 2018, 397).

Since all these technologies promise a human-centric approach, less waste and a more optimized process, it is assumed that their essence should also be in accordance with Sustainable development goals.

Reminiscent of the age of artisanal manufacturing, Industry 4.0 is speeding up the transformation from mass production to mass customization. Sharing distributed 3D printers (3DPs) and collaborating on the IIoT will result in a promising dynamic, globalized, economical, and time-saving manufacturing ecosystem for customized manufacturing products (Darwish et al. 2021, 196).

2.4.10 Increased Resilience

The construction industry is undergoing a transformation toward digitization and automation (known as Construction 4.0) because of the rapid growth of information and communication technologies, as well as 3D printing, mechatronics, machine learning, Big Data, and the Internet of Things (IoT). Such technologies are set to alter the design, planning, construction, operation, and maintenance of civil infrastructure systems, having a positive impact on overall project time, cost, quality, and productivity. Also, as a direct outcome of these new technologies, the industry will become more interconnected, and addressing cybersecurity becomes of the utmost significance (Mantha and Soto 2018, 1).

Cyber resilience encompasses security, monitoring, and business continuity/disaster recovery technology. For a successful cyber resilience strategy, however, a holistic approach is needed that starts with people and processes - only then followed by technology (CompTIA 2022, 1).

Natural and man-made events of late have underscored the fragility and vulnerability of the built environment to disasters. Traditionally, these physical systems have been designed, built, and maintained by the countless construction professions (Lizzaralde et al. 2018, 1).

As a result, designing and constructing a built ecosystem that can survive the consequences of disasters necessitates a deep understanding of the expertise and knowledge of how to prevent and mitigate the effects of hazards to secure a more sustainable future (Hamelin and Hauke 2005, 1; Bosher et al. 2007, 163).

Infrastructure protection is the ability to avoid or mitigate the consequences of a negative event. Infrastructure resilience is the ability to decrease the magnitude, impact, or duration of a disruptive incident. Resilience is thus also the ability to absorb, adapt to, and/or quickly recover of a potentially disruptive occurrence. For the purposes of the "Critical Infrastructure Resilience - Final Report and Recommendations" study, critical infrastructure resilience is further typified by three major attributes: 1) robustness (the ability to maintain critical operations and functions in the presence of a crisis), 2) resourcefulness (the ability to adeptly prepare for, respond to, and manage a crisis or disruption while it evolves), and 3) rapid recovery (the ability to restore and/or return to normal operations as rapidly and efficiently as possible after a disruption) (NIAC 2009, 8).

2.4.11 3D Printing Technology – In scope of Industry 4.0, Industry 5.0, and PM Context

3D printing is increasingly attracting public interest. As its popularity increases, more and more reports are being published endorsing the technology. There are many who forecast that it will revolutionize the way people are working and living (Thorsteinsson and Page 2018, 1).

Three-dimensional printing (3D printing) as an additive manufacturing (AM) technology is changing the design and manufacturing of products and components in a number of disciplines, but the architecture and construction industries have only very recently started to embrace these technologies for construction applications. AM is regarded as one of the most significant technological advancements in the paradigm shift to Industry 4.0 (the fourth industrial revolution) (Tahmasebinia et al. 2020, 379).

In researching the technologies needed for Industry 4.0, the United States and China are leading countries, followed by the United Kingdom, Germany, France, and Italy in Europe, and India, Japan, and Korea on the Asian continent. Most of the research is performed at universities or national laboratories. Consequently, the political will of the government and the well-functioning system that manages and sustains the research projects are the most significant characteristics that define the competitive ability of any country (Chun et al. 2018, 397).

The Industrial Internet of Things (IIoT) in conjunction with 3D printing is smoothing the path to the era of Industry 4.0 and smart manufacturing as the cornerstone of personalized production. If distributed 3D printers (3DPs) are used collaboratively and work together in the IIoT, a promising dynamic, globalized, economical, and time-efficient manufacturing ecosystem for customized manufacturing products will be created. The paper "Towards sustainable industry 4.0: A green real-time IIoT multitask scheduling architecture for distributed 3D printing services" suggests an environmentally conscious real-time multitasking architectural approach for personalized 3DPTs in IIoT. This particular proposed architecture is split into two interrelated areas, allocation and scheduling (Darwish et al. 2021, 196).

3 METHODOLOGICAL TOOLS FOR DEFINING 3D PRINTING SUCCESS FACTORS

3.1 Research model development

A conceptual model for 3D printing technology adaptation was designed to address the previously noted research void. When considering the adoption of 3D printing in construction, a beginning point is to examine different advanced technology deployment theories to identify the sequence of impacting factors (Besklubova et al. 2021, 1).

With this purpose in mind, a literature review was undertaken that contained a number of different theories which have been tested in information technology (IT) adoption, environment technologies, and industrial innovation research (Jeyaraj et al. 2006, 1), inclusive Theory of Reasoned Action (TRA) (Fishbein and Ajzen 1977, 1), Innovation Diffusion Theory (IDT) (Rogers 1983, 1), Technology Acceptance Model (TAM) (Davis 1989, 319), Theory of Planned Behavior (TPB) (Ajzen 1991, 93), Perceived Characteristics of Innovating (Moore and Benbasat 1991, 192), Contingency Theory (CT) (Donaldson 2001, 1), Social Cognitive Theory (SCT) (Bandura 2011, 349) and Technology Readiness (TR) (Başgöze 2015, 26).

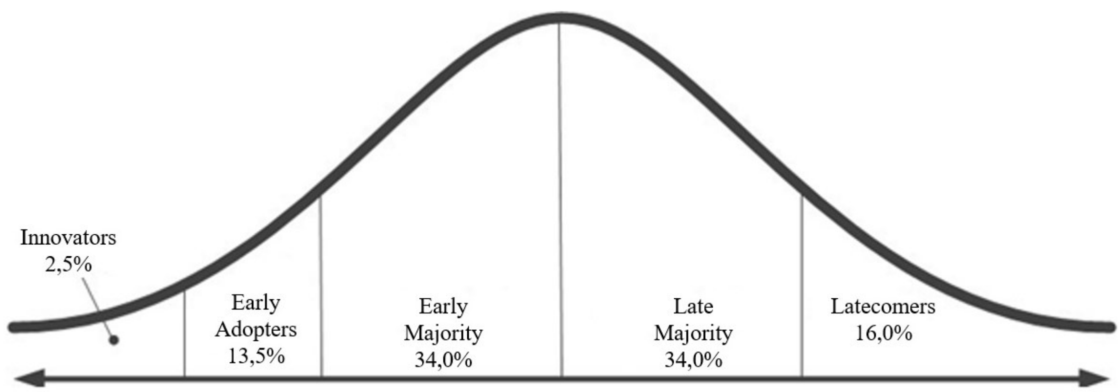
Since the introduction of 3D printing technology is triggered by creators as opposed to expressed needs of the market, it corresponds to the technology push model of adoption (Baumers et al. 2016, 193). The push argument asserts that innovation is pushed by the scientific community, which then pushes the technological sector and its implementation (Chidamber and Kon 1993, 1). As a resulting, only characteristics that focus on the technology and deliverables of 3D printing utilization may be included and studied. The SCT, TPB, and TRA were correspondingly eliminated from the conceptual model of technology adoption development as they embrace other perceptions that might affect consumer attitudes regardless of the perception of 3D printing technology usage results (Compeau et al. 1999, 145).

Considering that 3D printing technology has been primarily used for prototype and demonstration models (Mrazovic 2018, 1), the previously mentioned theories of technology adoption (SCT, TPB, and TRA) are considered challenging to investigate at this relatively young developmental phase of 3D printing technology. Nevertheless, TAM, IDT, TR, and CT are perceived to be the best suited theories in view of the conceptual model design development Moore and Benbasat (1991, 192) introduced the theory called "Perceived characteristics of innovating", having the same characteristics as Davis (1989) in TAM and Tornatzky and Klein (1982, 28) in their meta-analysis. Therefore, this dissertation examines variables from Tornatzky and Klein (1982, 28). study, with consideration of their similarities to the TAM (Moore and Benbasat 1991, 192). Chosen theories for additional examination are provided in section below.

3.2 Innovation Diffusion Theory

The innovation diffusion (IDT) is delineated as the procedure by which a novel technology is adopted via certain conduits, over time, amongst the associates of a social framework. This theory also implies that a time gap exists between the adoption of an innovation and its implementation successfully in the industry. Often, this gap stretches over multiple years (Rogers 1983, 1).

Figure 20: Diffusion innovation theory model applied to strategy and project management



Source: Reiling 2022, 1, based on Rogers 1962, 1.

Given this long interval, the innovation must achieve critical mass before it can become self-sustaining. Hence, innovation diffusion is primarily considered a social as opposed to a technical activity, as the innovation's scope depends to a great degree on the consumer focus of its diffusion mechanisms. Specifically, there are five features of innovation diffusion that define the speed of technology adoption in a given society/industry (Rogers 2003, 38):

1) " Relative advantage" is understood as "the extent to which an innovation is perceived to be better than the idea it supersedes" (Rogers 1983, 1).

Premkumar et al. (1994, 157) use analysis to demonstrate that "relative advantage" is among the key adoption determinants, reflecting users' beliefs toward the innovation. This concept can be phrased in terms of the economic return or it can be quantified in other manners, such as social benefits, time saved, hazards eliminated, etc (Tornatzky and Klein 1982, 28).

2) "Complexity" is typically described as "the extent to which an innovation is considered to be difficult to both understand and use" (Rogers 1983, 1; Rogers and Shoemaker 1971, 1). Some innovations, therefore, are easily grasped by most social system members, whereas others are more complicated and adopted at a slower pace (Rogers 1983, 1). I.e., more complex concepts are harder to comprehend and are thus adopted to a lesser extent.

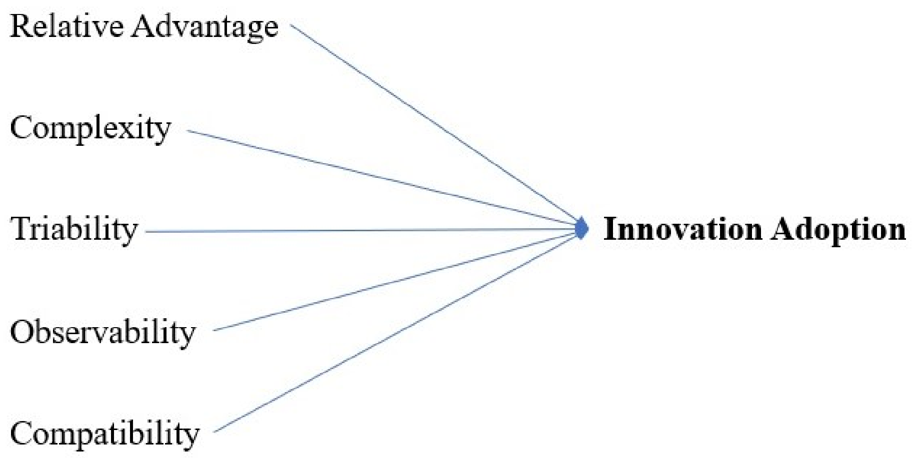
3) “The term "trialability" describes the extent to which an innovation can be experimented with on a limited scale. A testable innovation presents less innovation uncertainty for the consumers contemplating its adoption, since it is feasible to learn through practical action (Rogers 1983, 1).

4) "Observability" is the level at which the outcomes of an innovation are observable to the society. The observability contributes to communicating the evident advantages of the innovation (Rogers 1983, 1).

5) "Compatibility" of innovation is "the extent by which an innovation is apprehended to be in line with the existing values, previous experiences, and needs of the beneficiaries" (Rogers 1983).

Rogers five factors with relative advantage and compatibility are visible in the Figure 21 below.

Figure 21: Rogers five factors with relative advantage and compatibility



Source: Rogers 1983, 1.

3.3 Technology Readiness

Technology readiness (TR) is mirrored by consumers' willingness to adopt and utilize innovative technologies to meet their day-to-day/business objectives (Parasuraman, 2000, 307). It is a measurement of the positive or negative sentiments about the technology. Those sentiments are analysed in four subdimensions as defined by TR (Başgöze 2015, 26):

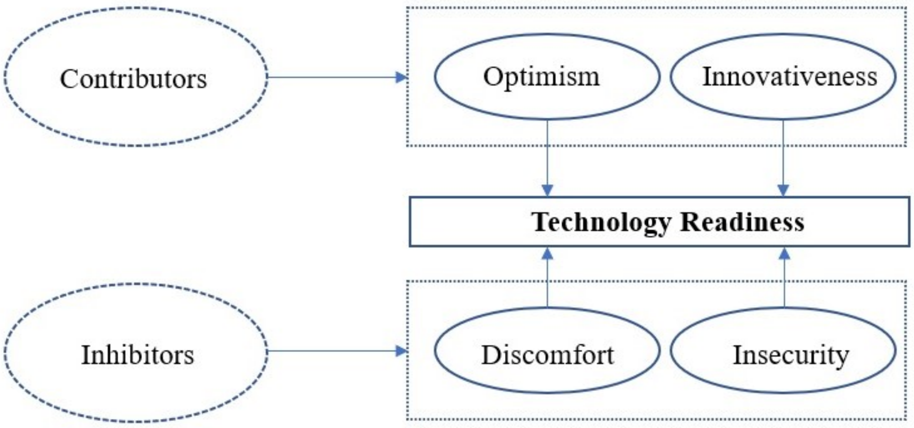
1) The "optimism dimension" is the tendency of individuals to believe that technology will assist them in achieving good results in their personal lives. It helps the individual to build trust and establish control over their performance (Walczuch and al 2007, 206).

2) The "innovativeness" dimension specifies the degree to which the individual intends to test out new cutting-edge technology products and/or new services prior to others (Sophonthummapharn 2007, 81).

3) The "uncertainty dimension" applies when the individual does not have confidence in the technological product and doubts that the product will do its job. Unlike the "optimism" dimension, the "uncertainty" dimension concerns a skeptical mindset of the individual towards the technology (Parasuraman 2000, 307).

4) The "discomfort scale" stems from the belief of the individual that their knowledge of the technology is unsatisfactory (Parasuraman 2000, 307).

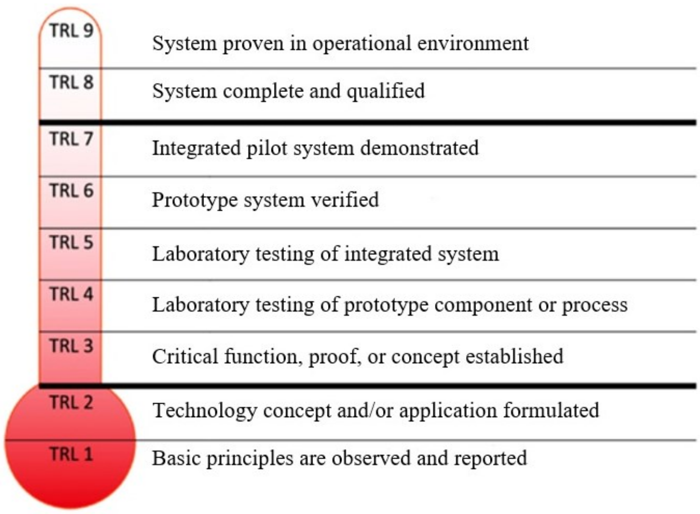
Figure 22: Technology Readiness Model



Source: Spicek 2022, based on Başgöze 2015, 6.

The picture below shows the three levels of technology readiness (TRL), namely research, development, and deployment, shown on an early NASA model (Fasterholdt et al. 2018, 1).

Figure 23: Technology Readiness Levels (TRL), based on early NASA model



Source: Fasterholdt et al. 2018, 1, based on early NASA model 1970.

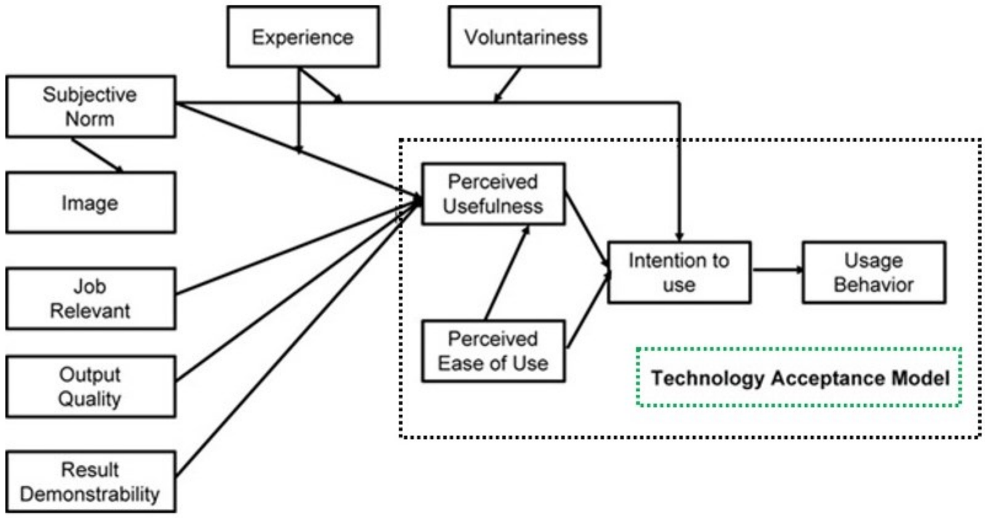
3.4 Technology Acceptance Model

Technology Acceptance Model (TAM) aims to clarify how users adopt and utilize a technology. This model assumes that several factors affect users' decision-making about when and how to utilize a new technology introduced to it (Başgöze 2015, 26; Davis et al. 1989, 982):

1) “Perceived usefulness” - defined as the extent to which an individual percieves that utilizing a specific system would enhance their job efficiency.

2) “Perceived ease-of-use” - defined as the extent to which an individual perceives that utilization of a specific system is possible with no effort.

Figure 24: Original Technology Acceptance Model



Source: Spicek 2022, based on Davis 1989, 319.

3.5 Contingency Theory

Contingency theory (CT) offers the opportunity to understand more clearly how context (situation, atmosphere) impacts the management of innovation (Tidd 2002, 169). Two drivers have a major impact on the organization and management of innovation:

1) “Uncertainty," described as "the extent to which the functional, social, and/or financial consequences of acquiring and utilizing innovations cannot be determined" (Arts et al. 2011, 134).

2) "Complexity," delineated as the " extent to which an innovation is considered challenging to comprehend and utilize" (Rogers 1983, 1; Rogers and Shoemaker 1971, 1).

Figure 25: The contingency theory of structural adaptation

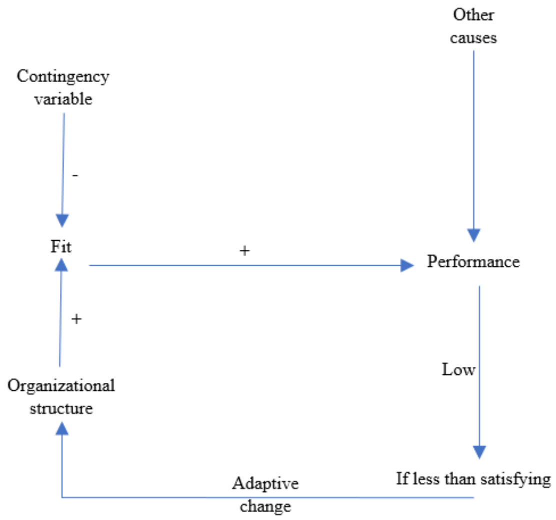


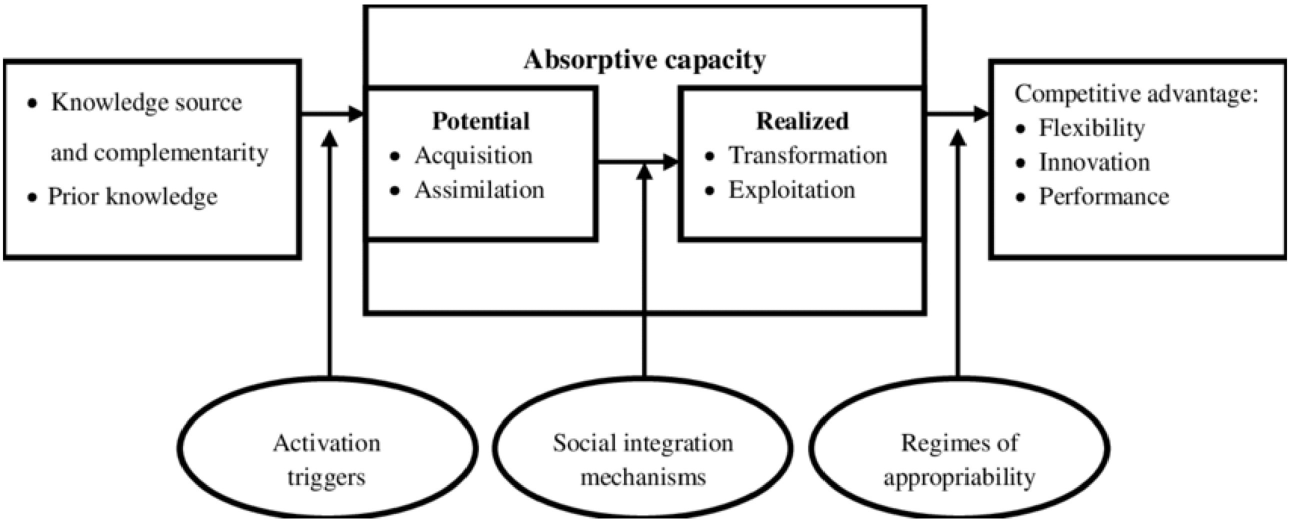
Photo: Spicek 2022, based on Donaldson 2001, 12.

3.6 Additional factors

In the literature on technology adoption, several other factors were identified which, although not referred to in the theories reviewed, are worth considering: 1) “absorptive capacity” and 2) “supply-chain management”.

"Absorptive capacity" is the capability of a company to utilize foreknowledge to identify the potential value of emerging, external information, to assimilate it, and to apply it for a commercial purpose.

Figure 26: A model of absorptive capacity based on Zahra and George (2002)

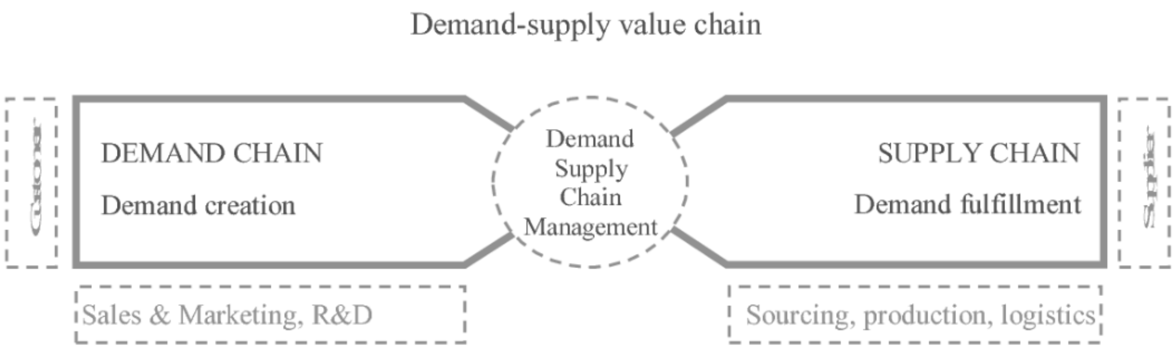


Source: Spicek 2022, based on Zahra and George 2002, 185.

"Supply chain management" encompasses the planning, control and execution of the project flow from the acquisition of raw materials through production to sales to the end consumer, as well as the related flows of information (Ofori 2000, 195).

In any material management process, two supply channels are established: (a) supply and (b) demand. Supply concentrates on material sourcing and the product engineering stage of a project. Demand is centred on the distribution of the product or the customer's purchase. Thus, the point of supply chain management is to make sure that these two channels operate in an organized and efficient fashion. The level of interest and the impact of the individuals and cross-functional entities participating in the process of innovation can affect both the manufacturing and consumer supply chain channels (Li et al. 2006, 107).

Figure 27: Demand-supply value chain



Source: Mahmood and Kess 2014, 7.

3.7 Proposed factors for 3D printing technology adoption model

Based on the above methodological tools and the analysis of the stated theories, the success factors of construction projects using 3D printing technology were defined. They will be visible and explained in more detail in the continuation of this thesis (Chapter 3.71. – Chapter 3.7.9.)

3.7.1 Relative advantage

The analyses of Premkumar et al. (1994, 157) indicate that "relative advantage" is among the most significant predictors of acceptance, representing the attitude of users toward the innovation. In TAM and TR theories, variables with analogous significances can be observed. TAM's "perceived usefulness" is defined as the subjective likelihood of the prospective adopter to utilize a certain application system by suggesting an enhanced work performance in some organizational related context (Davis et al. 1989, 982).

A further variable, the "optimism dimension," which is related to TR theory, boosts confidence in the consumer's ability to increase control, agility, and efficacy in both life and work (Walczuch et al. 2007, 206). The above notions from TAM and TR theory are very analogous to "relative advantage" as they express that consumer job performance can be boosted by the adoption of emerging technologies. The term "relative advantage" is acknowledged in a variety of different academic fields (Moore and Benbasat 1991, 192); therefore, this expression will be retained in this dissertation.

3.7.2 Complexity

"The phrase "complexity" applies to both IDT and CT. The "discomfort scale" of TR theory measures the degree of negative attitude of consumers to new technology in accordance with their comprehension of that same technology (Parasuraman 2000, 307). It can be equated with "complexity," where the adoption of innovative technology is determined by how challenging the consumer considers the new technology is to utilize. A counter term to "complexity" is "ease of use," which is defined in the TAM as the extent to which the prospective user would expect the intended system to be effortless to utilize. Indeed, the strong relationship between these two factors is apparent as they cover the same topic from both a positive and a negative point of view. For the purposes of this dissertation, the above-mentioned terms are summarized into the all-encompassing factor "complexity".

3.7.3 Trialability

In a research discussion, Moore and Benbasat (1991, 192) elaborate that "trialability," i.e., the ability to adopt an innovation on a limited scope, is closely related to "divisibility," i.e., the degree to which an innovation can be tested on a small scope prior to adoption. For this reason, the present dissertation will refer to these concepts as "trialability" to examine their impact on the adoption of 3D printing technology.

3.7.4 Compatibility

"Compatibility" may refer to conformity with the values or norms of the prospective adopters as well as to congruency with their pre-existing set of practices. Relying on a statistical analysis which blends a variety of studies, Tornatzky and Klein (1982, 28) conclude that the compatibility of an innovation is related positively to its adoption.

3.7.5 Absorptive capacity

The associated foreknowledge gives the capability to identify the value of new information, to assimilate it, and to exploit it for business ends. These capabilities collectively form the "absorptive capacity" of an organization. The capacity to harness external knowledge is a crucial element of innovation capability. On its most elementary layer, this pre-knowledge comprises basic skills, but may also involve familiarity with the most recent science or technological advancements in a specific domain (Cohen and Levinthal 1990, 128).

3.7.6 External pressure

The adoption of 3D printing technologies can also be the result of external pressures, e.g., the environment of an organization includes competitive market, changing customer needs, regulatory requirements, and evolving business fields and technologies (Porter 1989, 133; Porter 2008, 25). "External pressure" is delineated in this dissertation as the impact that external organizations exert on the organization, and it can vary from no encouragement/no pressure to recommendations, requests, or the granting of inducements as well as the threat of sanctions (Kamal 2006, 192). The "uncertainty dimension," associated with TR theory, is incorporated as a metric of external pressure covering cases where the consumers mistrust the capability of a technological good to accomplish its task (Parasuraman 2000, 307).

3.7.7 Uncertainty

Uncertainty (or risk) related to the adoption of innovative technologies presently has an important role in the feasibility decision (Arts et al. 2011, 134). If technology adoption is further in the future (i.e., in the development phase), uncertainties about its benefits are more significant, as opposed to when behavior change is forthcoming (in the near future), where consumers tend to focus more on the cost uncertainties related to transitioning to the innovation and learning the new set of behaviors (Castaño et al. 2008, 320).

3.7.8 Supply-side benefits

The supply side encompasses the supply chain from manufacturers of the machines to purchasers of the technology. This is the factor that has proven to be critical to the adoption of 3D printing (Mellor and 2014, 194). Often, new technology adoption necessitates greater collaboration with both suppliers and customers. Assistance from suppliers during the adoption process has long been acknowledged as a critical factor in the success of implementation (Rogers et al. 2016, 886).

3.7.9 Demand-side benefits

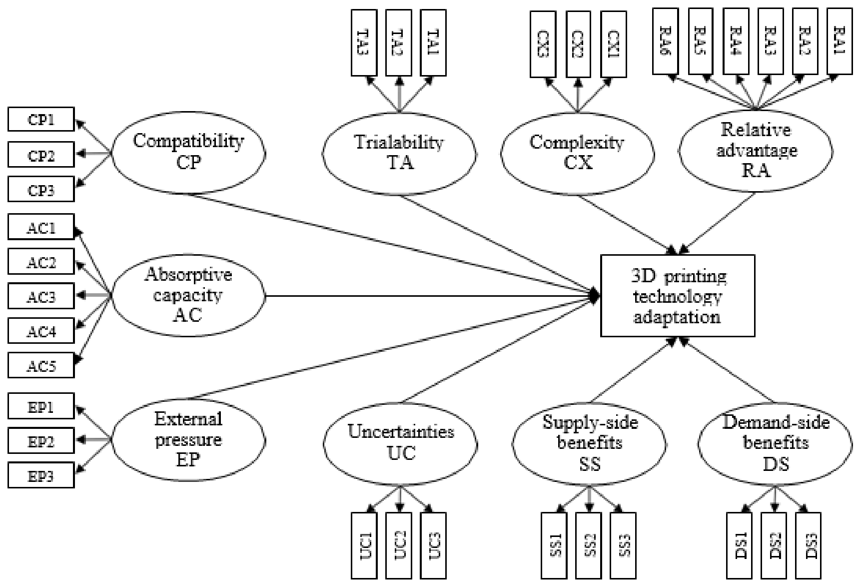
The demand chain is becoming an increasingly important factor in technology adoption as purchasers are incorporating the technology into their relevant supply chains, thereby impacting their customers and suppliers (Mellor and 2014, 194). Suppliers adopting a new technology are providing a number of services associated with 3D printing, from designing to fabricating (Rayna and Striukova 2016, 214).

3.8 Theoretical framework of 3D printing technology adoption model development

The nine factors determined on the basis of a literature review are challenging to be measured in a direct way given their abstracted character (Yang and Ou 2008, 321). Measurement variables, nonetheless, can be suggested to evaluate these factors.

In the absence of previous published studies identifying the measurement variables, they were drawn and modified from other innovation adoption fields of research, including industrial additive manufacturing, information technology (IT), and environmental technology. The factors of influence and measured values are illustrated in a model to represent their effects on the adoption of 3D printing technology graphically. In this model, the arrows represent the direction of impact. It is considered to be preliminary as this model was designed based on theories derived from the literature review and needs further verification of its structure and its quantification (Besklubova et al. 2021, 1).

Figure 28: Initial model of factors affecting 3D printing adaptation in construction



Source: Besklubova et al. 2021, 7.

4 CHALLENGES IN THE INTRODUCTION OF 3D PRINTING TECHNOLOGY IN CONSTRUCTION PROJECTS

4.1 Assumptions for adaptation of 3D printing technology in managing construction projects

Project success is the goal for practically every project. However, it means different matters to different people. While some authors consider time, cost and quality to be the predominant criteria, others believe that success is somewhat more complicated (Chan and Chan 2004, 203).

The idea that a project is successful if it merely meets the time, cost and quality targets currently seems to be outdated. This can be supported by (Collins and Baccarini 2004, 211), who believe that time, cost, and quality are not the only benchmarks for project success and that it is imperative to instruct project managers to also consider criteria other than this triad (Morteza and Kamyar 2009, 1).

Appropriate allocation of reduced resources will be aided by recognition of key factors in the success of construction projects (Chua and al 1999, 1).

However, one of the perennial problems with projects is the realization that implementation is poor, and the primary intended goals are not met, especially in terms of project deadlines and costs. Despite the lack of a unified definition of what project success entails, various authors agree that project success can be achieved through good actions on the part of the project manager (Radujkovic and Sjekavica 2017, 1).

The most important driving force of any project is people, and competent project managers are essential even for the success of megaprojects (Misic and Radujkovic 2015, 71). All of the aforementioned insights have contributed to the drawing of a conclusion about what project success means in terms of construction projects using 3D printing technology. This is how the assumptions/questions (Table 8), that preceded the identification of the critical success factors, emerged.

Therefore, the goal was to help standardize the decision-making tools for reviewing the critical success and failure factors in implementing 3D printing technology in construction projects. To achieve this goal, the following success / failure factors and answering the following questions / assumptions for adaptation of 3D printing technology in managing construction projects should have been evaluated (visible in the Table 8):

Table 8: Assumptions / questions and sources

Assumptions	Sources
1) How to optimize and incorporate more functionality into components/ structures?	(Buswell et al. 2008, 224; Weller et al. 2015, 43; Labonnote et al. 2016, 347; Wu et al. 2016, 21)
2) How to reduce manpower necessity?	(Lim et al. 2012, 262; Labonnote et al. 2016, 347; Wu et al. 2016, 21)
3) How to lessen cost of construction component/structure?	(Ling 2003, 635; Lim et al. 2012, 262; Zhang and Khoshnevis 2013, 50; Labonnote et al. 2016, 347)
4) How to reduce construction time?	Labonnote et al. 2016, 347; Lim et al. 2012, 262; Ling 2003, 635; Wu et al. 2016, 21; Zhang and Khoshnevis 2013, 50)
5) How to reduce safety hazards?	(Tay et al. 2017, 261)
6) How to reduce product quality challenges?	(Gann 2000, 1)
7) Is computer-generated design process simple?	(Buswell et al. 2007, 221; Petrick and Simpson 2013, 12)
8) Is managing digital construction process and operating 3D printer easy?	(Beatty et al. 2001, 337; Buswell and al 2007, 221; Labonnote et al. 2016, 347; Nitithamyong and Skibniewski 2006, 80)
9) Is maintaining 3D printer easy?	(Ungan 2004, 504)
10) Improved use of materials whose properties are predictable?	(Barnett and Gosselin 2015, 27; Labonnote et al. 2016, 347; Lim et al. 2012, 262; Wu et al. 2016, 21)
11) 3D printing product behaviour from a long-term perspective (e.g. length of the product life cycle)?	(Ghadim et al. 2005, 1; Hoeffler 2003, 406)

12) Is precision of the printed objects within acceptable tolerances?	(Weller et al. 2015, 43)
13) Suitability of printing various-sized conventional design elements for different construction needs?	(Khoshnevis 2004, 5; Weller et al. 2015, 43)
14) Compatibility of construction site environment with 3D printing technology?	(Skibniewski 1988, 188)
15) Matching available 3D printing materials with the characteristics of legacy construction processes?	(Khoshnevis 2004, 5; Weller et al. 2015, 43)
16) Substantial share of company capital expenditure devoted to R&D (produce, test) and implementation of 3D printing technology?	(Arvanitis and Hollenstein 2001, 377; Ling 2003, 635; Kamal 2006, 192; Nitithamyong and Skibniewski 2006, 80)
17) Major share of employees educated at tertiary level?	(Cohen and Levinthal 1990, 128)
18) Knowledge, expertise, talent, creativity, and skills of the company workforce?	(Zahra and Nielsen 2002, 377; Nitithamyong and Skibniewski 2006, 80)
19) Increasing collaboration among stakeholders (integrating a cross-functional team, suppliers, etc.)?	(Nam and Tatum 1992, 385; Ofori 2000, 195; Ling 2003, 635; Koufteros et al. 2005, 97; Kamal 2006, 192; Medeiros et al. 2013, 76; Mellor et al. 2014, 194)
20) Company team attitudes toward 3D printing in general?	(Nitithamyong and Skibniewski 2006, 80)
21) Competitive pressure?	(Arvanitis and Hollenstein 2001, 377)
22) Lack of technical standards, quality control standards and product certification matters?	Ling 2003, 635; Medeiros et al. 2013, 76; Mellor et al. 2014, 194); Weller et al. 2015, 43)
23) Sceptical mindsets / psychological barriers of consumers in relation to 3D printing technologies and product implementations?	(Hoeffler 2003, 406; Walczuch et al.

	2007, 206; Mellor et al. 2014, 194)
24) Perceived side effects associated with innovation?	(Hoeffler 2003, 406)
25) Resistance to environmental influences and failure with exposure to high stress?	(Petrovic et al. 2011, 1061; Berman 2012, 155)
26) Uncertainty in 3D printing technical/economic benefits arising from regulatory restrictions and isolation of contractors and consultants from one another?	(Feder et al. 1985, 255; Skibniewski 1988, 188; Ling 2003, 635)
27) Reducing and/or simplifying construction tasks and need for pre-assembly/ assembly activities?	(Holmström et al. 2010, 687; Weller and al 2015, 43)
28) Reducing the need for transportation services?	(Holmström et al. 2010, 687; Labonnote et al. 2016, 347)
29) Reducing the number of suppliers involved in construction process**?**	(Ofori 2000, 195; Koufteros et al. 2005, 97; Holmström et al. 2010, 687)
30) Freedom of design and customization of printed components at no extra cost?	(Hague and al 2004, 4691; Koufteros et al. 2005, 97; Buswell et al. 2008, 224; Lim and al 2012, 262; Medeiros et al. 2013, 76; Tay et al. 2017, 261; Wu et al. 2016, 21
31) Sharper reaction to changing customer needs?	(Weller et al. 2015, 43)
32) Production in collaboration with the customer and supplier (e.g., customers integrated in product development)?	(Ofori 2000, 195; Koufteros et al. 2005, 97; Kamal 2006, 192; Mellor et al. 2014, 194)

Source: Spicek 2022, based on Besklubova et al. 2021, 1.

These questions/assumptions, along with conceptual theories, served as a tool to determine critical factors for the success of construction projects using 3D printing technology. As part of these set of assumptions, subjects such as ethical issues and construction legislation problems were also recognized in such projects. In addition, the assumptions played an important role in developing the idea of incorporating 3D printing technology into a concept called “Construction 5.0”.

Research questions in this dissertation are introduced as a basis for building hypotheses in order to examine the key success and failure factors in managing construction projects using 3D printing technology through a prism of relative advantage, complexity, trialability, compatibility, absorptive capacity, external pressure, uncertainty, supply – side benefits and demand – side benefits. Other above mentioned aspects such as legislation, ethical issues, project organization structure, "Construction 5.0" and feedback from the practice were also researched when discussing the overall factors that make the use of 3D printing technology in construction projects successful or unsuccessful.

4.2 Legislative regulation of construction projects using 3D printing technology

In the field of legislation, there is a big gap between the research trend and the practicable implementation in reality. This fact is confirmed by the date of the only first 3D printed building put on the market in the USA (Builder 2021, 1) and the date of only first permitted 3D printed house in Germany (Peri 2021, 1).

For a more in-depth study of the process of obtaining building permits for structures constructed using 3D printing technology, two case studies (Augsburg, Germany and Zagreb, Croatia) were analyzed in detail, the results of which are presented below (Chapter 4.2.1. - Chapter 4.2.4.). The participants in the obtaining of the regulatory documentation serve as a sort of introduction to the project organization structure of construction projects using 3D printing technology, although it should be noted that the elements listed below represent only a small part of the overall scope of the project.

4.2.1 Project "Cabana" case study - Introduction

Building regulations do not follow the evolution of the need for 3D printing, and the legalization of 3D printed buildings is still a fairly unknown concept. This is backed up by the simple fact that the first 3D house in America was only legalized in 2018 (Rivera and Madelaine, 2019), and after that we again have a big gap until the first 3D printed real estate released on the market (Builder 2021, 1).

Consequently, from the perspective of this thesis, it was interesting to see how that process works in practice and what are the biggest problems / aversions of investors to get engaged in such a project in the first place. For this reason, it was decided to conduct a case study comparing the building regulations for 3D printed houses in Germany and Croatia.

4.2.2 Project "Cabana" case study - Research methodology

In this research the case study was used as a research method to create a deeper, more layered understanding of this complex topic in its real-world setting. A fictitious concept projects were constructed specifically for this purpose as a basis for a request for obtaining a building permit for the 3D printed building of approximately 52 m2 entitled: Project "Cabana".

The following describes the basic data of this conceptual design. Selected locations and thus offices for approval of permits / consulting on the preparation of project documentation were Augsburg (Germany) and Zagreb (Croatia). The net area of the planned building was approximately 52 m2. Supporting structure was foreseen in the form of the lattice supports. Materials that was used includes in general the extrudable concrete consisting of cement, sand, geopolymers, and fibres. The foreseen purpose of the building was a vacation house. The idea was to construct this holiday home of 52 m2, fully implemented in 3D technology. The assumption was that land has already been secured in Augsburg (Germany) and Zagreb (Croatia) and projects have been prepared which is why the next logical step would be to obtain a building permit. As this is even now a fairly unfamiliar subject, the point of this case study was to recapitulate the unknown's concerning legislation, possible obstacles and particular problems in relation to standard construction method, as well as contribution to standardization of the legislation process for 3D printing of objects in the future. All installations, fittings and final details (such as furniture) were in this case be of traditional material and traditional construction method.

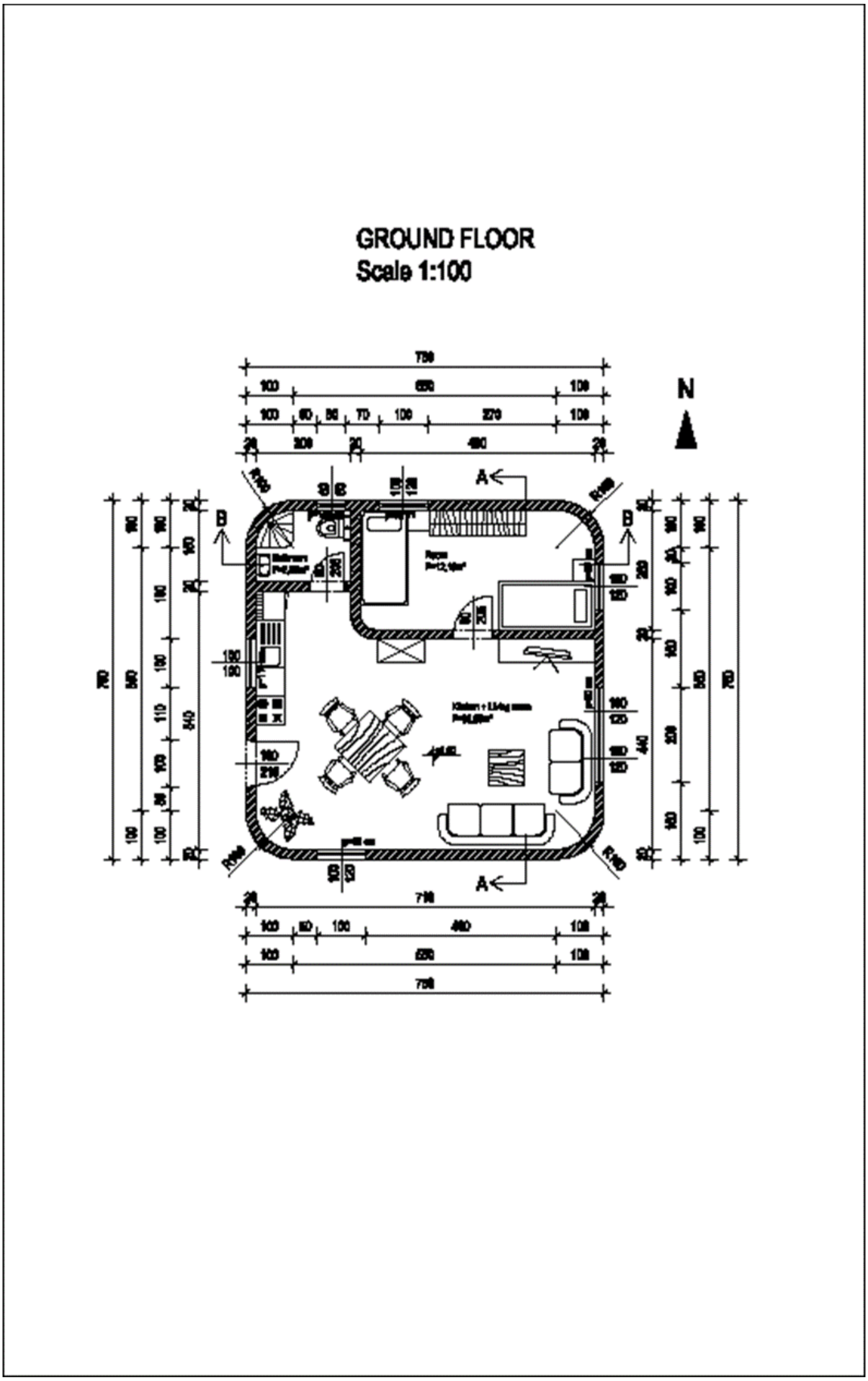
The focus was on the difference in the construction method of the external and internal walls of the house and in the construction related critical topics that need to be considered when legalizing this type of the building. The role of the respondents was to advocate the interests of an investor who does not have the technical knowledge to acquire a building permit for legitimate 3D printed building. Therefore, with the expertise of their team and their personal expertise, they should ensure all the necessary aspects to obtain a building permit. For this purpose, a workshop was organized for an open discussion on this subject. The following questions were defined as a basis for the discussion and can be seen in Table 9.

Table 9: Discussion questions in obtaining a building permit

Questions for debate
1) How familiar is your team and you personally with the topic of 3D printing in construction and what do you think subjectively about it (advantages, disadvantages, obstacles, challenges…)?
2) Did you had any experience with building permit documentation / producing of the documentation for 3D printed objects so far? If you had experience, what stage was it at (conceptual, start of construction, completed construction)?
3) When designing building permit documentation benchmarked to traditional construction, what would you pay specific attention to in terms of mechanical resistance and stability?
4) When designing building permit documentation compared to classic construction, what would you pay particular attention regarding the fire safety?
5) When designing building permit documentation compared to traditional construction, what would you pay particular attention to in terms of hygiene, health and the environment?
6) When designing building permit documentation compared to classic construction, what would you pay particular attention to in terms of noise protection?
7) When designing building permit documentation compared to classic construction, what would you pay particular attention to in terms of technical regulations?
8) How much do you think the people within the city administration are familiar with the topic and what potential problems / obstacles they might point out in relation to the traditional construction of the building?
9) Do you expect additional costs for the preparation of the building permit documentation in relation to the traditional construction, and if so, what justify the discrepancy?
10) What kind of future do you expect for 3D printing in the construction industry, and do you think it may play a more significant role in the real estate market in the near future (by 2025)?

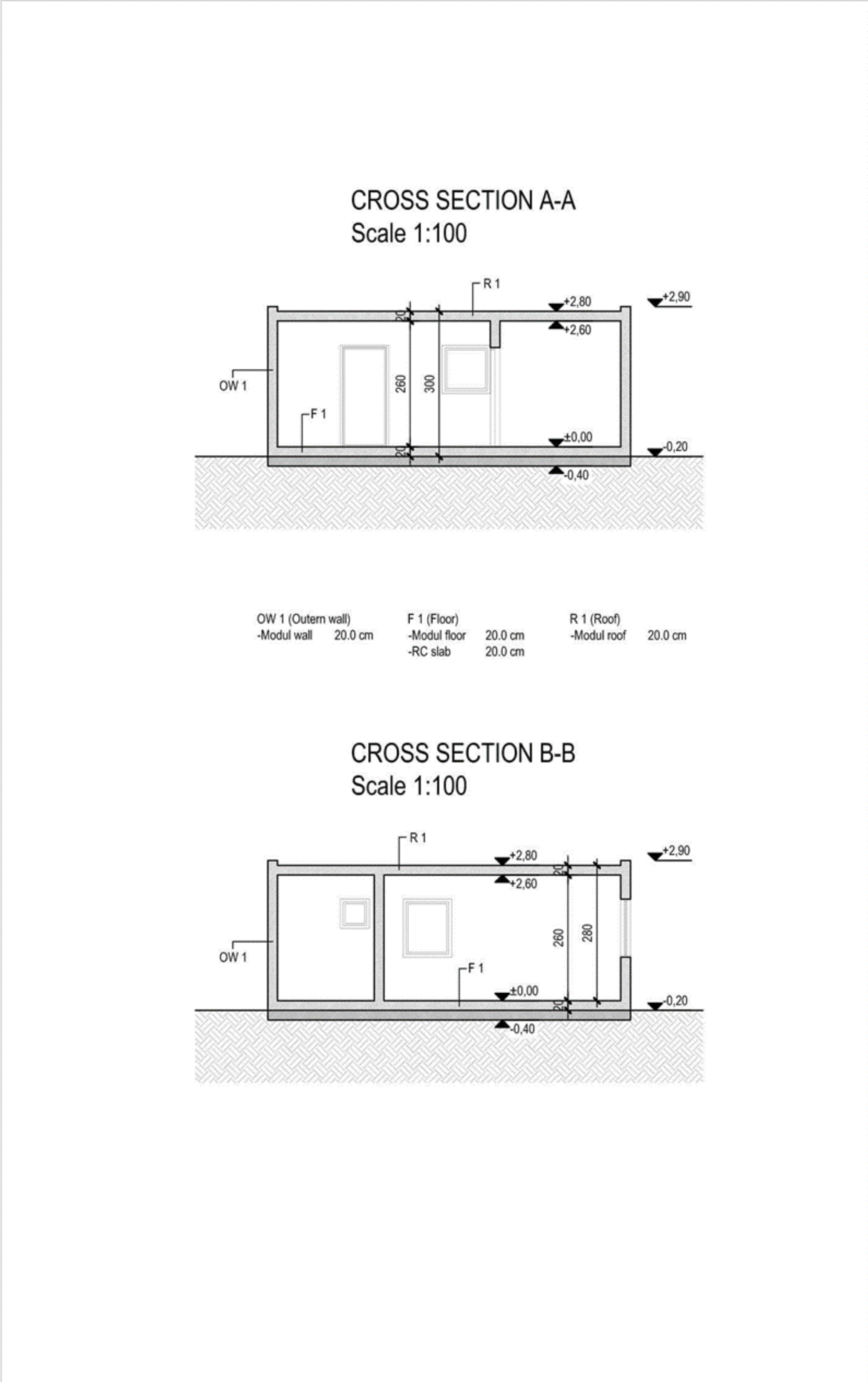
Source; Spicek 2020, 3.

Figure 29: Project "Cabana" Ground Floor



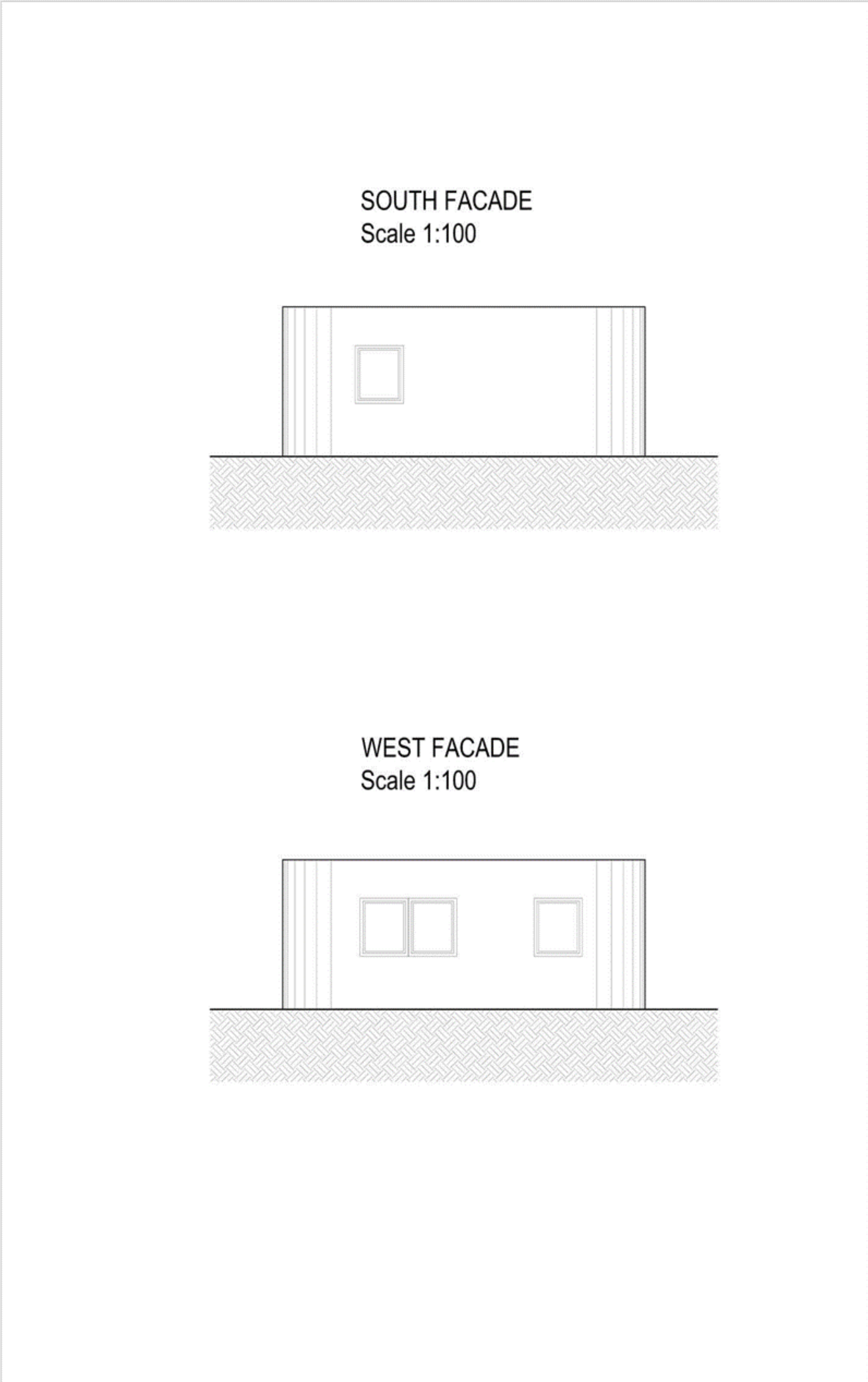
Source: Spicek 2020, 5.

Figure 30: Project "Cabana" Cross sections



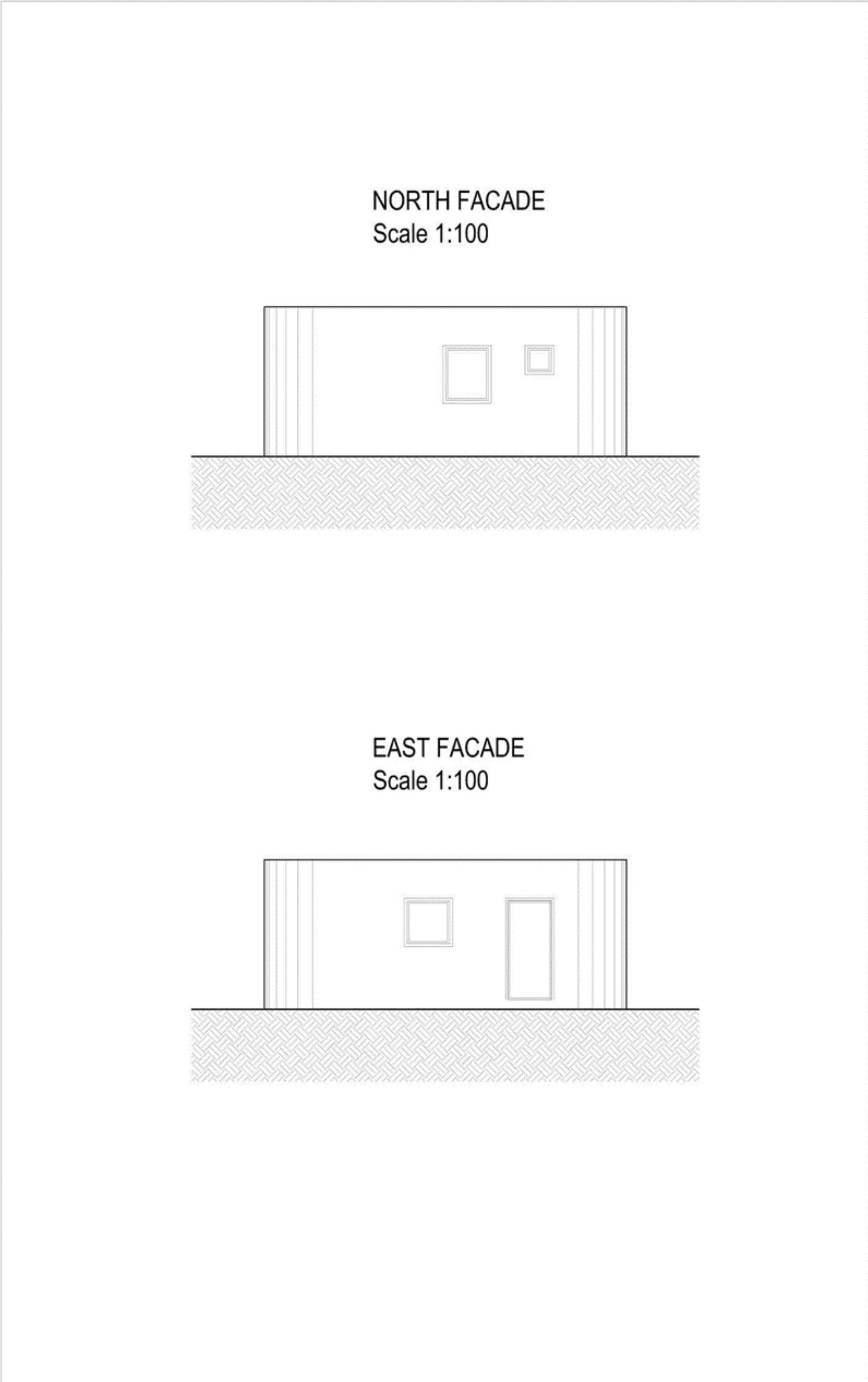
Source: Spicek 2020, 6.

Figure 31: Project "Cabana" Façades 1



Source: Spicek 2020, 7.

Figure 32: Project "Cabana" Façades 2



Source: Spicek 2020, 8.

Figure 33: Project "Cabana" Visualization 1

Source: Spicek 2020, 9.

Figure 34: Project "Cabana" Visualization 2

Source: Spicek 2020, 9.

Figure 35: Project "Cabana" Visualization 3

Source: Spicek 2020, 10.

Figure 36 - Project "Cabana" Visualization 4

Source: Spicek 2020, 10.

4.2.3 Project “Cabana” case study - Results

For both groups of the respondents the only real point of contact were the experiences during the studies and some ideas that mostly remained in the conceptual phase. Quite in agreement about the potential benefits of 3D printing, both groups note prefabrication (ability to "reprint" the building) and the modelling flexibility (a great benefit for architects) as most significant advantage. One drawback could be that building dimensions are limited to the reach of the printer and structural engineering issues (e.g., making reinforced concrete with 3D printing). Accelerating construction and improving insulation properties could also be one of the challenges. Another potential improvement is lower construction costs, but only if all processes are standardized, i.e. the more printing, the less expensive. One can see the clear apprehensions of the interviewees about the classification and standardization of the process. Both respondents also have in common that they have no or very little experience with the subject of legislation for such objects. All discussions were mostly at the conceptual stage, as a potential solution and possibly a better idea than traditional construction. Implementation usually did not occur because the possible costs were too high and open questions were still too high-risk to engage in this "venture". Regarding mechanical strength and stability, according to Augsburg 's case, construction is not very complicated and there should be no problems as long as all conditions prescribed by the city administration are met and all dilemmas are solved (such as the problem of flat roof in small buildings like this).

In Zagreb's case possible problems for the structural engineer in the calculation were named, as it concerns relatively unknown materials and, accordingly, unknown safety factors that must be considered. The situation is similar with fire protection, which should not really be a problem as long as all the conditions described previously are fulfilled. However, there are a number of unknowns when it comes to burning the material. There is not much difference from the standard construction in terms of hygiene, health and environment, and this aspect does not depend so much on the construction itself, but more on the finishing details (insulation, installation, etc.). Also in the following two questions, Augsburg's case does not bring up any major differences from the standard construction, and in Zagreb's case was once again emphasized the concern and need for material classification, which could play a significant role in the design of the building. One huge potential issue stems from the both respondents' concern that the city government most likely has little experience with issuing permits for 3D-printed buildings as well. Some of the legalization process comparable to conventional construction would likely not be a problem, but any novel and unfamiliar particulars could present an impassable barrier to the issuance of a permit. Regarding accepting work for this action, Zagreb's case pointed out that they very probably would not have accepted this job because of all the uncertainties, and the potential cost would probably have increased to twice the documentation effort for conventional construction. Although in Augsburg's case it is not sure whether and by how much the actual costs would exceed those of conventional construction, it is doubtful that a permit would even be granted and therefore is also sceptical that they would even engage in such an undertaking. In spite of all these obstacles, however, it is believed that 3D printing may have a promising future. Both evaluators concur that 3D printing could conceivably be more cost-effective if it is reused over and over again, as it is with modular designs. This, of course, requires standardization of the process, something that is very much optimistic in the near future.

4.2.4 Project "Cabana" case study - Discussion and Conclusion

With regard to all the above-mentioned aspects relevant to the issuance of a building permit (mechanical strength and stability, fire protection, hygiene, health and environment, noise protection, technical regulations), there seems at first sight to be no special distinctions between 3D-printed houses and conventionally built materials (e.g., wood or concrete). All the conditions imposed by the city authorities must be fulfilled, regardless of the material and construction technique.

Nevertheless, the study concludes that there are many unknowns when it comes to 3D printed documentation. These unknowns are common to both the German and Croatian experts. Even though it is a small sample, it can be cautiously stated that it is very probably that similar situations occur in other European countries as well. Main problems and insecurities are connected with the lack of classification and standardization in the field of 3D printing, the lack of any specific knowledge closely related to this topic within the city administration, as well as the relatively low, even almost absent, professional expertise (except in the design phase and for smaller models) of the same experts, who have about ten years of experience in traditional construction. This results in the scepticism on their part as to the realistic and feasible nature of this undertaking at all, and the expenses for their work in representing investors would surely far outweigh the costs in traditional construction. With a certain degree of caution, however, one can predict a glowing future for 3D printing in the construction sector, given that it offers some advantages over conventional construction techniques. One necessary condition for this is the standardization of the process, the classification of materials, and the training of both the city administration and the professionals who are involved in the preparation of the building permit documents. This should also be the direction for future research and permitting efforts.

Furthermore, many other factors (e.g., micro-location, reference projects, additional technical requirements, cost-benefit analysis, etc.) should be addressed in order to even start the project mentioned in this case report. Consequently, success factors for 3D printing in construction and methods to measure them need to be developed. Up until this major milestone, nowadays everything is still kept in the conceptual phase as something that has a lot of promise, but has not yet been standardized and researched enough. The responsibility lies with both theoreticians and practitioners to explore, identify, define, problem-solve and execute potential advantages over conventional construction to achieve possibly less expensive, more simple and more eco-friendly construction. This sustainability aspect provides perspective on the potential of 3D printing technology for meeting “Construction 5.0” specifications. However, based on the above inputs, it is also possible to question the sense of 3D printing without combining it, at least to some extent, with a traditional construction method.

5 PROJECT ORGANIZATION STRUCTURE

5.1 Project organization structure - Introduction

It has recently been announced that 3D printing technology may offer numerous advantages over traditional methods in construction projects, among them lower material and energy consumption (Berman 2012, 155; Khajavi et al. 2014, 50; Labonnote and al 2016, 347; Walter et al. 2004, 9), on-site production with less resource demand, and lower CO2 emissions throughout the life cycle of a product (Gebler et al. 2014, 158). It also encourages transformations in work structures, including a safer work environment, and leads to changes towards digital and localized supply chains (Ghaffar et al. 2018, 1).

From the perspective of an architect, 3D printing technology can shorten design and development cycles; it enables customers to co-design products that perfectly match their requirements and ambitions; it facilitates the realization of complex designs and the quick management of design alterations (Berman 2012, 155; Khajavi et al. 2014, 50; Labonnote et al. 2016, 347; Walter et al. 2004, 9; Ghaffar et al. 2018, 1).

In recent years, 3D printing, an automated manufacturing technique with layer-by-layer control, has made staggering progress. It has been used in the manufacturing industry for decades, and the technology has recently entered the construction sector to print houses and villas. Following years of further development, a systematic review shows that 3D printing technology can be used to print large-scale architectural models and buildings. Even so, the technology's capacity is restricted by the lack of large-scale execution, the development of building data models, the requirement for mass customization, and the life-cycle cost of printed projects (Wu et al. 2016, 21).

While 3D printing technology has significant potential, it has not gained acceptance as quickly as the market expected (Yeh and Chen 2018, 209). Nevertheless, with some caution, 3D printing can be predicted to have a bright future in the construction industry, as it offers several benefits over conventional construction techniques.

For this to happen, a necessary condition is the standardization of the process, the classification of the materials, and the education of both the city administration and the professionals participating in the preparation of the building permit documents (Spicek 2020, 220). It is anticipated that the use of 3D printing technology could have a positive effect on some crucial concerns in construction, including project cost and time (Radujkovic and Sjekavica 2017, 1), labour cost level (Guhathakurta and Yates 1993, 15; McTague and Jergeas 2002, 1; Soham and Rajiv 2013, 583), and construction and demolition waste management (Parasuraman 2000, 307). It is clear that new construction technologies not only should enhance construction processes, but also should bring construction closer to the current paradigm that balances the components of people, planet, and profit.

The viable solution is to incorporate new technologies and solutions into the management of construction projects. Technology readiness (TR) manifests itself in consumers' desire to adopt and use innovative technologies to meet their daily/business goals (Parasuraman 2000, 307). The acceptance of new technologies necessitates the use of the Technology Acceptance Model (TAM) principles, that presume that the acceptance of information systems is driven by two main variables: (1) Perceived Usefulness (PU) and (2) Perceived Ease of Use (PEOU) (Lee et al. 2003, 1). Nevertheless, since construction is a fully project-oriented sector, the question arises as to the status of the acceptance of inventive technologies within the project organization structure and what fluctuations it involves for the structure itself as well as for the roles, responsibilities and interactions among the key participants of such projects. The issue that also stays extensively unresearched is how to evade the scenario with the emerging 3D printing technology and the old/existing organization, as it has been realized from the experience that major changes or progressions in technology necessitate evolution or adaptation of the organization and management to secure all the advantages.

The International Organization for Standardization states that the project organization is a temporary structure that specifies roles, responsibilities and authorities within the project. Persons are designated nominally to particular project organization roles. The project organization should set clear leadership and management principles, be agreed and communicated to every stakeholder in the project. In addition, the project organization should be defined in sufficient granularity to grant each person to comprehend his or her role and responsibilities, as well as the roles and responsibilities of others with whom he or she is collaborating. Throughout the entire project life cycle, the responsibilities should be coherent and plausible (ISO 21502:2020 2020, 15).

The absence of any of the above specifics can lead to circumstances and scenarios that adversely affect the environment of the project and its outcomes. For this reason, the PM2 project management methodology (empowered by the European Commission) also recommends a very strong and translucent project organization, with an established and accepted structure, roles and responsibilities, accurately described by the RASCI matrix (CoEPM² 2018, 29).

Besides the general PM standards, nonetheless, in each country the key participants, their roles, responsibilities and their interaction within the construction project are regulated by national or local laws (legislation) and/or regulations. Due to the specific historical development and economic conditions, there are major variations in guidelines and procedures across regions and countries, and experts manage their duties by considering national regulations and integrating developed universal expertise. When applied to construction projects, we have come to believe that it functions, but there are numerous unanswered queries apropos whether and how the alteration in construction technology to 3D printing will impact the roles, responsibilities, and interactions of key participants inside the project organizational structure.

The conducted review of current academic literature did not offer any pertinent research findings on the organization of construction projects for 3D printing technology. Consequently, this study provided an insight into the literature, with a comparison and conclusions from other sectors that are leading the way in the application of this novel technology. The study combines such insights with the outcomes of three distinct explanatory, descriptive case studies from Germany (3D printed staircase formwork), the UK (3D printed panels and columns of a bus pavilion) and the US (3D printed housing, with only observed exterior and interior walls), whilst paralleling them with the setting and task of the project organization structure in construction projects constructed using the traditional method. The goal was to examine how this adjustment is manifested in the project team and whether and to what extent the roles, responsibilities, and interactions among key participants in a construction project that utilizes 3D printing technology are transforming. The primary research question was therefore marked as follows: "How do the roles, responsibilities, and interactions of key participants evolve on projects that utilize 3D printing technology benchmarked to the more conventional construction method?" In order to solve the main research issue, the three research sub-questions were determined:

1. What has been discovered to date about the roles, responsibilities and interactions of key participants in construction projects utilizing 3D printing technology?

2. What conclusions can be substantiated about the roles, responsibilities, and interactions of key participants in projects involving 3D printing technology linked to the conventional construction model?

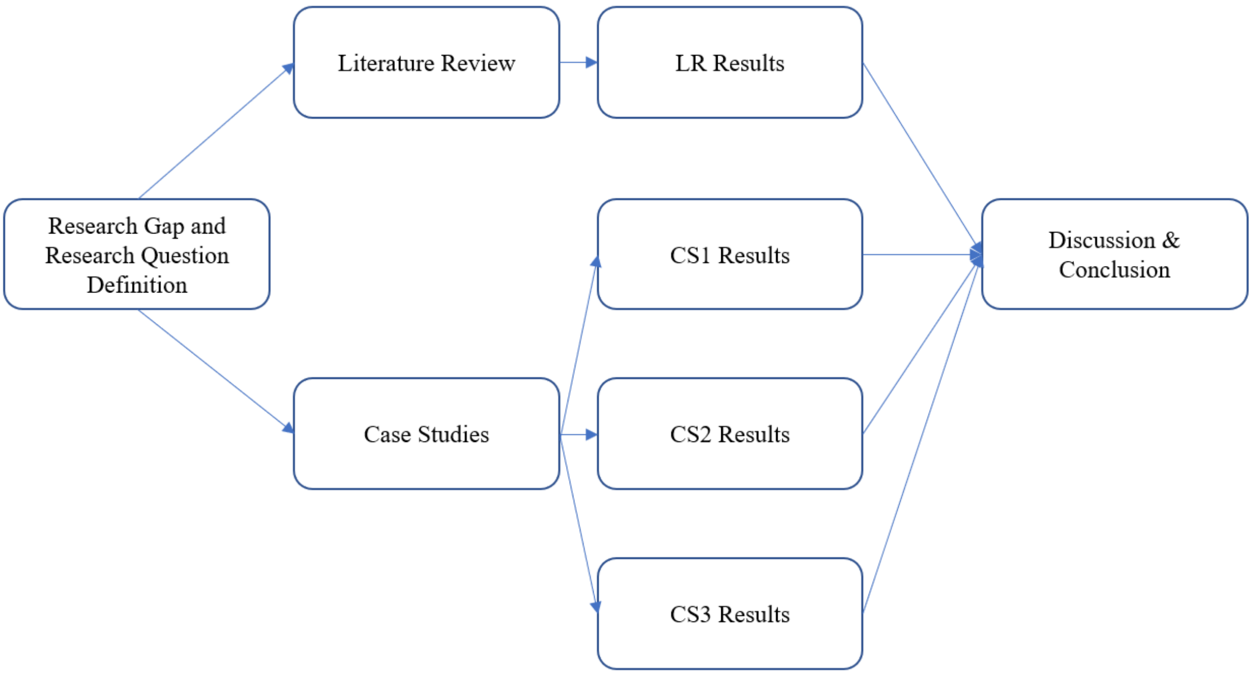
3. Do existing project management methods/project organization structures need to be modified to this comparatively innovative technology?

Key findings indicate that certain roles (client, project manager, quantity surveyor, structural engineer, contractor) will continue to play key roles in this new technology projects. That said, the new technology is expected to have an impact on their job, competences and responsibilities.

5.2 Project organization structure - Research methodology

In the first part of the paper, the literature review and the most important outcomes are addressed. Since the literature on project organization of construction projects using 3D printing technology is relatively limited, examples from other sectors are considered (e.g., IT sector, public sector management...). Alongside this, other designated components of construction projects in relation to the project organization structure (e.g., success factors, project team dynamics, working conditions within project teams, stress, and work climate within the project team…) were examined with an evaluation as to which of these insights could be applicated to construction projects using 3D printing technology. The second part of the paper covers three distinct case studies of projects conducted in Germany (3D printed staircase formwork), UK (3D printed panels and columns of a bus pavilion) and US (3D printed housing, with only observed exterior and interior walls). Discussions were undertaken with a range of project participants, and overall conclusions were summarized by combining insights from project documentation and personal observations following interviews with project team members and leaders. When selecting a case study, it was noted that there have not been that many targeted projects using 3D technology (or trends in new technologies in general), meaning that they were mainly in the start-up stage. As already mentioned in the "Construction 5.0" section of this thesis, it was understood that the movement is still mostly in its beginning, dissimilar to USA and China, as the furthermost leading countries, where a broader presence of comparable projects has been noted and with UK, Germany, France, and Italy in Europe and India, Japan, and Korea in Asia moderately following (Chun et al. 2018, 397). The projects for this study were selected based on the similarity of their organizational structure, as appropriate to the impacts of different practices and regulations. They were all conducted recently as well as in developed countries (as trendsetters), and in all of them 3D printing technology is acknowledged as a potential alternate to the issues of conventional construction. Results were presented independently for the literature review as well as for each case study, and then incorporated into the discussion part. The end of the paper contains assumptions, limitations, and suggestions for further research, all followed by conclusions.

Figure 37: Research Methodology Diagram



Source: Spicek et al. 2023, 5.

5.3 Project organization structure - Results

5.3.1 Project organization structure - Literature review findings

Generally, regarding the subject of the suitable project organization structure (optimal balance of roles, responsibilities and interactions) of the construction project team, there are numerous studies handling fundamentals such as project success factors (Radujkovic and Sjekavica 2017, 1), collaboration amongst construction project key performers (Deep et al. 2019, 919) or temporary multi-organization of the project (Fellows and Liu 2008, 219).

When it comes to construction projects that use 3D printing technology, nevertheless, a review of the literature has shown that these topics are principally under-researched due to the comparative freshness of the technology. The situation is likewise comparable with regard to the project organization structure (ISO 21502:2020 2020, 15; PM² 2018, 23).

The review proved that there is a shortage of papers linking the project organization structure and construction projects utilizing 3D printing technology. In addition, the laws and regulations of each country specify and categorize the roles and responsibilities of the key participants in construction projects, and these are approved and/or complemented by norms and standards both within the country and internationally. That said, we have up to now not found any such regulations or standards to be a uniqueness due to the emergence of 3D printing technology. However, this is usually the case with regard to standard construction, where innovative and unconventional technologies, involving 3D printing technology, have been mostly ignored initially. There is also an encouraging tendency noted in efforts to standardize all 3D printing technology activities by correlating them to more traditional construction model. Accordingly, in this paper, in the first part, throughout the categorisation of the literature review, it was conceivable to derive suitable deductions and probable bases for the explanation of the project organization structure of construction projects using 3D printing technology, mostly from the prior researches within traditional construction, but also from several studies from different industry sectors.

5.3.2 Case study 1 - 3D printed staircase formwork (Germany) findings

An analysis of the 3D printing of stair formwork used in the construction of the new bank buildings in Leipzig is provided in the first case study. Essentially, it is a curved arch of the lobby stairs, single-shell masonry (monolithic construction). Given the complexity of the project, it was ideal for incorporating 3D printed formwork, as the high-precision formwork was necessary to provide the staircase with a smooth and consistent curve. Considering that the shape of the staircase is triple curved, 3D printing was the plausible alternative, as the traditional manufacture of such a formwork would have been extremely complicated and consequently very expensive. The casting performance was ultimately so excellent that no distinction could be made between standard and 3D printed formwork panels. In general, the 3D printing project has resulted in major cost and time reductions for the entire project. The threefold bending could not be reproduced with this accuracy in a traditional manner. Besides, the 3D printed formwork elements are weather-resistant and can be exposed to wind and extreme weather without altering their characteristics. The surface was scratch-resilient, which implies that no distortions arose in the course of concrete casting (through compaction). Regarding the project organization, it was stated that the main part in the implementation of such projects is shared among the concrete specialist in collaboration with the structural engineer and the 3D printer operator/manufacturer. The dividing line between 3D printing and conventional construction is also specified by these trio. The concrete technologist with regard to the performing of the fabric, the structural engineer with regard to the requests / load-bearing capability of the element to be printed, and the "printer" with regard to what could be accomplished in terms of construction logistics and machinery technology. Together, they constitute the core team. As far as the individual project roles are considered, the client invests in a construction, and his/her principal concern eventually remains in the financial design of the merchandise and the additional benefit that can be attained with it. There is less room for improvisation for the project manager. Clearly defined procedures that require more complex pre-planning have been already introduced. Planning during construction will also no longer be feasible. The architect will be required to do more preliminary research than just designing and drafting. Level of upfront planning is going to considerably improve. This end-result must be existing (incl. practicalities) prior to issuing the tender. Increased expertise on feasibility and state of the art in designs needs to be incorporated. The structural engineer furthermore has to prove the stability. Nevertheless, he/she requires precise data from the concrete technologist and is not able to rely on standard reference values as used to. Possibly, he/she will define required bed strength values that the concrete technician must accomplish when preparing the admixtures. Construction operations and logistics will be considerably influenced by this new technology. Supply and transportation areas in conjunction with the different construction elements, i.e., what is printed and what is traditionally constructed, necessitate enhanced preparation of construction sequences and procedures. In terms of construction operations, the printer will likely interfere with conventional construction processes by obstructing transportation paths for its own material supply needs, etc. Hence, it will be more difficult to change processes "on the fly". Accordingly, the significance of project supervision would be considerably bigger than in conventional construction. Two fields of additive manufacturing are important to the contractor: printing of structures (3D printing of concrete or similar masses) and printing of construction supplies and prefabricated components. It was estimated that the contractor will have to drastically develop his/her expertise and knowhow or purchase this expertise externally. He/she will turn out to be more of a machine operator and in addition take over on sub-assignments (assembly of beams and/or lintels, etc.).

The typical construction procedure in unification with construction site logistics will appear totally different. A key aspect will also be that time should be distinguished between time used for 3D printing and time for the manual rework. For example, the printing times could run at night-time with single operator, while the required rework would be conducted throughout the day. There are also no longer any restrictions to the design of geometries. It is merely that the expertise passes from the person normally doing the work (in the traditional construction) to the designer who designs the finished parts in 3D. Different craft skills are consequently no longer just as crucial. The qualification of the workforce shifts from skilled construction worker/assembler to machine operator/service mechanic. As a result, costs will shift from manpower staff augmentation to suppliers and project management with high-level of expertise.

Figure 38: 3D printed formwork of the staircase

Source: Spicek and al 2023, 10, based on voxeljet 2021, 1.

Figure 39: View of the stairs after removal of the 3D printed formwork

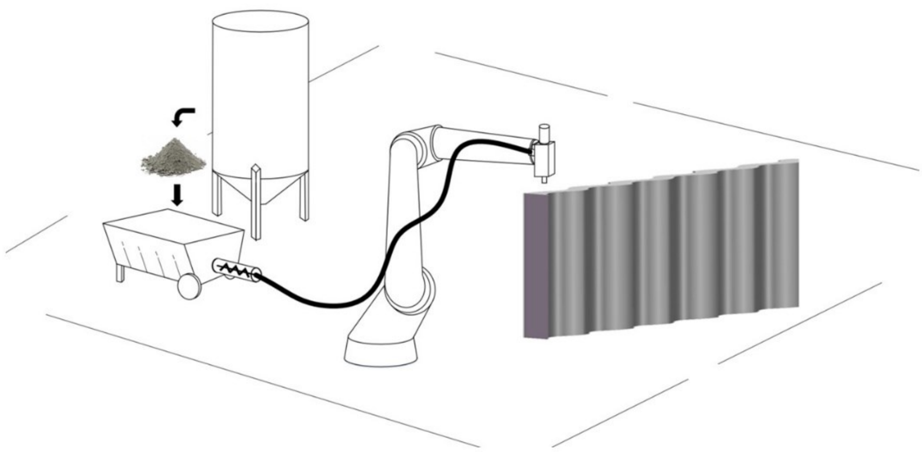
Source: Spicek and al 2023, 10, based on voxeljet 2021, 1.

5.3.3 Case study 2 - 3D printed panels and columns for wall sections UK findings

Second case study was studying the fabrication of panels and columns that are built into a construction whose ultimate purpose was foreseen as a bus stop (or pavilion). A 3D printing technology was selected with the goal of producing free-form structures with no requirement for the moulds. It also hints at the benefits of 3D printing method when it comes to adapting structures (e.g., topology-optimized structures, etc.). The biggest strengths were identified as free form and material efficiency, while the major weaknesses were surface finish, early investment in high-end machinery and the necessity for specialists (operators). From the findings of this case study, it has been shown that a proper project team should consist of experts from various backgrounds, e.g., materials, construction engineering, CAD/CAM/robotics, mechanical and manufacturing engineering, building services engineering, construction management, etc. This means fewer subcontractors for the client, and a project is easier to manage because a 3D printing company is likely to perform all the tasks.

Two separate situations govern the role of the project manager: 1) an on-site printing project is more about managing machinery and equipment than people, and 2) an off-site printing project and on-site assembly which demands more focus on supply chain and logistics. The major change in the architect's role is "Design for Manufacturing/Printing." An architect could in fact dictate a whole project, as his/her design should already consider the realisation of the printing process, or rather, the architect is element of a "manufacturer/designer". Most likely, there would be no difference in the role of the structural engineer. In any situation, all the requests for the mechanical strength and stability of the structure must be satisfied. Managing technologies and equipment could be more crucial than managing people, and the focus on supply chains and logistics will also be manifested in project supervision responsibilities. The main contractor's role will not change much - it will still be responsible for building the project and managing the construction. However, the work content may vary through the use of 3D printing methods, such as subcontracting to a 3D printing company or purchasing/renting equipment and services from a skilled 3D printing company to execute the work. As a consequence, this quickens the transformation in the occupation and/or employment of workers on the construction site, with higher expenses for the project team but reduced fees for labour and suppliers.

Figure 40 - Drawn based on the specifications of the project executing organization



Source: Spicek et al. 2023, 11.

5.3.4 Case study 3 – 3D printed housing (US) findings

Third case study focuses on the exterior and interior walls of a future residential building. A company that supplied and maintained the 3D printer was from Denmark (the same company as in the case of Beckum). It was therefore assumed that both the standard and the procedures were embraced from comparable projects previously conducted in Europe. Especially in the creation of CAD files, but also in all other segments, a gap was observed between the new technology and the old / existing paradigm, which hindered the desirable project success. As a client experiment, the 3D printing project was conceptualized with a drive for automation as a feasible answer to the market's shortage of qualified workers. Despite this, it was noted that the existing level of automation is not as anticipated and the dependency on human intervention is still extremely high. This also means that research and development are necessary in all directions and in all aspects (software, materials, hardware, etc.).

Thinking outside the box was the greatest task, as the typical case of a new technology and existing/old paradigms led to a weaker outcome than projected. 3D printing technology, though, could offer a possible solution for any unique/complex concrete form that requires unique/customized formwork, so 3D printed concrete should be counted as an alternate, as demonstrated in this case study. Given the specifics of each project and the lack of reference examples, it was quite challenging to make broad statements about what the ideal project team should consist of. In terms of the client, the main deviation was that in this particular case, the investor has to buy or rent a 3D printer, which is obviously the most crucial component of a project of this kind. In this case, however, it was not a for-profit project, but a straightforward educational purpose that differs from the usual objectives of conventional construction projects (especially as regards the client's role). The project manager's job is generally to manage a number of various aspects, only in this situation, it was additionally to organize facets of engineering that some subcontractors have almost certainly not ever seen before. Furthermore, practically every participating company on this construction site had their own project manager, making it difficult to universalize their roles. The architect should be conscious of the 3D printer's abilities and apply them to his rendering to bring it to life. Not every axis can be printed precisely to our vision/design. Consequently, in this case, the architect should have been aware of the physical limits of 3D printers from the start. There is currently no distinction in the manner in which a structural engineer treats a 3D-printed home in comparison to a traditionally built home, as all projects will always require some type of conventional structural measurement (e.g., vertical load, column load-bearing capacity calculation etc.). Thus, structural engineers did not really pay much attention to the load-bearing capacity of the 3D-printed walls themselves, because in this case they only serve as "formwork" for basically everything else. But this "formwork" must also satisfy all the technical requests, same as the concrete in the usual formwork (together with reinforcement). Nevertheless, the structural engineer's role should be adjusted, and there should be a revised approach to structural integrity testing. Basic cylinder tests that structural engineers typically conduct are insufficient. Once again, there was a demand for a paradigm shift that has not yet occurred, and the issue of when it will remain unanswered. No particular difference in the role of the quantity surveyor was noted. All otherwise observed risks, precautions and methods should also be considered here as well. Also in this case, all otherwise observed risks, precautions and methods should be respected. For the most part, the role of the contractor is much like that of the project manager. The unique feature, once again, is that it was a specific and inimitable structure for which even the contractor, notwithstanding his overall expertise, is not likely to have any referential knowledge for those specific instances. While the full potential of 3D printing has yet to be adequately defined or realized, it is speculative to talk of what will eventually happen to the demand for manpower. The trend is to automatize the processes, but we are still a far away from this. It's also almost impossible to get a precise costs figure because companies are still battling to find investors in such cases. In addition, this project had many volunteers and workers who worked without compensation, which muddies the true picture of costs benchmarked to a conventional construction site. In summary, there was no exact costs for a 3D printed house because there is no way to buy one at a certain price from a company using the standard buying /selling procedure and they are always part of a one-time experiment. However, the price of works / sale would probably turn out to be far above average (ca. 30-40%) than that of conventional construction method.

Figure 41: Three-story house 3D printed (exterior and interior walls)

Source: Spicek et al. 2023, 12, based on Kuchinskas 2022, 1 and Courtesy of Peri/3D Construction Inc.

Figure 42: 3D printed exterior and interior walls, retained in their originally layered state

Source: Spicek et al. 2023, 12, based on Kuchinskas 2022, 1 and Courtesy of Peri/3D Construction Inc.

5.4 Project organization structure - Discussion and Conclusion

The conducted study implies that there is a dearth of studies on the effect of 3D printing technology on roles and responsibilities within the project organizational structure of such construction projects. It would be encouraging to see much more research on this topic in the future, as new technologies require a new organizational paradigm, or at least an adaptation of the current paradigm. With this in mind, this research provided the key findings of the case study approach. Although 3D printing has yet to have a major impact on the construction market as a whole in today's construction industry, and hence also in the cases discussed here, it was considered that it is an evolving trend and an exceptional timing for research. The decision to focus on the first group of key project stakeholders stemmed from its resemblance to the conventional project organizational model for construction projects. For the future, the study confirmed that selected roles (client, project manager, quantity surveyor, structural engineer, contractor) will continue to play key roles in construction projects involving new technologies. Nevertheless, it is to be anticipated that the new technology will impact their actions, their responsibilities, and their competencies. The case study results indicate that new technology will principally affect design, supply chain, and quality, which means management will need to align integration, scope, procurement, risk, and stakeholder management responsibilities and practices. At the same time, there is a well-founded expectation that the new technology could have a positive impact on the famous "iron triangle" of time, cost and quality. The implications of the above on HRM in projects will be specially interesting, which is possibly the key area that will be influenced, as there are always specific people and their competencies behind any human activity and results. It is evident that shifting some of the activities from construction sites to industrial plants will have a positive impact on the shortage of construction workers, especially in developed countries. The study affirmed that clients/investors are concentrated on the business case and value creation of the project and will only adopt new technologies if they encourage that interest. An architect's role will be faced with a more challenging process of eventual later modifications to the design. At the same time, he or she will have to work even more closely with other experts, such as concrete technologists and structural engineers. One might predict that "a certain quartet" consisting of architect - technologist - structural engineer - printer operator/manufacturer might form a sub-team beginning from the design process. Due to the move closer to off-site production, the quantity surveyor / site supervisor job may change considerably. Undoubtedly, it impacts contractor on the largest scale, as they will be confronted to dilemma either to manufacture or subcontract, to purchase 3D printing machines or not etc. Nevertheless, contractors or suppliers need to acquire new expertise and skills and establish the machine operator movement. In general, 3D printing is expected to generate a new reality with "fewer people and more skills" that will affect the project manager in a major way. The project manager typically assumes the role of coordinator, guided by expectations and circumstances and governed by participants and practices. It is anticipated that within this framework, the complexity of his/her work will increase even though there is less manpower on construction site. Processes will change and the pool of participants will expand (new professionals), requiring a new set of interactions between parallel on-site and off-site activities. Pressure on management's "iron triangle" delivery criteria will increase due to expectations of new technology. And this is precisely what can and must be managed by a more efficient and effective organization within the project, which must be tailored to the blend of on-site and manufacturing production. Based on the main assumption of this study, 3D printing technology is considered as an emerging trend that will be accepted by the construction industry and bring the expected benefits to the stakeholders, mainly a more streamlined and productive work where more added value is generated. Study limitations stem from the fact that the results were collected in three cases where 3D was implemented in the early stages, i.e., they were more like pilot cases. Needless to say, the future development of 3D printing technology will be based on product quality control, including rheological control of materials, geometric and dimensional conformity, structural performance, etc., in order to achieve customized mass production with predictable quality and to ensure that the geometry and dimensions of individual components are within tolerances and that the entire assembly is provided. From the other perspective, there is a reasonable anticipation that new technologies will bring demonstrable benefits and profits. Whereas clients/investors will mainly concentrate on the implications for the value to be created and the financial details, contractors will also focus on the supply chain and delivery processes, while management experts will face new challenges, particularly in the fields of integration, scope, risk and stakeholder management. Great attention should be paid to the competency model and its updating in all key positions of the planning and construction implementation. By doing so, future studies on the proposed subtopics would be stimulated.

6 3D PRINTING TECHNOLOGY FOR MEETING "CONSTRUCTION 5.0" CRITERIA

6.1 3D printing technology as a component of "Construction 5.0" - Introduction

"Industrial Revolution" is one of the few expressions in the personal vocabulary of business historians to have entered the mainstream of the language (Coleman 1956, 1). Any industrial revolution causes transformations in the technological, socio-economic and cultural fields (Poór et al. 2019, 1).

What characterizes all industrial revolutions is the alteration of the way of technological functioning as a result of the massive adoption of accumulated industrial innovations and systemic transformations in the industrial sector, which lead to radical changes in logistics and manufactured goods (Popkova et al. 2019, 21).

As the world is currently in the Fourth Industrial Revolution or Industry 4.0, it is considered as an innovative industrial phase where various emerging technologies are converging to provide digital based solutions (Frank et al. 2019, 15).

The digitalization is reshaping the environment of business and organizations are experiencing challenges to progress (Machado et al. 2019, 1113).

Such challenges demand the evolution of various organizational and technological skills (Scremin et al. 2018, 224).

By analogy, the construction sector is modifying its operations and working practices, and expansion of new technologies in the last decades has resulted in a new concept known as "Bauen 4.0", a term first minted in Germany in 2016 (Forcael et al. 2020, 1).

The construction industry has a pivotal economic role in the economies of any country (Craveiro et al. 2019, 251). It is a strategically vital sector for the European economy as well, with the involvement of a multitude of stakeholders and corporations, providing 20 million working places (European Commission 2014, 3).

The World Economic Forum reports that a 1% productivity increase globally has the potential to save $100 billion annually in construction related costs (World Economic Forum 2018, 1), contributing to a country's competitiveness and sustainable development (National Research Council 2009, 1; Despotovic et al. 2016, 656; World Economic Forum 2018, 1).

Despite the ability of Industry 4.0 technologies to enhance the design, management, operation, and decision-making of construction projects, the capacity to incorporate the technologies completely within the construction sector is poor (Merschbrock and Figueres-Munoz, 2015, 247). Today, the concept of Industry 4.0 represents a future vision of manufacturing. However, a lot of individuals are unconvinced by this new approach, or even dismissive of it (Kolberg and Zühlke, 2015, 1870).

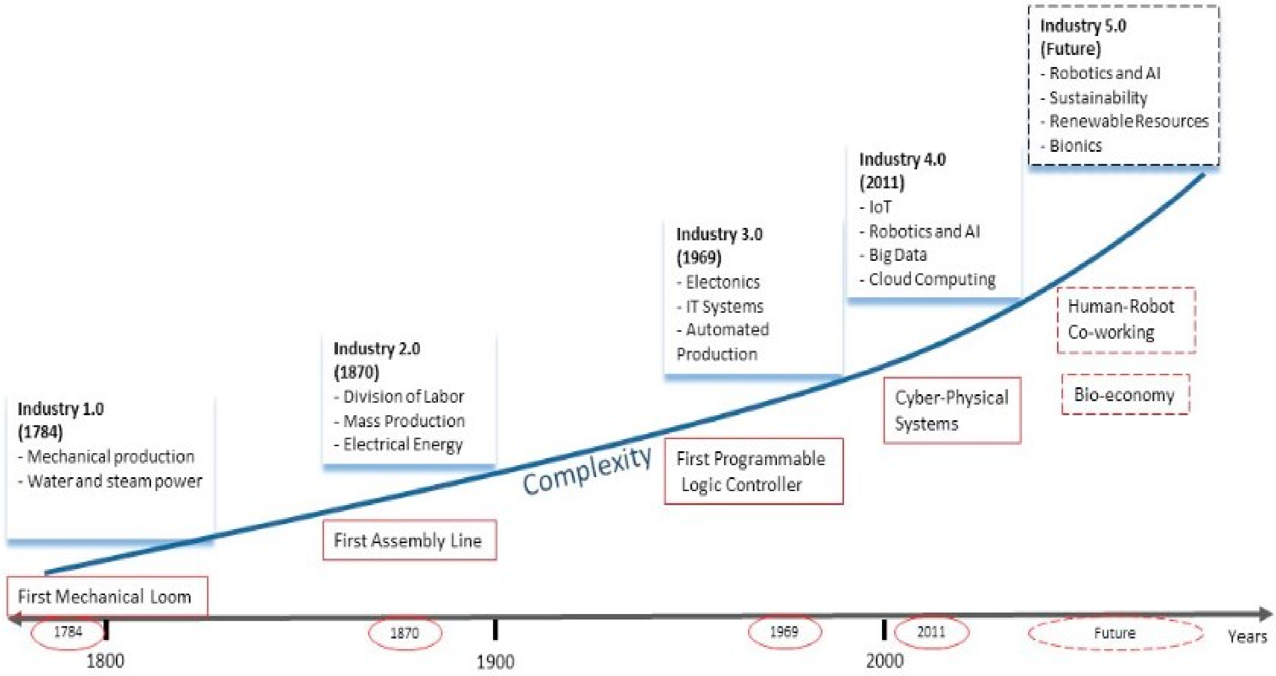
Nevertheless, even before realizing the complete extent of the potential of Industry 4.0 and Construction 4.0, the terms Industry 5.0 and "Construction 5.0" are coming into focus. Whereas most organizations are already engaged in digitalizing their businesses by integrating artificial intelligence (AI), Internet of Things (IoT), cloud technologies, and further sophisticated technology, another level of the industrial revolution is imminent (Paschek et al. 2019, 1).

Industry 5.0, the fifth industrial revolution, is composed of smart digital information and manufacturing enabling technologies (Javaid and 2020, 507). "Industry 5.0 - A Human-Centered Solution" article presents the Industry 5.0 idea in which robots are entwined with the human brain and operate as a collaborator instead of a rival (Nahavandi 2019, 1). New paradigm of Industry 5.0 includes the intrusion of artificial intelligence into people's daily routine, their "collaboration" aiming to enhance human performance and putting humans back into "the center of the universe" (Skobelev and Borovik 2017, 307).

As such, Society 5.0 is a notion that outlines the transformation in people's lives as the fourth industrial revolution progresses (Maddikunta et al. 2022, 1).

Furthermore, whereas Industry 4.0 implicates technology such as BIM, drones, robots, and artificial intelligence including Big Data and augmented reality, the 5.0 aspect is adding the social perspective of digitalization, inclusive of the dedication to the Sustainable Development Goals (SDGs). Subsequently, "Construction 5.0" is the amalgamation of the erstwhile Construction 4.0 and Sustainable Construction working groups (CICA 2022, 1).

Figure 43: Moving from Industry 1.0 to Industry 5.0



Source: Demir and al 2019, 688.

It is expected that several very promising technologies and applied sciences will underpin Industry 5.0 to boost manufacturing and instantaneously provide tailor-made goods (Maddikunta et al. 2022, 1).

These technologies could include 3D printing, artificial intelligence, Big Data, cloud computing, and the Internet of Things, all of which are essential for Industry 4.0 (Chun et al. 2018, 397). A key focus of this thesis is 3D printing technology within that context.

The goal of the “Construction 5.0” working group for the coming years is to generate specific recommendations/action plans for the construction industry regarding best practices for sustainable building and construction innovation (Construction 4.0). Furthermore, the goal is to primarily define CO2 reduction and energy use saving possibilities from the construction companies' point of view (e.g., recycling frameworks, capital investment portfolios that enable carbon emissions reduction, etc.). Over the next two years, the targeted action area and corresponding KPIs should be defined to enable measuring the influence and impact of the construction sector on the accomplishment of the Sustainable Development Goals (SDGs) (CICA 2022, 1).

This raises the question of how 3D printing technology fits primarily into the concept of Industry 5.0, but also what impact it potentially has on fulfilling the Industry 5.0 criteria as well as the “Construction 5.0” sub-concept.

This led to research questions which were:

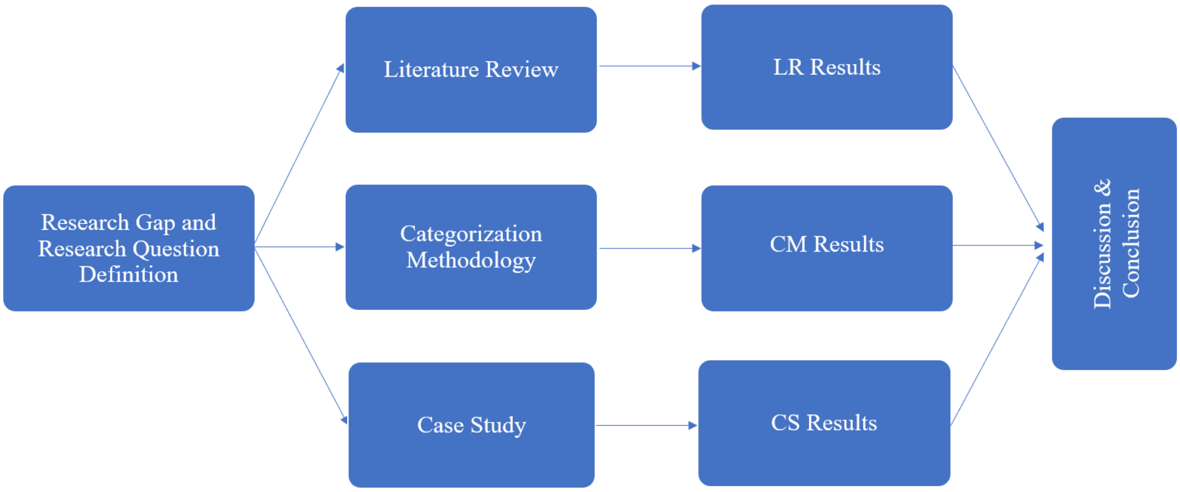
1. Is 3D printing technology in line with the characteristics of the "Construction 5.0" paradigm?

2. What are the implications of 3D printing technology that meet the criteria of “Construction 5.0”?

6.2 3D printing technology as a component of “Construction 5.0” - Research methodology

In this paper, mixed research methods were used. The initial segment of the paper addresses a review of the literature. Since the paradigm of “Construction 5.0” is addressed only very reluctantly in the literature because it is a fairly innovative idea, parallels and conclusions are drawn from Industry 4.0 and Construction 4.0, based on the assumption that “Construction 5.0” is a further extension of Construction 4.0 and that there is no satisfaction of the “Construction 5.0” criteria without concurrent completion of the Construction 4.0 criteria. The second part of the paper refers to the categorization methodology. Based on the literature review - the approach, tools and taxonomy of the impact of 3D printing technology on the realisation of “Construction 5.0” criteria are projected and cumulatively evaluated in the discussion part. In the third part of the work, the same criteria were verified through case studies. Case studies included four separate descriptive, evocative case studies from Germany (Leipzig – Stairs Formwork), China (Tianjin - Zhaozhou Bridge) and Switzerland (1. Zurich - Smart Slab and 2. Zurich - Integrated Funicular). At the end, a conclusion was drawn and a proposal for further research was made.

Figure 44: Research methodology ("Construction 5.0")



Source: Spicek 2022.

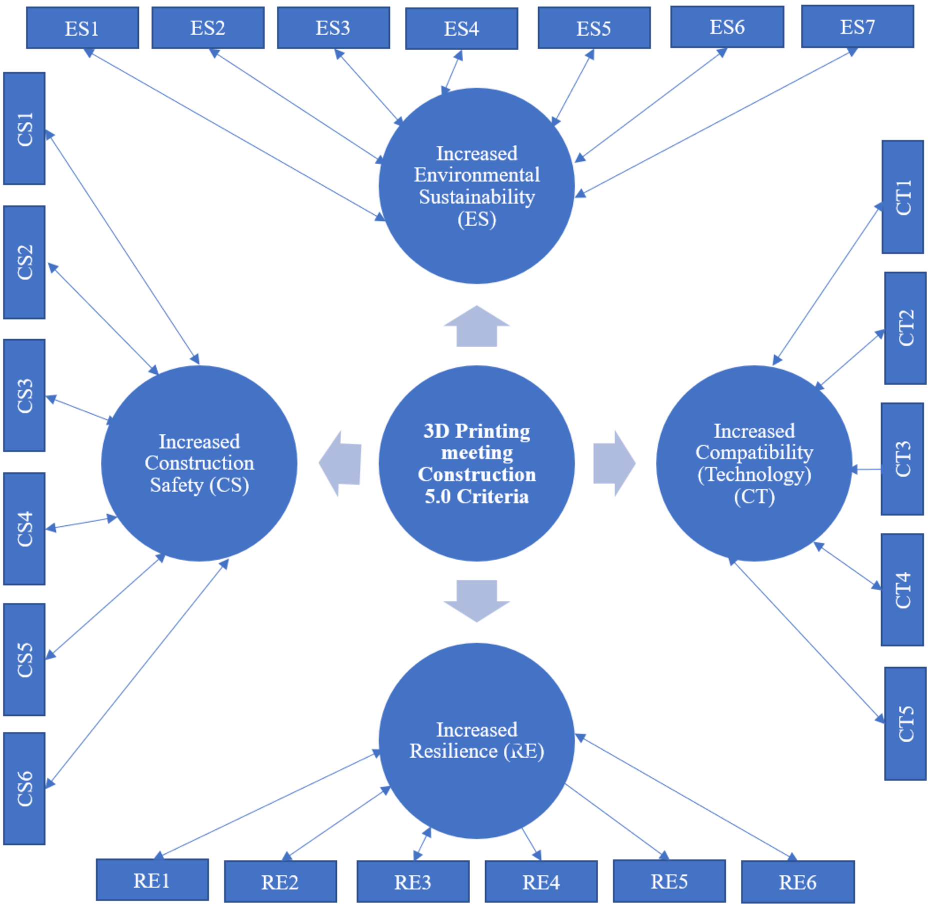
6.2.1 3D printing technology as a component of "Construction 5.0" - Tools / methods / approaches and taxonomy

It was determined, based on the literature review, that the most critical impact dimensions in addressing the "Construction 5.0" criteria when utilizing 3D printing technology in construction projects are as follows: Increased Environmental Sustainability (ES), Increased Construction Safety (CS), Increased Compatibility (Technology) (CT) and Increased Resilience (RE).

The field Increased Environmental Sustainability (ES) contains Reducing CO2 emissions (ES1), Reducing Carbon Footprint (ES2), Reducing energy consumption (ES3), Reducing water use (ES4), Reduce construction time (ES5), Waste generation reduction (ES6) and Using local materials (ES7). The group named Increased Construction Safety (CS) includes: Reduce biological hazards (CS1), Reduce chemical hazards (CS2), Reduce ergonomic hazards (CS3), Reduce psychosocial hazards (CS4), Reduce physical hazards (CS5) and Reduce mental fatigue of workers (CS6). The following group is defined as Increased Compatibility (Technology) CT and involves Compatibility with IoT (CT1), Compatibility with Big Data (CT2), Compatibility with BIM (CT3), Compatibility with Cloud Computing (CT4) and Compatibility with Artificial Intelligence (CT5). The final impact dimensions set is specified as Increased Resilience (RE) and incorporates Resilience for natural hazards (RE1), Resilience by Cyber Security challenges and vulnerability (RE2), Robustness (RE3), Resourcefulness

(RE4), Rapid recovery (RE5) and Redundancy (RE6). Each of the impact dimensions is graphically represented in the diagram below. Further clarification of these dimensions can be seen in “Appendix C” as part of the case study responses.

Figure 45: Initial model of impact factors of 3D printing technology on meeting the criteria of “Construction 5.0”



Source: Spicek 2022.

Case study 1 – "Sächsische Aufbaubank" in Leipzig, Germany

During the construction of the headquarters of the "Sächsische Aufbaubank" in Leipzig, a half-spiralled staircase with intermediate landing was to be erected, which is saddled on a supporting wall. To give it a smooth and even curve, highly precise concrete formwork was required (voxeljet 2021, 1).

The responsible parties placed their trust in the globally renowned formwork supplier for this job. After extensive analysis and definition of the formwork shape for the staircase, the surfaces were categorized according to their complexity. Uniaxially curved surfaces with cylindrical or conical shapes were formed conventionally. The special feature of this staircase, however, was the triaxially curved surface, which reproduces the fillet of the staircase soffit to the inside of the bearing wall (voxeljet 2021, 1).

Figure 46: 3DP makes complex concrete formwork more efficient

Source: voxeljet 2022, 1.

Case study 2 - Old stone bridge in Tianjin rebuilt with 3D concrete printing, China

Zhaozhou Bridge, a famous stone arch bridge from China's Sui Dynasty, was 3D-printed concrete bridge reconstructed by Hebei University of Technology in Tianjin, China, on Oct. 14, 2019. The 3D-printed bridge has the longest single span of 17.94m among 3D-printed bridges in the world, with a total length of 28.1m. This was printed off-site using a modular process and then assembled on-site to the 1:2 scale of the original ancient bridge. The printed material and mechanical equipment were specially designed and engineered. This bridge has a high safety coefficient, as the loading of different bridges has been considered.

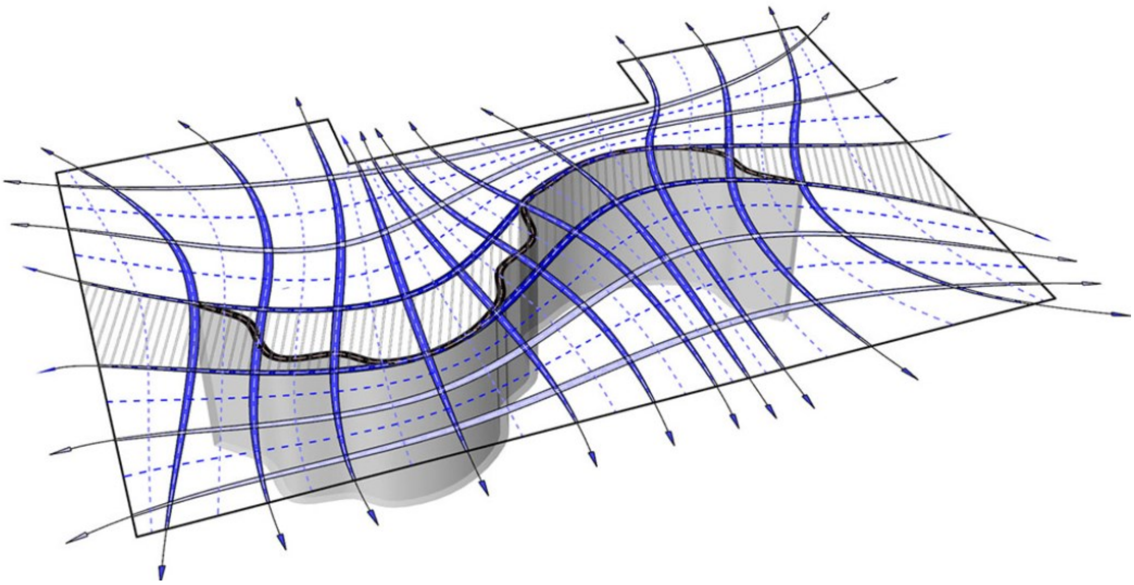
Figure 47: Old stone bridge in Tianjin rebuilt with 3D concrete printing

Source: China Daily 2022, 1.

Case study 3 – Smart Slab, Switzerland

Smart Slab is the first load-bearing concrete slab produced with 3D-printed formwork. The lightweight concrete slab is characterized by its three-dimensional geometric differentiation on multiple levels. The project combines the excellent structural properties of concrete with the geometric freedom of 3D printing. This construction method enables the design of highly optimized concrete components with complex decorative structures.

Figure 48: Load-bearing concrete slab

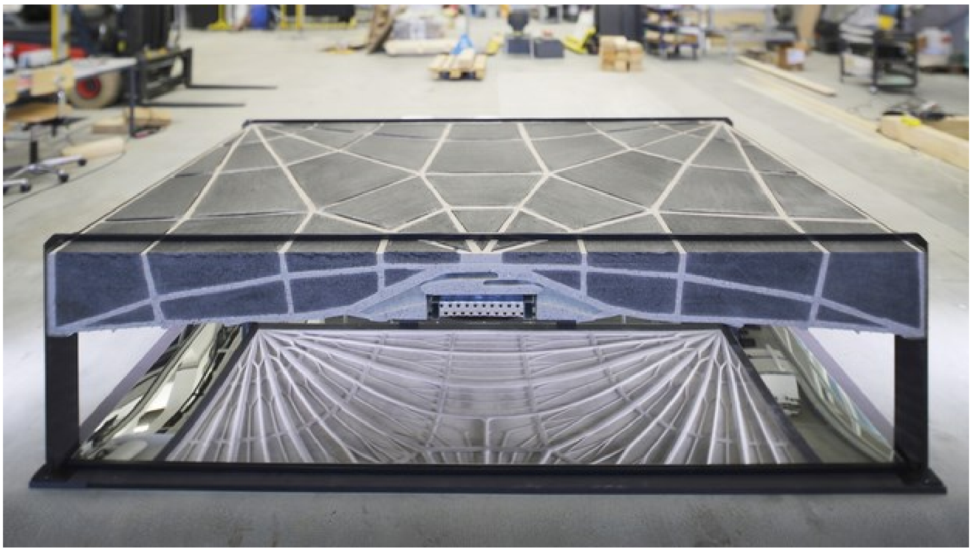


Source: DFAB House 2022, 1.

Case study 4 - Integrated Funicular Slab

This case study is based on the state of the art and demonstrates how fused layer 3D printing can be used to produce a customized formwork from fully recyclable materials for a functional concrete slab. The resulting demonstrator is structurally effective and only weighs 30% of a traditional solid slab. In addition, it showcases the integration of a complex chilled beam ventilation system within the slab's 30 cm deep structure. All these complex geometric features are achieved with an ultra-light 3D-printed formwork that weighs less than 10 kg for the whole 600 kg concrete slab.

Figure 49: 3D Printed Formwork for Integrated Funicular Concrete Slabs



Source: Jipa and al 2019, 1.

6.2.2 3D printing technology as a component of "Construction 5.0" - Literature review findings

As the concept of "Construction 5.0" is relatively new and the literature on it is still in its infancy, concurrent deductions from Industry 4.0, Construction 4.0 and Industry 5.0 were used as a foundation for determining the impact dimensions. Industry 4.0 was considered a new industrial phase in which several evolving technologies converge to provide digital solutions. The applicability of Industry 4.0 in manufacturing logistics was also found to vary depending on the production setting, with companies with a lower degree of repeatability in production seeing less potential for applying Industry 4.0 technologies in manufacturing logistics than companies with high repetitive production. This brings us to a potentially useful application of lean methodology in project management of projects aimed at the application of the industry

4.0 paradigm authenticity. As a result, it is noted that Construction 4.0 technology provides the ability to enhance the planning, management, operations, and decision making of construction projects. Given the pervasive use of Building Information Modelling (BIM), lean principles, digital technologies, and offsite construction, the industry is on the verge of this change. Construction 4.0 stands for the exploration of new technologies by the architecture, engineering, construction and operations industries and is the analogy of Industry 4.0 in the manufacturing world. The concepts are not only related to technological matters, but also to management and processes. This is why the adoption of Industry 4.0 is a major challenge for the construction industry (Construction 4.0). In parallel to the term Industry 4.0, we already meet the concept Industry 5.0. While Industry 4.0 is regarded as technology-oriented, Industry 5.0 is value-oriented. It defines Industry 5.0 as increased collaboration between people and intelligent systems via high-precision industrial automation supported by critical thinking. The paper, "Industry 5.0-A Human-Centric Solution," also delineates a set of key features and common concerns that any manufacturing organization may have about Industry 5.0, shaping the future from digital manufacturing to digital society. A number of visions for Industry 5.0 exist, and one emerging theme is human-robot cooperation. Whereas there are many studies on human-robot collaboration in simple tasks that focus on the development of robots, studies that focus on organizational issues that arise from human-robot collaboration have been lacking. Not only knowledge and digital life, but also robots that behave like humans are going to occupy a large scope in the nearest future.

It has also been revealed that “Construction 5.0” is aiming to encourage the alignment of technological and digital innovations for the construction sector with the social dimension. The “Construction 5.0” is the amalgamation of the previous Construction 4.0 and Sustainable Construction working groups. Construction 4.0 covered technologies such as BIM, drones, robotics, and artificial intelligence, including Big Data and augmented reality, while the 5.0 dimension is bringing in the social aspect of digitalization, including engagement with the Sustainable Development Goals (SDGs).

From the project management standpoint, one part of the work ecosystem within the new industrial requirements is the way in which project teams should be managed. It is stated that speed and flexibility are necessary to implement the various technologies that form the basis of the fourth industrial revolution. This will also require project teams and project managers to adapt their behaviour. Both in the context of projects and Building 5.0, sustainability is one of the most important challenges of our time. It is acknowledged that projects play a pivotal role in achieving more sustainable business practices, and an emerging theme in project management research is the relation of projects to sustainability. The notion of sustainability in project management is expected to grow in importance in the years to come. At present, the conditions (socioeconomic, environmental, and technological) in which organizations operate and projects are executed are continuously evolving. As a result, sustainability is emerging as one of the most significant factors in organizations and projects, which makes the relationship between project management and sustainability a crucial one. The integration of sustainability into project management demands the consideration of a holistic set of sustainability principles, rather than just a set of indicators. Given the amount of concrete produced and the number of concrete structures built, the problem of associated environmental impacts is an essential part of the overall global problem of sustainable development. The use of ecologically optimized concrete structures, therefore, offers the possibility of increasing the quality of construction and thus reducing the environmental impact. Another study found that local materials reduce construction energy use by up to 215% and transportation impacts by 453%. In reaching the goals of “Construction 5.0”, it can be reasonably concluded, with some caution, that the lean methodology of project management is beneficial. In fact, one definition of lean construction reads: "The continuous process of eliminating waste, meeting or exceeding all customer requirements, focusing on the entire value stream, and striving for perfection in the execution of a construction project." Increasing numbers of academics and construction professionals are not making progress with traditional construction management to provide better value to customers while generating real profits. Consequently, lean tools have evolved and are being used successfully on both simple and complex construction projects. Generally, lean construction projects are simpler to manage, safer, completed faster, cost less, and are of better quality. Unfortunately, here is again an obvious example of the conflict between the principle of line production and the project ecosystem.

The safety culture concept is relatively new to the construction industry, but is gaining popularity because it involves all perceptual, psychological, behavioural and management drivers. Within the workplace, there are many kinds of hazards. Among them are ergonomic, chemical, biological, physical, psychological, etc. hazards that can cause harm or have a negative effect in the workplace. As the use of digital technologies in the design of buildings and infrastructure increases, the question of their implications for safety in construction arises.

6.2.3 3D printing technology as a component of "Construction 5.0" - Case studies findings

Through 4 case studies, the description of which is in the area of methodology of this chapter, interviews were conducted with focus groups, and these answers were later numerically / quantitatively supported by a 5-point Likert scale, according to the rating classification below:

- Allocation of value (always compared to traditional construction):

1 - much worse

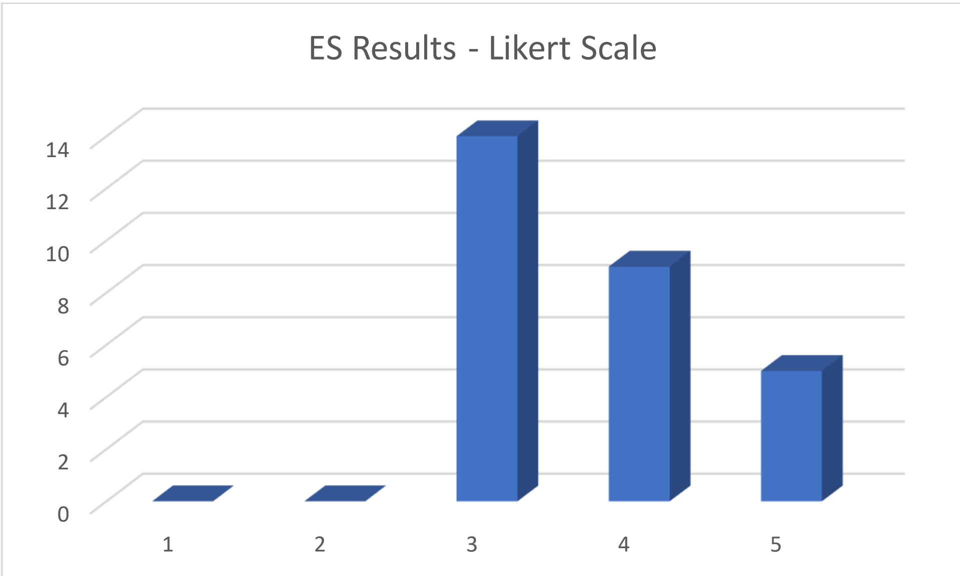
2 - worse

3 - no difference / not recognized

4 - better

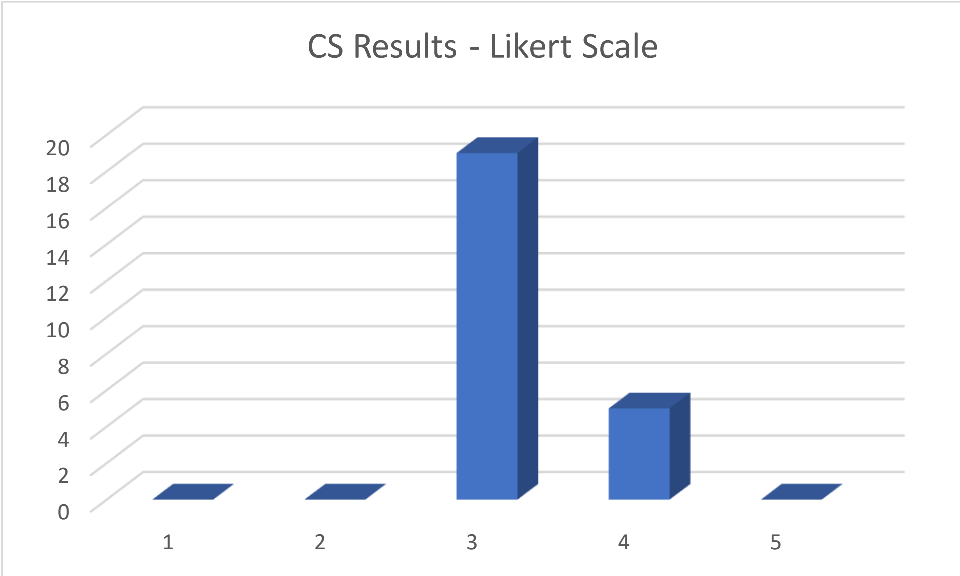
5 - much better

Figure 50: ES (Increased Environmental Sustainability) Results – Likert Scale



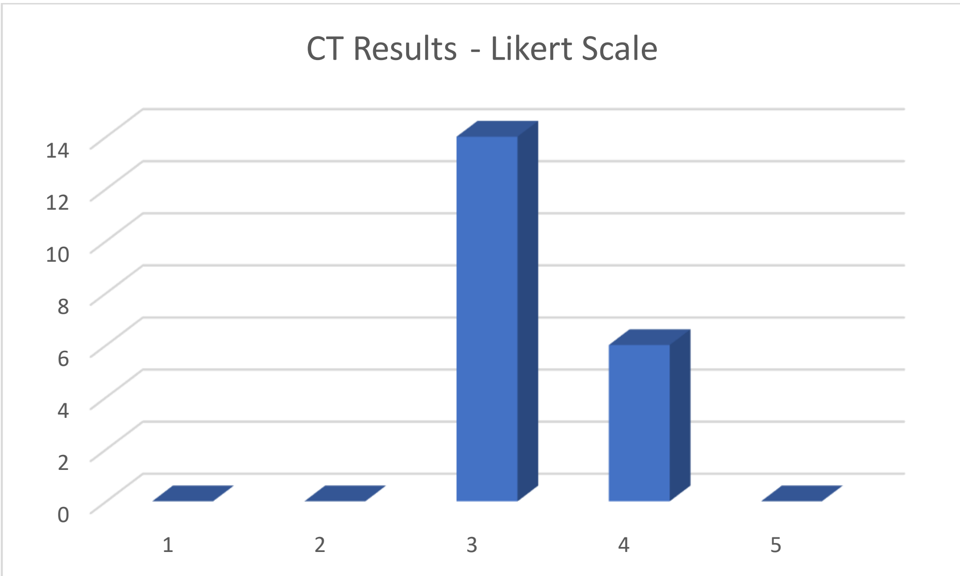
Source: Spicek 2022.

Figure 51: CS (Increased Construction Safety) Results – Likert Scale



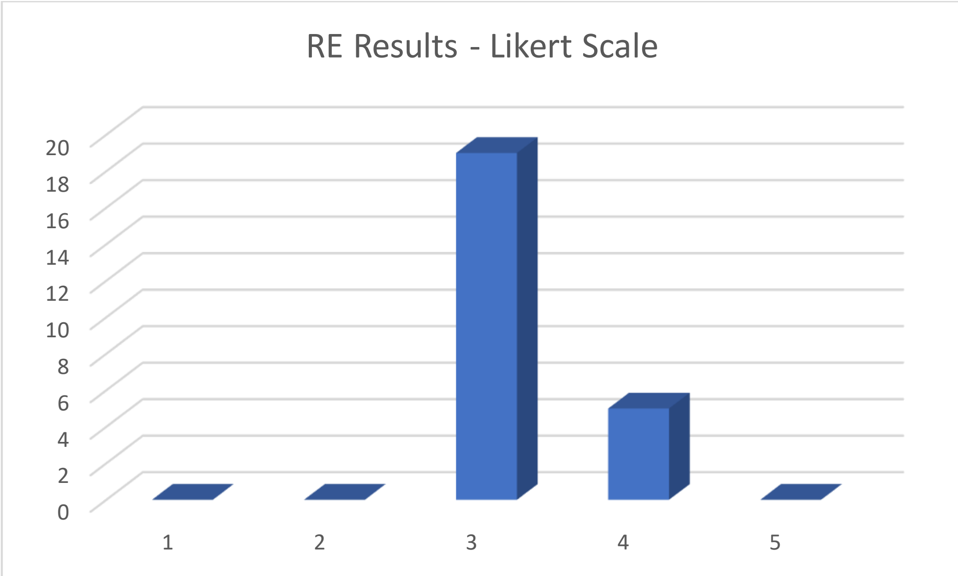
Source: Spicek 2022.

Figure 52: CT (Increased Compatibility - Technology) Results – Likert Scale



Source: Spicek 2022.

Figure 53: RE (Increased Resilience) Results – Likert Scale



Source: Spicek 2022.

6.3 3D printing technology as a component of "Construction 5.0" - Discussion and Conclusion

Running parallel to the term Industry 4.0, we are already encountering the concept Industry 5.0. Whereas Industry 4.0 is regarded as technology-oriented, Industry 5.0 focuses on value. This defines Industry 5.0 as intensified cooperation between people and intelligent systems through highly precise factory automation, which is supported by critical thinking. It also has been revealed that "Construction 5.0" is intended to promote the alignment of technological and digital innovation within the construction sector in terms of the societal aspect. This study once again highlighted the gap between Industry 5.0 and "Construction 5.0", with the construction sector lagging behind in all areas, both scientifically and practically. In addition, the need for a holistic approach to managing the sustainability of projects is evident, as is the need to more consistent application of lean management principles with the aim of achieving better overall project success.

Prompted by analogy and conclusions from Industry 4.0, Construction 4.0 as well as Industry 5.0 "Initial model of impact factors of 3D printing technology on meeting the criteria of "Construction 5.0" was proposed. This model covers 4 dimensions of impact, respectively: "Increased Environmental Sustainability", "Increased Construction Safety", "Increased Compatibility (Technology)" and "Increased Resilience". To test this initial model, 4 different case studies were sampled. Focus group interviews were conducted, and respondents' answers were additionally quantified in numerical form using a 5-point Likert scale.

In the vast majority of responses, it was undoubtedly obvious that the specified aspect is either not recognized or that there is no difference between construction projects using 3D printing technology and traditional construction techniques. Nevertheless, 3D printing technology is recognized as at least better than conventional construction methods in almost all aspects, which is particularly visible in the Impact Dimension named “Increased Environmental Sustainability”.

From the above results, it can be concluded with certain caution that 3D printing technology meets the criteria of “Construction 5.0”. A larger sample of observed cases is required for a more reliable confirmation, as well as a clearer definition of the objectives of the "Construction 5.0" concept from a higher-level perspective.

7 CASE STUDIES IN CRITICAL SUCCES FACTORS ANAYLSIS

7.1 Case studies in critical success factors analysis - Introduction

To date, there has been a rather absence of studies that have addressed the rate of adoption of 3D printing technology in the construction industry as a whole. A new 3D printing technology adaptation model has been created to decrease this research gap. As a starting point for this goal, advanced theories of technology adaptation were used to determine the relevant influencing factors, where only theories that concentrate on the technology and the outcomes of the use of 3D printing can be studied and analysed (Besklubova et al. 2021, 1).

The technology acceptance model (TAM) (Davis 1989, 319), innovation diffusion theory (IDT) (Rogers 2003, 1), technology readiness (TR) (Başgöze 2015, 26), and contingency theory (CT) (Donaldson 2001, 1)) were therefore viewed as the most fitting theories with regard to the development of a conceptual model.

The factors from the above theories of technology adaptation were compared to determine their similarity and to generate a list of factors that stimulate the adaptation of 3D printing technology in construction, in sequence: (1) Relative advantage; (2) Complexity; (3) Trialability; (4) Compatibility; (5) Absorptive capacity; (6) External pressure; (7) Uncertainty; (8) Supply – side benefits; (9) Demand – side benefits (Besklubova et al. 2021, 1).

As a plausible addition to the establishment of success factors for construction projects using 3D printing technology, the attention of this paper was to validate them by means of a case study. The first legal, fully 3D-printed house on German soil, in the city of Beckum (Peri 2021, 1), was selected as an explanatory, descriptive case study. This is a high-quality residential building with a living area of 160 square meters. Through documentation, meetings with various relevant project participants and the concluding interview with the company's team leader for the organization of 3D printing, the above-mentioned success factors were explained and inspected. To contrast the actions of the same success factors within conventional construction projects, an additional case study was fabricated. This was the construction of a 172 square meter house constructed in Berlin using conventional/traditional construction method, but with the usage of various innovative technological solutions.

Research questions are defined to provide answers to the conundrum of how this success factors are applicable through case studies of 3D printing projects and how these same factors behave in the context of more conventional construction approach. The comparative resemblance of the application possibilities of these factors in each case study as well as the fairly equal ratio of advantages and disadvantages of application in both construction methods was demonstrated. This generated the need to develop a decision-making tool for potential investors on which construction method to choose, but also highlighted the fact that 3D printing technology could almost certainly never be fully sustainable without combining it with traditional construction methods. Also, the findings of the study "Logistic cost analysis for 3D printing construction projects using a multi-stage network-based approach" indicate that the leading logistics cost component for 3DP is transportation, the careful considering of which provides the feasibility of a 3DP construction project (Besklubova et al. 2023, 1).

7.2 Case studies in critical success factors analysis - Research methodology

To explain the factors affecting the adaptation of 3D printing technology as wells as their measurements (which were utilised as the basis for case studies), the study entitled "Factors Affecting 3D Printing Technology Adaptation in Construction" (Besklubova et al. 2021) was considered. These factors are outlined in Table 10 below.

Table 10: Factors affecting 3D printing technology adaptation and their measurements

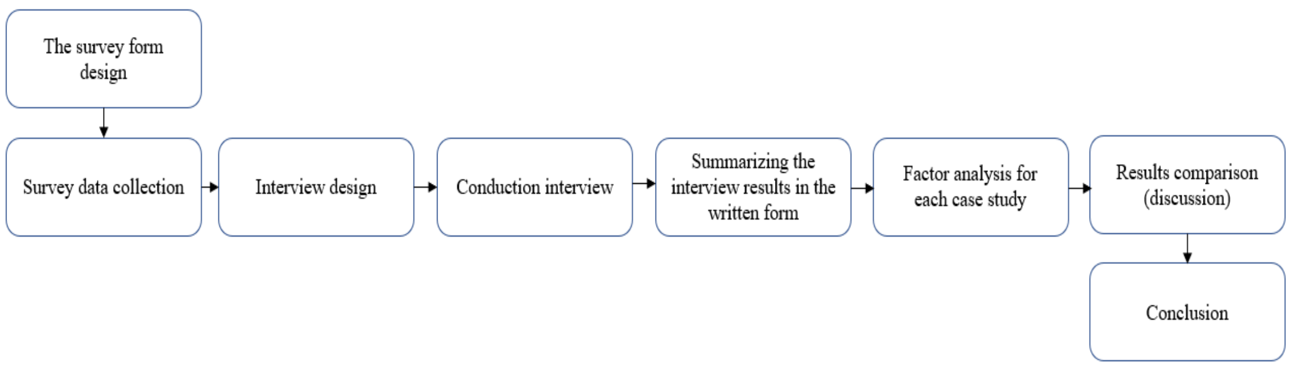
Factor	Code	Measurement items
Relative Advantage (RA)	RA1	Optimize and integrate more functionality into components/ structures
	RA2	Reduce manpower requirement
	RA3	Reduce cost of construction component/structure
	RA4	Reduce construction time
	RA5	Reduce safety hazards
	RA6	Reduce product quality problems
Complexity (CX)	CX1	Computer-generated design process is easy
	CX2	Managing digital construction process and operating 3D printer is easy
	CX3	Maintaining 3D printer is easy
Trialability (TA)	TA1	Improved material usage the properties of which are predictable
	TA2	3D printing product behavior from a long-term perspective (e.g., length of the product life cycle)
	TA3	Precision of the printed objects is within acceptable tolerances
Compatibility (CP)	CP1	Suitability of printing various-sized conventional design elements for different construction needs
	CP2	Compatibility of construction site environment with 3D printing technology
	CP3	Matching available 3D printing materials with the characteristics of legacy construction processes
Absorptive capacity (AC)	AC1	Significant share of company capital expenditure devoted to R&D (produce, test) and implementation of 3D printing technology
	AC2	Major share of employees educated at tertiary level
	AC3	Knowledge, expertise, talent, creativity, and skills of the company workforce
	AC4	Increasing collaboration among stakeholders (integrating a cross-functional team, suppliers, etc.)
	AC5	Company team attitudes toward 3D printing in general
External pressure (EP)	EP1	Competitive pressure
	EP2	Lack of technical standards, quality control standards and product certification issues
	EP3	Skeptical attitudes/ psychological barriers of consumers in relation to 3D printing technologies and product implementations
Uncertainty (UC)	UC1	Perceived side effects associated with innovation.
	UC2	Resistance to environmental influences and failure with exposure to high stress
	UC3	Uncertainty in 3D printing technical/economic benefits arising from regulatory restrictions and isolation of contractors and consultants from one another

Factor	Code	Measurement items
Supply-side benefits (SS)	SS1	Reducing and/or simplifying construction tasks and need for pre-assembly/ assembly activities
	SS2	Reducing the need for transportation services
	SS3	Reducing the number of suppliers involved in construction process
Demand-side benefits (DS)	DS1	Freedom of design and customization of printed components at no extra cost
	DS2	Faster reaction to changing customer needs
	DS3	Production in collaboration with the customer and supplier (e.g., customers integrated in product development)

Source: Spicek 2022, based on Besklubova et al. 2021, 1.

The following criteria were used to select the case studies: (1) a real-life sample to demonstrate the applicability of the model in the operating environment; (2) the case studies had to be from the same country and use comparable pricing strategies and the same currency; and (3) the data used in this case study cover a wide range of angles, including material amounts, expense levels, transportation distances, and volumetric capability. Each of the factors was analysed for both chosen case studies, and the results were presented separately for each case study and then consolidated in the Conclusions section.

Figure 54: Research methodology (Benchmarking critical success factors)



Source: Spicek et al. 2023, 1.

The 7-step methodology was used in this paper to address the research question (Figure 54). Given that the case study data were obtained at different levels of the employee hierarchy, different approaches were adopted correspondingly. A questionnaire with short and rather technical questions was developed for the operational level employees. The interview was conducted with senior executives to elicit responses to open-ended questions that would empower them to express their critical views on the application of 3D printing technology. By combining technical and open discussion of the contributing factors, it was made possible to capture comprehensive project data. Interviews were performed in German and the responses were afterwards compiled into written form in English. Documents and papers related to the case study and accessible in the open source were screened and deeply perused. In developing the form and preparing for the interviews, for example, some technology questions were eliminated because the specific information could be found in a credible source or was phrased to corroborate published findings.

7.3 Case study 1 (Beckum) - Interview Results

7.3.1 3D printing technology case study - Overview information

The initial case study focuses on the 3D printing of a residential building in Beckum (Germany), with a floor area of 160 square meters, which initially served as an exhibition space with the anticipation to be inhabited by residents before the end of 2022. 3D printing as a construction method in this case was incomparably shorter than the specified alternative example of conventional construction, due to the design's complexity and the project's scope. Material amounts and machinery costs are estimated to be in the same range as for conventional construction, as well as labour costs. Supplementary tools to the 3D printer were almost not needed, and the rest of the building materials were applied in a more traditional way (insulation, windows, plaster, etc.). The ambition was to achieve free forms that nevertheless have a function. Therefore, the aim was to build in a material-saving, sustainable and cheaper way and to simplify the entire construction process (due to the established shortage of skilled workers and a lack of resources in general). Consequently, there was an idea to build automatically/ autonomously, and this is something that 3D printing ensures. Such design and its completeness would not be feasible with a conventional method of construction. As a result, the customer has a completely unique, individually designed house.

7.3.2 3D printing technology case study - Relative advantage

It was noted that the waste of materials can certainly be decreased. Design freedom has been accomplished, however with the extra costs. The additional costs for “free design” were drastically lower than with conventional construction, but free forms are always linked with further costs, even in 3D printing. Improvement was attained in almost all segments/by all means (e.g., printing at dam level, leaving the openings free, printing the tub foundation, etc.).

It was found that it is indeed possible to print in a harsh and aggressive environment. The manpower requirement has been absolutely reduced, which was the point/background of the entire topic. As far as reducing the cost of components/structures is concerned, the technology is not so advanced nowadays. The costs are still considerably higher than in conventional construction (about 20% more expensive in comparison with the conventional construction, but with the tendency to change the trend). Construction period was shortened, which is also one of the most important motives behind this technology, in addition to the reduced need for workforce. It was necessary to construct a machinery in such manner that it would be safe. In this case, an extremely large machine that moves a lot was involved and making such a large machine safe understandably requires a plenty of effort. It is also crucial to have a relatively clean construction site, since a clean construction site denotes a safe construction site. The estimated level of human intervention was therefore roughly 3. As far as quality is concerned, the standard in Germany is already extremely high. And raising this standard even further is a tremendous undertaking. It should be gratifying to achieve the same quality, so that should be the general quality goal in such projects.

7.3.3 3D printing technology case study - Ease of use (complexity)

The computer-generated design process was described as straightforward, and someone familiar with CAD would have no trouble being successful. Controlling the digital build process was also not a big issue. Operating the printer itself was relatively easy, but it takes experience to set the material properly. This was not always trivial, particularly when dealing with different environmental conditions. The maintenance was likewise described as relatively uncomplicated.

7.3.4 3D printing technology case study - Trialability (divisibility)

The properties of the 3D-printed material were only partially predictable, as this knowledge is still not widespread. Different weather conditions (wind, rain, sun, whatever) also played their part. It could simply not be predicted as reliably as with conventional building methods. Since it is a relatively new technology, there are still many unanswered questions, and there is just no possibility of retrospective analysis for buildings that have already been printed. All tests were carried out in a laboratory environment (static analysis, stability and vibration analysis). The tolerances were definitely met and are within the range of the usual construction tolerances.

7.3.5 3D printing technology case study - Compatibility

Flexibility was undoubtedly existent (at least in the machines used here since they are modular). The machine used here needed some space around the building, whereas other machines do not need this kind of space. It is valuable to note that there will certainly be many diverse machines for diverse projects in the future, but 3D printing is compatible with different construction sites globally. Printing standard design elements was said to be financially unviable and completely senseless for the time being (except for research purposes). 3D printed materials can very easily be compared with their counterparts in traditional construction because, after all, it is merely concrete. It is safe to say, with some degree of caution, that 3D printing of buildings will almost certainly never be profitable without combining it with conventional construction.

7.3.6 3D printing technology case study - Absorptive capacity

Successive work was done with different companies and universities, so the calculation of business investment spent on R&D was not so straightforward. In this case, most of the employees had a university degree. A broad scale of expertise was mandatory, e.g., in mechanical engineering, electrical engineering, civil engineering and materials science. The fact that it is an interface technology is also a special feature of 3D printing. Furthermore, because it is an interface technology, a large and cross-functional team was required. The project executing company, as a family business, has faith in this technology, otherwise it would not be undertaking this. In general, the entire company was described as open to innovation and upheaval. The project holder's resources were there and ready for all aspects of 3D printing from the very beginning.

7.3.7 3D printing technology case study - External pressure

Market competition pressure was assessed as within normal limits. Nevertheless, it was concluded that the pressure will surely follow soon, that is undeniable and certain, and this is the point that does not allow such company, as the sponsor of this venture, to rest. There are no real technical standards available today particularly for this technology, and that's simultaneously a positive and a negative aspect. The printing company can design its own quality assurance standards, as an instance. They are not bound by old standards and can introduce new materials and corresponding certifications. Sceptical attitude was depicted as completely predictable. For most customers, this is probably the greatest investment of their lives, so healthy scepticism makes perfect sense. Shortage of available data on the technical and economic benefits of innovation and the constraints imposed by regulations, contractors and consultants who are insulated from each other are the issues that complicate matters for the customer somewhat. But this as well is absolutely natural for such a young technology.

7.3.8 3D printing technology case study - Uncertainties

No substantial side effects linked with the innovation were noted. Innovation has every time positive impact on the image. And image, in turn, is essential for acquiring qualified personnel. Resistance to environmental influences and failure under high stress was the assignment that should always be placed with such projects. Profitability was also still an outstanding issue that must be appropriately proven to customers.

7.3.9 3D printing technology case study - Supply-side benefits

Effort on the construction site got much simpler, e.g., for electricians. Pre-assembly and assembly activities become lessened as well when printing on the construction site (the question of profitability in this case remains). The transport was not described as simpler/reduced. It is unlikely that this will change that much. Possibly it will be worse due to the size of the printer, but this reduces the need to transport material on the other side. In domain of transport and unload, everything was easier. The number of suppliers is not expected to change drastically. It will most likely remain comparatively fixed. In terms of improving collaboration between stakeholders (architects, engineers, designers, suppliers, etc.), "improvement" may be the wrong word, but this technology ensures that it all occurs sooner. More in the planning phase and less in the execution phase, respectively.

7.3.10 3D printing technology case study - Demand-side benefits

Custom production of printed components is one item that is desired by the "margin", but it is a relatively narrow item. Modifications are therefore always expensive, and the market rarely demands expensive solutions. This is only ever a niche, regardless of the type of construction. The "demand" is for faster and cheaper, as trivial as that may sound. Faster, cheaper, more sustainable is the key.

7.4 Case study 2 (Berlin) - Interview Results

7.4.1 Traditional construction case study - Overview information

The second case study is a conventionally built residential building in Berlin, Germany, with a living area of 172 square meters, where the family of the construction manager will be both landlords and residents of the building. Contrasted to the potential substitute (3D printing technology), about 200 tons of material were spent and the cost of the machines was around 200.000 €. Extra tools needed were a bit more expensive than with potential 3D printing, and building materials were in the same span. Manpower costs per day (in €) were likewise in the same range. Yet, since the first day of planning, nothing other than the conventional way of construction was ever considered. The potential problem identified with 3D printing was plastering (to achieve the same aesthetic level), which was not necessary at all with clean sand-limestone blocks used here. The only interrogative point was whether or not to use a prefabricated concrete staircase, but that was rapidly scrapped because it was pricey and had a long waiting list. Perceived reliability and durability, good transparency, ease of monitoring and quality control were the described benefits that client received from using the conventional construction method. The ability to make last-minute minor geometry adjustments on site or "on the fly" and the capability to take parts of the design "in-house" were also rated as favourable enablers. There was no computer-aided designing performed. Minor problems were found related to the maintenance of the machines for the conventional method (e.g., the saw for the sand-lime blocks was not well maintained, resulting in excessive dust on the construction site until appropriately cleaned). No difficulties were encountered in managing the digital construction process, as all planning was done by one individual with extensive understanding of the process.

7.4.2 Traditional construction case study - Relative advantage

Given that the project was planned in BIM with exact block accuracy, there was practically no waste in the wall blocks. Also, the excess concrete was not wasted, but used to pour paths that were later repurposed. It was aimed for "freedom of use" rather than "freedom of design." There were no free forms required, but a house was built with almost complete freedom in the construction of the interior walls. The structure itself has only one staircase and a smaller internal wall. The freedom to design the space, leaving the rooms or anything else open was nearly 100%. There was almost no significant construction waste recorded. Virtually no partitions provided flexible and interchangeable functions as well. Using conventional construction methods and building manually means that the building is exposed to the weather until the shell is completed, and this cannot be avoided, as with almost all methods. The construction was planned considering the weather conditions and making day-to-day alterations if required. Most likely, this is an advantage of building everything by hand, because with good planning it costs about zero for workers to modify positions or not come the next day, and in the interim other work could be accomplished (installation, earthworks, insulation, piping...). Thanks to good communication and weather-related planning, there were no interruptions in the construction process due to external conditions. Since there were on average only 2 people on the site and it was a small-scale site, the component of reducing the need for personnel is not very high-ranking since it is not likely to go considerably lower. As for the qualification, it is a job with low qualification but with experience needed, so a 3D printing procedure would be difficult to be attractive in this case since the training of the operator on site would have to be much higher than that of the bricklayers. It has been noted that the professionals who advocate conventional construction can still personally dominate for quite a while in reducing the cost of components/structures with proper structural design, but in large-scale projects, it is impractical to perform all the high-end planning correctly. A further hazard that needs to be alleviated is the time taken for design compared to the time taken for construction. There were a lot of errors that only become visible on the construction site in the building process. When the structure is optimized with generative design and then printed with 3D printers, there must be room for changes and errors. With some reluctance, it can be stated that the construction time reduction factor is not a major factor in a small project like this, and the estimated level of human intervention was probably level 3 as well. Quality issues were generally avoided or reduced in a crafty manner.

7.4.3 Traditional construction case study - Ease of use (complexity)

Real computer-generated designs were still described as a field with a high level of proficiency that even some experts and "common engineers" could not handle. By no means was the management of the digital construction process easy. The tools of today and the near future were described as not being nearly as good as they need to be in terms of "communicating with each other" and “ease of use”. Even a "simple" clash recognition requires a high level of expertise and knowledge of the project and the various disciplines to be performed correctly. Conversely, the operation of traditional machines was simple for most people with experience in the use of advanced machinery. Maintenance of conventional machines has not continually been simple, as it can clash with the production schedule, especially when failures arise, and machines have to be absent for reparation.

7.4.4 Traditional construction case study - Trialability (divisibility)

For the case of reinforced concrete and sand-lime blocks, the building material characteristics were foreseeable. The static tests performed for the forecast of the structural behaviour were only informal (concrete pours of the additional concrete were made on the side of the paths, broken with a hammer after 1 day, 3 days and 7 days, just to see if they behave as anticipated by experience). The accuracy of the components built in was totally within adequate tolerances.

7.4.5 Traditional construction case study - Compatibility

Flexibility in producing components in different sizes for various construction industry requests was acknowledged in this project, as well as the compatibility of the site environment with the machines and the appropriateness of the conventional construction elements. In this project, no care was taken, and no care needed, to ensure that the available alternative materials matched the properties of the old construction methods.

7.4.6 Traditional construction case study - Absorptive capacity

A significant portion of the company's investment in R&D was not included, as all R&D was performed by the owner. Findings revealed low operatives' education but high owner involvement (supervisor/engineer) in preparation. The owner was characterized as a very driven and well-rounded engineer with leadership skills who knows the processes thoroughly. Subcontractors were positive about the owner's attention to detail and the pre-planned work schedule. It was comfortable for them not to have planning on their part, and there was no civil engineer or construction manager in attendance. The competence of the contractor's resources to fabricate, test, or implement conventional construction techniques was labelled as advanced.

7.4.7 Traditional construction case study - External pressure

Virtually no competitive pressure was noted. Technical standards, quality control norms and product certification issues were also not perceived in private single-family house construction. The detailed and well-designed plans and drawings met with a high level of acceptance overall.

An information deficit could not be identified. Rather, in this case, the analysis of all this available information spoke in favour of conventional construction.

7.4.8 Traditional construction case study - Uncertainties

Those involved were initially under the impression that it was easy to prepare a project so well and that it did not require much expertise and know-how. This was subsequently characterized as a misconception. Resilience to environmental conditions and failure under high stress was defined as not very vigorous, as the conventional method has its own pace and is only impacted by extreme weather conditions. Uncertainty about the profitability of the conventional method was described as ambiguous, as it was largely related to price increases due to Covid-19. Labour costs were the same as in the contract (distinct from materials).

7.4.9 Traditional construction case study - Supply-side benefits

The reduction and/or simplification of the construction tasks was illustrated as not being applicable. It was planned from the beginning to accomplish "diminished" and uncomplicated implementation. First the method and tools were selected, then the materials, and then the geometry was planned to match. No pre-assembly/assembly actions were involved. Timely planning and knowledge of logistics and vehicle capacities optimized transportation from the start. On-site purchasing also made matters economical. There were only four suppliers: one for concrete, one for reinforcing steel, one for the wooden structure and one for the sand-lime blocks and all other materials. As for the collaboration among the parties involved (architects, engineers, contractors, suppliers, etc.), only the owner (one person) had direct communication with all suppliers.

7.4.10 Traditional construction case study - Demand-side benefits

Custom fabrication of components was described as most likely an insignificant factor in overall construction costs. A sharper reaction to varying customer needs was barely feasible, since the client was the planner and construction manager and planned all backwards down to the tiniest aspect. This mitigating fact also relates to manufacturing in partnership between the customer and the supplier (e.g., customer integrated into product development).

7.5 Case studies in critical success factors analysis - Discussion

In this paper, project success factors, exclusively created for construction projects utilizing 3D printing technology, were investigated. They were first studied in one case study (3D-printed house - Beckum) and then benchmarked and analysed on another case study, a building constructed using conventional construction methods (sand-lime blocks - Berlin). In the segment of Relative Advantage, both constructions indicated analogous attributes in terms of construction waste minimisation, reduction of labour force requirements and regarding the possibility to perform even in difficult weather conditions. 3D construction technology has demonstrated pluses in free form construction (particularly exterior walls), but on the other hand it is still roughly 30 percent more expensive than conventional construction. The projected level of human intervention needed was Level 3 in both situations. In both cases quality disputes were averted as well. Conventional construction method proved, as expected, superior resilience to faults, while in the case of 3D printing technology the design phase must be virtually flawless.

Concerning Ease of use (complexity), in construction of 3D printed house, computer-generated design procedure was labelled as simple and somebody who comprehends “CAD Program” would be effective and deprived of difficulties. In the conservative building project, there was a thought-provoking debate about what computer-generated design involves and real computer-generated design was still defined as an area of excessive knowledge that even some specialists and “ordinary engineers” cannot do. Handling digital construction procedure was likewise not a great effort for 3D printing method, but a massive problem for conservative construction method (a more multifaceted understanding of the same was considered). It was moderately simple to operate the 3D printer per se, but experience is essential to fine-tune the material properly, while the same can be deducted for the operating of traditional machinery. The very same applies for 3D printer / traditional machinery maintenance.

3D printing technology material properties, as a component of segment Trialability (divisibility) were just partly predictable since that expertise is still deficient. Within typical construction method, in the case of reinforced concrete and sand-limestone blocks, built material properties were extremely predictable. The different weather conditions (wind, rain, sun, whatever) also play a big role in 3D printing. Although it is possible to print in all weather conditions, it was merely not as consistently predictable as in traditional construction practices. As this is a relatively new technology, there are still many unanswered issues, and there is just no possibility of retrospective analysis for already printed buildings, due to the lack of reference projects. The tests were completed in a laboratory setting (static analysis, stability, and vibration analysis) for 3D printing technology and unofficially, directly on construction site for conventional building. Besides, construction tolerances were absolutely respected in both situations.

In area of Compatibility, the flexibility was undeniably existing in both cases, once more remarking that the procedure is considerably easier with 3D printing (due to process automation). While 3D printing is generally compatible with numerous construction site settings, it is essential to say that in the future there will certainly be many more unique machines for various projects. 3D printing of conventional-design-components was defined as merely economically unprofitable and totally inconsequential for the time being (excluding research and development objectives). It was stated that 3D printed materials could be benchmarked incredibly good with their counterpart in conventional construction (above all the concrete, but also other resources). With certain reservation, it can be stated that 3D printing of constructions will never be cost-effective without unification with traditional building methods.

On the subject of Absorptive capacity, in the case of 3D printed house, it was collaborated effectively with several various firms and universities, therefore the sum of company investment spending committed to R&D is not so straightforward. In opposition, by traditional construction, a considerable split of the capital expenditure devoted to R&D was virtually none since the whole R&D was the owner himself. Most 3D printing workforce had a college degree, while workers in traditional construction had a lower education level. 3D printing technology project necessitated a comprehensive variety of expertise, such as mechanical engineering, electrical engineering, construction and materials science, as well as a large, cross-functional project team. The owner in traditional construction project was a very ambitious and adaptable engineer that knows the process well. The subcontractors appreciated his awareness to details and pre-scheduled working plan. This reduced the requirement for a planner, a construction manager, and construction supervision. Sufficiency of execution firm sources to manufacture, assess or execute traditional building structure was depicted as excellent.

Pertain to External pressure, the competitive pressure is maintained within regular boundaries in case of 3D printed project and virtually none was observed in traditional construction project. Nevertheless, the tension will most surely rapidly arrive for 3D printing technology. It was also stated that today there are no actual technological standards for 3D printing method which is simultaneously positive (possibility of creating individual quality insurance guidelines) and negative (lack of experience and reference projects). The suspicion linked with the absence of data, professional guidelines and quality control in 3D printing project was described as extremely high, but also healthful and anticipated. In contrast, with traditional construction method, good preparation and planning, and the knowhow of the proprietor, the suspicion effect was almost non-existent.

No significant side effects of 3D printing related to innovation were found in the Uncertainty chapter. Resistance towards environmental influences and resistance to high stress failure is the challenge that should always be imposed on these types of 3D printing projects. Unfortunately, profitability is as yet an outstanding concern in 3D printing projects, so it is essential to demonstrate it adequately to clients. The traditional construction method runs at its own tempo and is only impacted by the most extreme of weather conditions. Uncertainty in the profitability of traditional construction method was identified as momentous because it was largely related to the price increase due to Covid-19. The costs of the work were the same as in the contract (regardless of the material which was affected by price increases).

As far as supply-side benefits are concerned, 3D printing made work on the construction site a lot simpler for electricians, in particular. Pre-assembly and assembly activities were reduced when printing directly on site, but the issue of profitability persists in that case. Transportation was not described as being made simpler/reduced as a result of the 3D printing project. The quantity of suppliers was also not expected to alter considerably. "Increasing" collaboration among key project participants is perhaps the incorrect term, but this novel technology ensures that collaboration occurs sooner. Hence more in the planning stage and less in the implementation stage. Whereas, on the other hand, the reduction and/or simplification of construction tasks was described as not applicable in traditional construction. It was planned from the very beginning to be reductive and simplistic. In the case of traditional construction, no pre-assembly/assembly activities were required. Well-timed planning and understanding of logistics and vehicle capabilities improved the transportation segment right from the start. Buying locally made this efficient as well. Only four suppliers were involved. In terms of collaboration between stakeholders (architects, engineers, contractors, suppliers, etc.), only the owner (one individual) had a direct interaction with all the suppliers.

On the Demand-side benefits, custom production of 3D printed components is a point of marginal desirability, thus a relatively minor area of concern. In other words, customization is always expensive, and the marketplace hardly demands expensive. This is always only a niche, irrespective of the construction style. The "demand" is constantly for quicker and less costly, as trivial as that may seem. Faster, cheaper, more sustainable - that is the key. In conventional construction, custom fabrication of building components has been described as a likely neglectable contributor to overall construction costs. Responding more quickly to changing customer needs was hardly possible, since the owner was the planner and construction manager and had planned everything in reverse, down to the tiniest possible detail. The same extenuating factor is applicable for production in cooperation with the customer and the supplier (e.g., customers involved in product development).

A limitation of this study was that only two case studies were conducted, with some non-comparable considerations necessitating deeper analysis through several more cases. It is assumed that both projects are reference representatives of their construction method, but particularly 3D printing project as the first house of its type on German soil). For further studies, it is recommended to conduct more case studies in other countries around the world where the benchmarking would be even more rigorous and intriguing. There is also a need to develop a scale/mechanism for evaluating these factors as a basis for future investors' decision-making tool on which construction method to select.

7.6 Case studies in critical success factors analysis - Conclusion

In this context, the project of 3D printing technology, as a potentially viable alternative to conventional construction, was confronted in the success factor test with the tangible example of traditional construction, which was carried out with engineering expertise and innovativeness of the future owner. 3D printing technology has proven beneficial in the production of free-form shapes, while accomplishing almost identical outcomes as conventional construction in several other facets such as material savings, labour reduction, and construction waste reduction. The requirement for human interference was rated at Level 3 in both cases. 3D printing requires a superior level of upfront planning, a more educated workforce, and more funding for research and development. Conversely, conventional construction method has shown a greater susceptibility to error and a greater ability to adjust design during the construction phase. The operation and maintenance of the machines is exemplified as straightforward in both cases, as well as compatibility with the construction site setting. A healthy scepticism can be observed with 3D printing, related to the lack of reference projects, lack of standards, and comparatively unpredictable material behaviour, since it is a relatively modern technology. In terms of supply and demand side benefits, it was discovered that there are no major discrepancies. As a next step, it is necessary to develop a scale/mechanism for appraising these factors, which will provide a basis for future investors' decision-making tool on what type of building method to choose. Nonetheless, it is reasonable to say that 3D printing of buildings will never be profitable without combining it with conventional construction.

8 FEEDBACK FROM PRACTICE ON 3D PRINTING SUCCES FACTORS

8.1 Feedback from the practice - Introduction

One of the enthusiastic companies seeking broader application of 3D printing technology is company named “voxeljet”, based in Friedberg – Augsburg (Germany). This company has already proven itself as one of the most successful 3D printing companies (Pistilli 2020, 1). Its roots date back to 1995 with the first successful dispensing of UV resins. As part of a "hidden" project, the first 3D printing trials were carried out at the Technical University of Munich. In 1996 the project participated in the 1st Munich Business Plan Competition and in 1998 the first patent was granted. In 1998, the first sand moulds were printed at the university (voxeljet, 2022, 1).

Founded with the aim of developing new generative processes for the production of castings and plastic elements by means of 3D printing, the company was initially operating with four employees at the Technical University of Munich. The headquarters in Augsburg were established shortly thereafter (voxeljet 2022, 1).

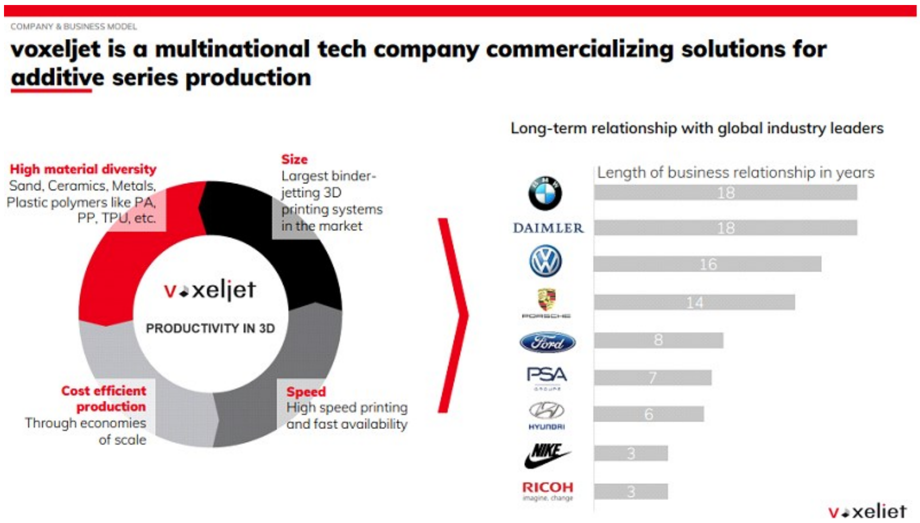
8.2 Feedback from the practice - Research methodology

On September 01, 2020, the 1st official visit to the company took place. On this occasion, the offices and production facilities of the company were exhibited. During this walkthrough, the initial discussion about the troubles, challenges, opportunities and strategies for the feasible growth of the company as well as generally about the worldwide expansion of 3D printing technology took place. This visit provided a much better awareness of the actual issues implicated in the planning and implementation of the 3D printing process, which had a constructive effect for ranking the priorities of the industry issues. After that, a workshop was organized with a focus group in which the preliminary questions / assumptions for adaptation of 3D printing technology in managing construction projects were debated (previously mentioned 32 assumptions – Chapter 4.1.). From these originated ideas for different projects, various case studies (within this dissertation and beyond) as well as a valuable interchange of connections among enthusiasts of this technology.

8.3 Feedback from the practice – Results

The observed company operates in many industries, including foundries, automotive, reverse engineering, aerospace, pump and heavy industry, construction and architectural design, art and design, film, museum, etc. and it is global premier provider of large-format, high-speed 3D printers as well as on-demand 3D printed parts for industrial and commercial customers (voxeljet 2022, 1). Components manufactured by using this 3D printing machinery are flying in space, increasing the efficiency of mobility and enabling the creation of new technical solutions (voxeljet 2022, 1).

Figure 55: Company & Business model – multinational tech company commercializing solutions for additive series production



Source: voxeljet 2022, 1.

As of December 2019, they had 188 installed bases for 3D printers, research and development costs amounted 29% of total revenue, they had more than 420 patents and patent applications and more than 100,000 printed parts per year (on average), as well as one of the largest additive manufacturing centres in Europe (voxeljet 2022, 1).

In a construction context, recently, the construction industry has emerged as one of the most prominent research fields in the area of service robotics (Balaguer and Abderrahim 2008, 1). That said, 3D printing is a relatively new technology that has yet to gain real momentum. Accordingly, there are many prospects to advance the company in the field of automation and robotics (additive design, automated design, additive manufacturing). Although the company, as stated above, is one of the global leaders in the field of 3D printing, with any new technology it takes time for the ideas to become reality. Sometimes the robots and machines responsible for the physical implementation of these ideas cannot follow the ideas of their creators. In this regard, the company is already evolving numerous innovative solutions with the goal of reproducing the most progressive systems capable of meeting and adjusting to the requirements of clients. Similar opportunities exist in the area of producing and discovering new and better materials, contributing to legislation, training professionals to apply these technologies, etc. However, most actions here, especially in the construction sector, are limited to demonstration models, pilot projects and spontaneous initiatives by 3D printing enthusiasts and research institutions. Consequently, the critical success factors identified in this dissertation have not yet been applied in practice. Nevertheless, the feedback from the workshop was quite positive and it could be deduced that the mentioned critical success factors could be a reliable basis for the decision on the construction method, as well as an explanation of why some construction projects using 3D printing technology can be considered successful and others not.

Below are several pioneering projects of the company in the field of construction / building materials:

Figure 56: Complex formwork for concrete casting - 3D printing comes into action

Source: voxeljet 2022, 1.

Figure 57: The Pillar's New Clothes - How 3D printing of facade elements innovates modern architecture

Source: voxeljet 2022, 1.

Figure 58: The advantages of 3D printing of formwork are proven once again

Source: voxeljet 2022, 1

Figure 59: Detailed concrete facades with industrial 3D printing: the voxeljet company stone

Source: voxeljet 2022, 1.

8.4 Feedback from the practice – Discussion

Visiting the company "voxeljet" offered an insight into the "tangible" world of 3D printing technology with all the surrounding contents that are necessary for these operations. Printers of state-of-the-art technology were presented, focusing on the main opportunities, but also barriers in the implementation of new ideas of the company. As already noted, the company is one of the leaders in the market, therefore, in most cases, the problems could be generalized as global challenges in the application of this comparatively novel technology. On the one hand, the need for alternatives is once again evident, due to the aforementioned problems of the modern construction sector, such as labour shortages, project budget and deadline overruns, supply chain issues, demand for housing, failure to build in line with sustainable goals, and the like. On the other hand, there is once again an apparent gap in the capabilities of technology, at least for now, in the form of unrealistic expectations regarding time and quality, as well as the obvious lag of the construction sector compared to other industries. It should therefore be noted that these aspirations are not entirely feasible or reachable at the present time, but the tendency of companies such as "voxeljet", as well as other zealots, is to aim in this direction. Many great pioneering efforts have already been made, both in the construction industry as well as in all other fields (sand casting, investment casting, reverse engineering, aerospace, pump and heavy industry, art and design, film and museum, etc.), to encourage the application of this technology and make it possible. It is actually a whole new world that represents the future that the market expects in the coming years. The community of 3D printing technology enthusiasts is still quite narrow; hence it would be interesting to gather as many as possible specialists from other companies for the professional "knowledge-transfer" dialogue, with a common goal - to contribute to the development and implementation of this expertise. The critical success factors outlined in this thesis could definitely serve as a tool to better understand why some of these projects are successful and others are not, and what factors drive potential investors to choose or not choose this construction method.

8.5 Feedback from the practice – Conclusion

Touring the company provided an invaluable experience that gave a glimpse into the power, scale and worth of this key player in the 3D printing technology market. The workshop / expert discussion led by the marketing director proved to be a genuine platform for discussion of current topics on the global scale. The subjects were exceptionally diverse, including advantages, disadvantages, opportunities, obstacles, and recommendations for the future work of the company itself as well as indirectly of the future advancement of the entire technology in general. Nevertheless, there are still many unexplored corners that provide an opportunity for further research and most crucial of all, as with most new technologies, to bridge the gap between research ideas and practical implementation. This is a tedious process that must involve experts from all areas of 3D printing technology. Only more 3D printing implies greater standardization of the process, less expensive and easier printing, and the establishment of regulatory bodies that are ready to transform enthusiasts' ideas into successful ventures. Critical success factors could play an essential role here, as they determine when construction projects using 3D printing technology will be successful and when they will not. Consequently, their understanding and application could be a crucial aspect when choosing a construction method. Given their existing negligence in practical applications, their future utilization represents an anticipated scenario.

9 DISSCUSION

The purpose of this chapter is to elucidate the position, significance, and consequence of the findings of this thesis. These outcomes are discussed with the objective of initiating scientific brainstorming in the area of project management associated with this research.

It has already been mentioned several times that the construction sector is lagging behind other industries in many areas, which in this instance is clearly visible in the area of both robotization and automation. Moreover, today's construction sector is fraught with shortcomings, such as project deadlines and budgets not being met, lack of skilled labor, increased demand for housing, expensive construction costs, insufficient quality and risk management in construction projects, poor waste management, lack of sustainable aspects, etc.

3D printing technology as a potential solution to the above problems has been gaining momentum in third decade of the 21st century, despite the fact that it is still mostly limited to pilot projects, demonstration models and projects still in the design phase. Therefore, the main focus of this dissertation was to investigate why this is the case and what factors/aspects will determine the success or failure of construction projects utilizing 3D printing technology. The individual responses to this complex question are presented below through the lens of each supplemental research question, and the conclusions thereof are summarized in Chapter 11.

<u>MRQ</u>: “What are the critical factors in ensuring success (or causing failure) of 3D printing technology in construction project applications?”

Methodological tools, i.e., analysis of conceptual theories of innovation adoption, delineated the key success factors of construction projects using 3D printing technologies. These practical factors include: 1) Relative advantage, 2) Ease of use (complexity), 3) Trialability (divisibility), 4) Compatibility, 5) Absorptive capacity, 6) External pressure, 7) Uncertainties, 8) Supply-side benefits and 9) Demand-side benefits.

Some other drivers that may affect the feasibility of the 3D printing project are also identified, such as 1) Ethical issues, 2) Changing roles and responsibilities of the project team members as well as the 3) Process of obtaining a building permit.

Given the importance of sustainable construction, the impact dimensions that should allow 3D printing technology in construction projects to meet the criteria of “Construction 5.0” paradigm, were established as: 1) Increased Environmental Sustainability (reducing CO2 emissions, carbon footprint, energy consumption, water use, construction time, waste generation and using local materials), 2) Increased Construction Safety (reducing biological, chemical, ergonomic, psychosocial and physical hazards as well as reducing mental fatigue of workers), 3) Increased Compatibility – Technology (compatibility with IoT, Big Data, BIM, Cloud Computing and Artificial Intelligence) and 4) Increased Resilience (resilience for natural hazards, resilience by Cyber Security challenges and vulnerability, robustness, resourcefulness, rapid recovery and redundancy).

All of these determinants, which to some extent govern the success and feasibility of a construction project, might potentially help guide project managers' choice of construction means and methods. Understanding them is crucial to minimize the risks of introducing new technologies.

SRQ1: *"What are the impacts on construction project management by such disruptive technology as 3D printing?"*

It was shown that the impact of 3D printing on project management in the construction sector is complex, and this technology will have an influence on the role of the project manager. The requirements of the procedure for obtaining a construction permit will change. The importance and scope of the roles, responsibilities, and interactions of key stakeholders within cross-functional teams in such projects will become more relevant. Project success factors related to 3D printing technology will be important in determining viable construction methods. All activities where changes are to be anticipated due to the special nature of 3D printing projects, are to a certain extent, part of the project manager's job description. The organizational structure and management must keep pace with the development of new technologies. The competency model and updates for all key roles in the preparation and construction related activities need to be fully addressed. As a result, project management methods in the construction industry need to be readjusted and refreshed to meet the demands of new technology.

SRQ2: *"How can these impacts be addressed / investigated with the purpose of achieving the economic profitability, quality, and safety of construction projects?"*

Based on literature research, various characterises of construction projects involving 3D printing technology, and relevant practical experience, it can be concluded that the right way to look at these impacts is to research and fully understand diverse factors contributing to the success or failure of construction projects utilizing 3D printing technology, as well as to take the right actions and/or countermeasures. This involved examining how the success factors of such projects are shaped within the context of 1) Relative advantage, 2) Ease of use (complexity), 3) Trialability (divisibility), 4) Compatibility, 5) Absorptive capacity, 6) External pressure, 7) Uncertainties, 8) Supply-side benefits and 9) Demand-side benefits. Considering the novelty of the 3D printing technology, it was important to test the same factors in the context of traditional construction projects, where many parallels can be drawn when it comes to the success or failure of the project.

Due to a scarcity of relevant studies, a similar situation applies in the area of ethical challenges, changing roles and responsibilities of project participants, as well as the process of obtaining a building permit for 3D printed projects. The only possible way to gain knowledge is to draw parallels and then search for specifics compared to more traditional construction.

Assuming that economic profitability, quality and safety are part of sustainability ideas, it can be said that the attitude of all these factors is an important element in the realization of the "Construction 5.0" paradigm. Both the term "Construction 5.0" and 3D printing technology itself are relatively new notions compared to traditional construction. Also, any innovation comes with certain unknowns, new regulations, changing job responsibilities and scepticism. Therefore, only by being aware of these factors and their implications as well as having a reliable measuring instrument for them, it is possible to determine the construction method in advance and create a trustworthy decision-making tool in the case of a dilemma regarding the best construction technique.

<u>Project organization structure:</u>

SRQ3: *"What has been discovered to date about the roles, responsibilities and interactions of key participants in construction projects utilizing 3D printing technology?"*

The research conducted has shown that there is a lack of existing body of research on the impact of 3D printing technology on the roles and responsibilities within the organizational structure of a construction project. As practitioners work on 3D pilot projects, they are gathering the initial insights that validate the necessity of parallel project management development as well as organizational evolution along with the new technology.

Numerous project management standards and/or methodologies such as ISO and PM², as well as laws and regulations of individual countries, were dissected to identify the roles, responsibilities, and interactions of key stakeholders in the organizational structure of construction projects.

However, these examples predominantly refer to more conventional construction methods. Given this apparent deficiency of research, many equivalents from traditional construction projects have been drawn upon, to explain potential alterations in roles, responsibilities, and interactions among stakeholders in construction projects incorporating 3D printing technology.

SRQ4: *"What conclusions can be substantiated about the roles, responsibilities, and interactions of key participants in projects involving 3D printing technology linked to the conventional construction model?"*

The research acknowledged that the identified roles (owner, project manager, surveyor, civil engineer, contractor) will remain key on projects using this new technology. That said, it is reasonable to assume that the new technology will affect their work, responsibilities, as well as competencies. Evidence from the related case studies demonstrates that the primary impact of the new technology will be on design, supply chain, and quality, which means that project management will be required to coordinate integration, scope, procurement, risk, and stakeholder management responsibilities and processes. In tandem, there is also a well-founded assumption that the new technology could have a positive impact on the "iron triangle" formed by time, cost, and quality.

3D printing technology will lead to a new perception of reality with fewer people and more skills, which will greatly impact the project manager. Typically, a project manager takes on a coordinating function, shaped by both expectations and realities, and boxed in by stakeholders and processes. Within such a framework, it is assumed that the complexities of the job will grow despite fewer workers in the field. Processes will evolve and the stakeholder set will expand to embrace new specialists and require new interactions between parallel on-site and off-site activities. Delivery criteria pressures from management's "iron triangle" will also increase due to expectations of new technology. That must be managed with precision by a more organized and effective structure in the project.

It will be interesting to see how all these drivers will influence human resource management in projects – a potent area of influence, as behind every human endeavour and outcome there are invariably particular people as well as their skills. It is clear that moving some of the activities from construction sites to industrial facilities will have a positive outcome in solving the construction manpower deficit problem, notably in developed economies/countries.

SRQ5: *"Do existing project management methods/project organization structures need to be modified to this comparatively innovative technology?"*

It can be assumed that project management professionals will be confronted with new set of challenges, specifically in the fields of integration, scope, risk and stakeholder management. Particular focus should be given to the competency model and its actualization for all key roles during the preparation and building processes. In this way, it is expected that project management methods focused on construction projects will need to be modified and upgraded. This scenario also highlights the inadequacy of forcing the existing and outdated organizational paradigm, given all the specifics that this new technology brings. It is necessary to think beyond the traditional organizational structure and to adapt the role of the project manager even more significantly.

"Construction 5.0":

SRQ6: *"Is 3D printing technology in line with the characteristics of the "Construction 5.0" paradigm?"*

It is certainly evident in the predominant number of answers within this small sample that the mentioned aspects are either not identified or that there is no distinction to be drawn between construction projects that implement 3D printing technology and conventional building techniques. Yet, among the aspects under consideration, 3D printing technology was acknowledged to be at least moderately superior to that of more common construction methods in practically all regards, which is particularly evident in the impact dimension entitled "Increased Environmental Sustainability (ES)."

In view of these preliminary observations, it can be stated that 3D printing technology fulfils the "Construction 5.0" paradigm criterion. The very fact that 3D printing technology has proven to be particularly viable in the field of sustainable construction shows that its extensive application, together with the standardization of processes, could be a positive response to the current problems evident in all three pillars of sustainability (environmental, social and economic).

SRQ7: *"What are the implications of 3D printing technology that meet the criteria of "Construction 5.0"?"*

The model propounded in this research encompasses a large number of impact components, which are narrowed down to 4 impact dimensions to allow for easy clustering and/or consistent organization of analysis. Proposed impact dimension that includes 1) Increased Environmental Sustainability, 2) Increased Construction Safety, 3) Increased Compatibility (Technology)" and 4) Increased Resilience, define the criteria of the concept "Construction 5.0" in their individual manner.

It can be asserted that in every one of these impact dimensions (where impact is being addressed), 3D printing technology is meeting the criteria of "Construction 5.0" and in that way is helping to shape a more sustainable future of construction, that is so much desired. More particularly, through the prism of the human-centred approach and human-robot collaboration, humans will be able to maximize their creative and inventive potential, while robots will perform dry, repetitive, and even very complicated tasks by means of automation. It is a type of win-win situation in which the current problems of the construction industry are solved through the use of new technologies, but also the sustainability issues, for which the construction industry and its traditional methods are a very important negative contributor.

<u>Benchmarking critical success factors:</u>

SRQ8: *"How are this success factors applicable through case studies of 3D printing projects and how these same factors behave in the context of conventional construction projects?"*

For the most part, research on the adoption of 3DP technology in construction disregards the widely accepted theories of technology acceptance as compared to industry standards of practice. Because of this, factors from the aforementioned theories of technology adoption were assessed to validate their consistency and provide a list of factors that impact the adoption of 3D printing technology in construction projects.

It was established that these factors are 1) Relative advantage, 2) Ease of use (complexity), 3) Trialability (divisibility), 4) Compatibility, 5) Absorptive capacity, 6) External pressure, 7) Uncertainties, 8) Supply-side benefits and 9) Demand-side benefits. The dilemma arose as to their applicability and compatibility, where a potentially useful analogy of their behaviour in more traditional construction projects was identified. Therefore, the project involving 3D printing technology was contrasted with a real-life instance of conventional construction in a review of the success factors defined specifically for construction projects using 3D printing technology.

In both cases, the factors mentioned are identified as being tangible, relevant, applicable, and research worthy. 3D printing technology has been shown to be useful in free-form manufacturing, while achieving nearly identical results to traditional construction in multiple other facets, such as material reduction, workforce reduction, and construction waste minimization. Human intervention requirements in both cases were evaluated as Level 3. 3D printing demands a more extensive amount of pre-planning, more advanced labour trainings, as well as more resources for R&D. In contrast, traditional building demonstrates a higher tolerance to error and a stronger capacity to accommodate design modifications during the build process. Machine operation and servicing in both cases proves straightforward, as well as compatibility with on-site constraints. As for 3D printing, a healthy scepticism can be noted, associated with the absence of benchmark projects, the unavailability of norms, and unforeseeable performance of construction materials. In terms of supply and demand side benefits, there were no significant differences highlighted within these case studies.

The contents of the papers reviewed in this research do not include practical case studies from which to draw findings. This gap for construction projects using 3D printing technology was present in the area of obtaining a building permit, the roles and responsibilities of key project stakeholders, the measurement criteria of "Construction 5.0", as well as testing success factors compared to traditional projects." Through this dissertation, insight is provided into how 3D printing success factors behave in a real-world construction project scenario.

10 ASSUMPTIONS AND LIMITATIONS / RESTRICTIONS OF THE PRESENTED RESEARCH

This chapter explains the most crucial assumptions, limitations and restrictions of this thesis. Each of these premises is clarified on the basis of the corresponding main segment of the research (Chapters 2. – 8.).

In looking at the adoption of 3D printing in the construction industry, the initial place to begin was to explore different theories about the application of such advanced technology. In order to do this, a literature review was undertaken that included a number of different theories that have been tested in the areas of information technology (IT) adoption, environmental technologies, and industrial innovation research as potential avenues for drawing parallels to this innovative technology. Therefore, the first assumption was that these theories are worth researching and that the conclusions obtained from them for other branches of industry can be potentially applicable in determining the critical success factors of construction projects that use 3D printing technology. Also, since the majority of the research in general has mostly identified examples where 3D printing technology is only being used for both prototyping and demo modes, it was assumed that some of the earlier mentioned theories of technology adoption (SCT, TPB, and TRA) are difficult to examine at this fairly young phase of 3D printing technology evolution. Thus, these same theories were per se limited and to a large extent ignored in further research. The most important general limitation refers to the lack of studies that provide theories for defining success factors for construction projects involving 3D printing technology, where the aforementioned conclusions from other areas of the business were necessary. In addition, the time limit in this case was a period of one year due to the progression of the articles which were based on these theories.

With the aim of contributing to the establishment of a decision-making tool when choosing a construction method, 32 different notions were defined to check the usability of success factors. Accordingly, it can be said that each of those 32 statements accurately represents the assumptions of the upfront part of the research within this dissertation.

In the part of the research dealing with building regulations for projects using 3D printing technology, the main assumption was that these two examples would provide a clearer picture of the current attitude of city institutions towards such projects, as well as a possible indicator of inexperience with these types of situations. It was also assumed that cities will face problems and ambiguities when issuing building permits for the construction of similar projects.

In examining ethical issues during the upfront research, the most important assumption was that parallels can be drawn with other industries (e.g., medicine) based only on the lack of reference research in construction projects that use 3D printing technology.

The formation of 32 theses was logically limited to the conceptual theories already mentioned. Hence, the research into the factors that influence the success or failure of 3D printed construction projects was also limited to these 32 statements.

The most important limitation of the building regulation part was the selection of only two case studies from only two cities / two countries. Already at the beginning it can be stated that case studies in other countries and even in other cities within Croatia and Germany could show quite different results, and thus exceptions to these conclusions are potentially possible. The limitation of the ethical part of the research was primarily related to the limited research time of 3 months and the restriction to the review of the literature, as these conclusions in this form were necessary for the continuation of the main research.

The primary general assumption of this research is that 3D printing is an upcoming trend that will be embraced by the construction industry and will provide the anticipated advantages to the project participants, in particular, a more efficient and effective operation in which increased value will be generated. Therefore, it was also assumed that the roles, responsibilities and relationships within a project team participants of the construction projects using 3D printing technology are worth investigating. The limitations of the results emerge from the fact that they were collected in only three cases where 3D printing was applied in the early stage, where these projects can be freely described as pilot projects. Likewise, when drawing conclusions, there was also a restriction on other industrial sectors, since there is an evident lack of scientific articles dealing with project organization within construction projects with the application of 3D printing technology.

In another part of the research, it was assumed that the principles and fundamentals of 3D printing technology in construction projects can meet the concepts of the term “Construction 5.0”. Therefore, it was logically perceived that 3D printing technology can be aligned with the “Sustainable Development Goals” and is potentially a technology that contributes to achieving more sustainable building in general. Due to the aforementioned problem of the construction sector lagging behind other sectors in terms of automation and robotics, the conclusions are largely limited to conclusions drawn from the larger concept called “Industry 5.0”. Another limitation is that only four case studies were used here (all of which were largely in the pilot phase), so again it is to be expected that the results could vary when drawn from other projects, in other countries, and at other stages of project implementation.

An obvious shortcoming that limits the generalizability of the conclusions in benchmarking construction methods is that the study includes only two construction projects in the same country as well as the fact that two buildings of almost the same size and style were studied. To use this illustratively, 3D printing could be of more significant value for smaller buildings, or for buildings in dissimilar countries, and so on. It is assumed that both projects are typical representative of their construction methods (specifically 3D printing as the first permitted building achieved through construction project utilizing 3D printing technology within the Germany).

When gathering feedback from the practice, the main assumption was that the company in question is a true representative of the developments of this technology on a global level. The company’s expertise and positive references conditioned the assumption that the practical state of this new technology, which may not always fully correspond to the academic state, can be seen on their example. Based on these assumptions, practical problems for this new technology were defined.

The main limitation was the fact that it is only one company whose conclusion may vary when compared with the findings of other similar companies. Moreover, the next major limitation was the fact that, as it has already been seen several times, the construction sector also fall behind other industrial branches (e.g., metallurgy) within the observed company, and the restriction of construction projects that use 3D printing technology is mainly reduced to pilot projects or projects in the initial phase of implementation. The success factors of construction projects using 3D printing technology defined in this thesis were also largely neglected in this real-world example. Likewise, most efforts in terms of selecting construction methods and promoting 3D printing have been limited to self-initiated attempts by enthusiasts and research institutions. Therefore, future understanding of the role of these factors could be key to standardizing the process and controlling the conditions under which the development of such construction projects occurs.

11 CONCLUSION

The use of 3D printing technology can provide numerous environmental advantages, such as lower material and energy consumption, on-site production with lower resource requirements and reduced greenhouse gas emissions throughout the built product life cycle when compared with more conventional construction methods. 3D printing technology encourages transformations in work patterns, encompassing a safer work environment, and helping to achieve digitally-enabled and localized supply chains. From an architect's point of view, 3D printing technology has the potential to accelerate design and engineering delivery and to enable customization of products that are well suited to client requirements. It also enables the implementation of complex design intents as well as simpler piloting of design alterations.

Although this technology is both potentially superior and more sustainable than traditional construction, it has not reached full maturity as of yet. For this technology to fully blossom and to shift the focus from demonstration models and pilot projects to more tangible construction projects, there is a need for process standardization as well as an answer to the question of what makes construction projects using 3D printing technology successful or unsuccessful. The issue arose as to why, despite the advantages offered by this technology, its adoption in construction projects is still underrepresented as well as how understanding the success factor can help facilitate the decision to embrace 3D technology as a construction method.

Literature research, analysing Innovation Adaptation theories and a total of 11 case studies were used to search for an answer to this phenomenon. Consequently, it was important to examine the impact of this disruptive technology on project management, where the necessity of modern project management methodologies and a renewal of the organizational structure of the projects was noted. In the course of the literature review, it was found that these implications will be also manifested in some other related areas of construction projects.

The examples selected and later elaborated in this dissertation provide detailed description of construction legal matters, ethical and policy issues in such projects, changed roles and responsibilities of key project participants as well as other examples that indirectly or directly determine the success of projects and thus the selection of the construction method to be used in the future projects. Furthermore, the contribution of 3D printing technology adoption to the concept of "Construction 5.0", which combines Industry 4.0 concept with sustainable development goals, was discussed.

Architectural preservation policy issues such as the renovation of historic buildings and monuments using 3D printing technology will also be an important consideration when choosing a construction method. In addition, obtaining building permits in light of scepticism of decision makers (city administration), will need to be clarified in order to normalise the use of 3D printing in construction. Currently, the main problems include the lack of construction material standardization for 3D printing, the lack of training by building and design code implementers, and low levels of relevant technical expertise.

Based on various conceptual theories and 32 different assumptions about potentially important dimensions of influence on the success of 3D technology adaptation in construction projects, critical success factors were defined. As elaborated in this dissertation, the main factors for the success of 3D printing projects include: 1) Relative advantage in comparison with conventional construction methods in a given project scenario, 2) Ease of use (complexity), 3) Trialability (divisibility), 4) Compatibility, 5) Absorptive capacity, 6) External pressure, 7) Uncertainties, 8) Supply-side benefits and 9) Demand-side benefits. Their meaning and feasibility, as well as the need for their further examination, were demonstrated through case studies, even in a setting where they were compared with more traditional construction techniques.

There was a lack of prior research on the roles and responsibilities of participants in construction projects using 3D printing technology, so some of the conclusions refer to parallels with traditional construction. From the case studies, it was concluded that 3D printing technology will likely alter the roles and responsibilities of key project participants, affecting their competencies and skills, necessitating them to change. It will also be necessary to adapt the existing project organization to the specifics of construction projects using 3D printing technology. The role of the project manager will require significant adjustments, new set of skills, different or upgraded competencies, and more attention to the quality, deadlines and budget of such projects.

By enabling humans and robots to work together and taking advantage of automation, 3D printing technology is expected to help put humans at the centre of attention and allow them to better realize their creativity. As a result of the human-robot collaboration, new dimensions of impact have emerged, each in its own way demonstrating the aspects in which 3D printing technology is expected to meet the criteria of "Construction 5.0" and thus contribute to more sustainable construction. Solving problems in the construction sector itself, concurrently, would contribute to a broader picture of addressing sustainable issues of the present, expressed in the environmental, social, and economic conception of sustainability.

The adoption of 3D printing technology as a construction method will be successful only in the presence of predetermined conditions. The already mentioned necessary factors for success include: 1) Relative advantage, 2) Complexity, 3) Trialability, 4) Compatibility, 5) Absorptive capacity, 6) External pressure, 7) Uncertainty, 8) Supply-side benefits and 9) Demand-side benefits. Understanding and considering them could provide standardization of the process, while having more positive examples directly contributes to an easier decision to choose a construction method in favour of 3D printing technology.

The choice of optimal construction means and methods as well as the factors that lead to the success or failure of projects is a rather complex issue. 3D printing technology has shown an advantage in enhanced freedom of design and free-form execution capabilities, greater requirement for specialized personnel (but less manpower), greater R&D expenditures and with reasonable scepticism related to lack of benchmark projects. Conventional construction methods, on the other hand, are less prone to errors and omissions and offer greater ability to improvise during ongoing projects. The need for human intervention, equipment maintenance, and the benefits of supply-side and demand-side were analogous in both cases. As shown in this research, 3D printing technology will not be fully viable unless it is combined with more traditional construction methods.

Based on the practical example from the chosen 3D printing company observed, it became apparent that there are plenty of unresearched angles that offer an opportunity for further research and, above all, as with most emerging technologies, to bridge the gap from research inspiration to implementation in practice. Consideration of the success factor as an important process in the selection of construction techniques is an important step along this path.

To bridge the gap between presented research results and their implementation is a long-term process that must include expertise from multiple experts involved in 3D printing technology development. More 3D printing will lead to standardization of the processes, simpler and less expensive printing techniques, established roles and responsibilities of project stakeholders, as well as establishment of regulatory bodies to transform the concepts of 3D printing to successful projects. When these prerequisites are met, it will be possible to better grasp 3D technology in the context of the decision-making tool when selecting adequate construction technique. These steps are therefore important for the adaptation of any innovative technology. The understanding of the critical success factors will play a role in this transformation. Modern project managers with adequate knowledge and skills are also an indispensable part of this evolution.

Future research will involve similar investigations in the contexts of different construction projects, conducted with the use of different materials and in different geographic locations. This will enable to further validate the relevance of the success factors identified in the currently completed work.

12 CONTRIBUTIONS TO THE BODY OF NEW KNOWLEDGE

This chapter outlines the implications of this dissertation for the scientific community and practice. In addition to providing a brief explanation of the research problem that preceded the ideas of this dissertation, the major discoveries are explained from the perspective of expanding the "body of knowledge". In addition, the contribution to the "practical world" is presented, which is in urgent need of mechanisms to bridge the gaps between scientific research and its practical application.

Recommendations for further research are also provided subsequently. They are founded on the results of this research and will encourage new researchers to continue and enrich it, by pursuing further scientific research from their point of view. Likewise, at the very end of this chapter, recommendations for applying the lessons learned in this thesis to real-world practical examples are highlighted, with the goal of inspiring the field of applied expertise.

12.1 Contribution to the knowledge

In a setting where 3D printing could be a better, faster, more economical and environmentally friendly alternative to traditional construction, we are witnessing insufficient momentum of the technology and an insufficient adaptation rate of 3D printing technology in construction projects. Therefore, the intended contribution to the science (and also practice) of this research was principally in establishment of the knowledge-organization framework, including a consideration of technical and economic decision criteria for the use of 3D printing technology in construction projects, and in the exposition of the types of data to be delivered for decision-making on a case-by-case approach.

In designing the relevant and observable success factors, a reasonably long list of positive statements and/or hypotheses was established that advocate the use of 3D printing technology in construction projects. Each of these hypotheses was analysed in detail through case studies and contributes to the overall knowledge base with concrete and tangible examples. Similarly, the importance of ethical issues in construction projects using 3D printing technology has been highlighted as well as a real-life examples of obtaining a building permit for such projects was analysed.

There is a great need for defining building codes and regulations, and some jurisdictions already have such initiatives in progress. However, since there are very few specific examples, this thesis contributes to potential investors by providing a list of possible barriers for all segments of project documentation required to obtain construction permits for projects that involve 3D printing technology.

In the area of roles, responsibilities and interactions of key project participants within the project organization of construction projects using 3D printing technology, the example of 3 specific case studies was also used to show how roles and responsibilities will change, and it has contributed to the knowledge base by highlighting the need to adapt the role of project managers and their competencies, as well as to transform the project organization itself in comparison to traditional construction projects.

Using the concept of "Construction 5.0" as an inspiration, 3D printing technology was presented in terms of a potentially more environmentally friendly technology, i.e., a technology that better meets sustainable development goals. It contributed to the information base on this phenomenon by opening up a rather new field of research, given the lack of relevant studies linking 3D printing technology to this relatively new concept, i.e. the latest phase of the industrial revolution.

The part of the thesis devoted to the analysis of the critical success factors and comparison of their specifics with the example of the traditional construction method contributes to the scientific base with two case studies, since such concrete examples are largely lacking at present. In these examples, the observed success factors were confirmed as both practical and meriting research and the indication of their importance is provided regarding decision on the construction method to be used in the coming construction projects.

12.2 New contributions to practice in construction project management

Using the correct and credible decision-making tools for the application of 3D printing technology in construction projects, the aim was to participate in the creation of a catalogue of successful solutions/practices of 3D printing technology in the management of construction projects. Additionally, the goal was to contribute to the improvement of productivity and the minimization of waste with the right implementation of 3D printing technology in the management of construction projects.

An analysis of a company specializing in 3D printing technology confirmed that the construction sector has a lot of catching up to do compared to other industries as well as noted a large gap between research ideas and implementation in the practice. In terms of realization, the technology is relatively limited to demonstration models and pilot projects, at least in the construction sector. An important contribution is the conclusion that standardization of all processes is necessary to overcome this problem. This is only possible by first comprehending the performance of the critical success factors of construction projects that use 3D printing technology. Also because of a certain scepticism of future investors towards the advantages of 3D printing technology, the aim of this thesis was to contribute to the adjustment of risk evaluation procedures when managing construction projects implemented by use of 3D printing technology. This understanding of potential risks should contribute to the minimization of unknowns as well as easier definition of measures to respond to problems.

12.3 Recommendations for future research

Each construction project is individual and has its own peculiarities. In line with the main limitation of this research, namely the relatively small number of case studies, the main recommendation would be to extend the testing of the usability of the defined success factors to more projects, more different countries, with different phases of project implementation as well as different building dimensions.

In the area of roles and responsibilities of key stakeholders in construction projects using 3D printing technology, significant consideration should be given to the competency model and its refreshment for all key roles during the preparatory and building phases. In future, as new technologies require a new organizational paradigm, or at least an adaptation or conversion of the pre-existing paradigm, it would be necessary to do much more research on this specific issue. In the same manner, it is anticipated that extensions of project management methodologies targeted to construction projects will need to be also modified and kept up to date. Therefore, these suggested subtopics are highly encouraged for the future studies.

The example of the "Construction 5.0" part of the research is of a similar nature. For a more robust validation, a wider scale of observed examples is needed, as well as a more explicit specification of the goals of the "Construction 5.0" framework from an overarching point of view. This should be the basis for further research on this topic.

Consequently, based on the example of the analysis of critical success factors of construction projects utilizing 3D printing technology, the recommendation for any further study is to undertake a greater number of case studies in different locations across the world, making the benchmarking even more critical and more relevant. In addition, there is a need to establish a scale/mechanism for rating these factors as a definite foundation for future investors' decision process on which construction method to choose.

12.4 Recommendations for practical application

In view of the identified discrepancy between scientific articles and the insufficient application in practice, i.e., application limited to demonstration models and pilot projects, the most important recommendation is the harmonization of all procedures that enable more secure and more transparent 3D printing in construction projects. As in many other areas, the construction sector is deficient compared to other industries, and it is recommended to draw parallels to positive examples from other sectors. The only way standardization will happen is if there is more 3D printing and a greater number of completed tangible projects. On the other hand, a greater number of projects using 3D printing technology is only possible if the factors that determine the success or failure of such a project are addressed properly and if there are mechanisms for their application and/or countermeasures. Therefore, the main area of application of this research is to create a reliable tool for decision making in choosing the degree of 3D printing technology adoption in construction projects. Such a tool is only possible if the factors that determine the success or failure of these types of projects are properly analyzed and understood completely. This is a necessary step for their application in practice.

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ANNEXES

Annex A: Project Cabana

Questionnaire / interview

1) How familiar is your team and you personally with the topic of 3D printing in construction and what do you think subjectively about it (advantages, disadvantages, obstacles, challenges…)?	**Augsburg:** About the only experience I've had with 3D printing was during college, when we occasionally used it to produce architectural models. No experience on a larger scale whatsoever. The same applies to the rest of my team. One advantage that I can see is in prefabrication. As soon as the details are determined and digitized, you will be able to "reprint" the building as often as you wish. And, the more times you print it, the more cost-efficient the project gets. A disadvantage might be that the building dimensions are restricted to the reach of the printer. **Zagreb:** While I have seen 3D printing of small models or small parts of larger objects, I have not yet witnessed 3D printing of a "regular-sized" building. This is applicable for the entire team as well. However, I would imagine that the biggest advantages are the modelling flexibility, which is a great benefit for architects. The disadvantages could be construction related issues (e.g., to make reinforced concrete with 3D printing). Making construction faster and improving insulation properties will be one of the challenges.
2) Did you had any experience with building permit documentation / producing of the documentation for 3D printed objects so far? If you had experience, what stage was it at (conceptual, start of construction,	**Augsburg**: No, we have very limited experience with building permit documentation for such constructions. Nonetheless, as part of a project, the client was interested in the construction of a 3D-printed, 25 cm thick, wavy polycarbonate sheet plastic prefabricated façade. For this action, according to the cost-benefit analysis, the costs definitely outweighed the benefits, but the client was still only motivated by the desire for innovation and presentation. Sadly, this remained only at the design stage (mere sketches). The main problem was that just for this particular project it was necessary to construct a unique and very specialized 3D printing machine. **Zagreb:** So far, we did not have any previous experience with the permit documentation of 3D-printed entities or the

completed construction)?	preparation of such documentation. We suspect that there will be a lot of calculation issues when creating the mechanical strength and stability related documents.
3) When designing building permit documentation benchmarked to traditional construction, what would you pay specific attention to in terms of mechanical resistance and stability?	**Augsburg:** In our estimation, the building per se does not appear to be mechanically sophisticated. In terms of statics, it is also a "simple" building. The only thing we don't know is how the roof will be 3D printed. Within our projects, we have often debated the option of permitting and constructing flat roofs for small scale buildings like this. But considering some size-comparable examples (e.g., student bungalows at the "Olympiastadion", Munich), we suppose that it won't be a big challenge either. **Zagreb:** When preparing building permit documents regarding the mechanical strength and stability of 3D-printed buildings, it becomes a more serious issue to calculate them as it is not a material of standard and it has different compression and tension strengths, so there are going to be some difficulties in specifying the safety factor. In addition, there are issues with the boundary conditions in the calculations.
4) When designing building permit documentation compared to classic construction, what would you pay particular attention regarding the fire safety?	**Augsburg:** In order to build in Munich and/or Augsburg, the construction must comply with all the requirements of the "Bayerische Bauordnung" (Bavarian Building Code). On first sight, we don't perceive any difficulties in this case. The emergency exits are in place and the used materials are not flammable. **Zagreb:** The problems with fire safety, in our opinion, are not in the field of evacuation, but in the fire resistance classification of materials and the fire supporting on the surface, unless it is strictly specified for the material from which the building is composed.
5) When designing building permit documentation compared to traditional construction, what would you pay	**Augsburg:** We don't see any distinction from traditional construction when the building is completed. But, if you want to deal with environmental issues, we believe you have to compare them during the construction phase and in the materials used. Nevertheless, some questions must be answered: "What is the expected lifespan, what is the embodied energy of extruded concrete in comparison to regular concrete, etc.?" In this

particular attention to in terms of hygiene, health and the environment?	particular project, we should consider comparing it with a wooden structure, which is much more environmentally friendly and would be the classic material for building such a cottage. **Zagreb**: There is no real difference we see between 3D-printed buildings and conventional buildings because hygiene, health and the environment are linked more to the installations rather than to the construction. Thus, we presume that the water and sanitary installations will be performed in the conventional way, just as in traditional building.
6) When designing building permit documentation compared to classic construction, what would you pay particular attention to in terms of noise protection?	**Augsburg:** A more detailed analysis is required here, e.g., of what? Of the noise coming in or going out? Or of the room acoustics inside? Sound waves bounce off hard materials. Consequently, if soft materials such as curtains, carpets, etc. are not being used, we can assume that the acoustics in the room are rather bad. Protection from surrounding noise is accomplished with the proper windows and doors, which should not be a problem and has nothing to do with 3D printing. **Zagreb:** In our opinion, there could be some issues in defining the technical properties of the materials from which the house is made. Therefore, we could have problems with the noise protection classification. There could possibly be problems with impact noise when someone walks on the upper floor, but as this house has only one floor, there won't be that type of problem.
7) When designing building permit documentation compared to classic construction, what would you pay particular attention to in terms of technical regulations?	**Augsburg:** It's not obvious to us why a 3D-printed building should be anything different, at least in terms of the procedure. As for classification, it is still a huge obscurity. **Zagreb:** Technical regulations are a big concern when we use new, non-classified materials, particularly when we don't have materials data and have to calculate whether the building complies with all key technical requirements.
8) How much do you think the people within	**Augsburg**: In the city administration, we don't think the people have any prior experience at all. Nor do we think they need to have. During the building permit process, they only neeed inspections are: - Does the building comply with the zoning plan

the city administration are familiar with the topic and what potential problems / obstacles they might point out in relation to the traditional construction of the building?	(development plan: usable area, floor area, residential units, etc.)? – Does it fit into the surroundings (the flat roof and the round corners could pose a potential problem in this case)? – How is the building connected to water, electricity and sewerage etc? **Zagreb**: Actually, we don't think the people in the city administration are acquainted with this issue. So, any difference that arises that is not the identical to traditional construction becomes a big administrative problem, as they probably don't know how to categorize the building and will thus not grant us a building permit.
9) Do you expect additional costs for the preparation of the building permit documentation in relation to the traditional construction, and if so, what justify the discrepancy?	**Augsburg:** We don't expect that, although a detailed analysis of all potential problems should also be carried out before the bid is submitted, that is, before the contract is agreed to. But we doubt there would be approval at all considering all the ambiguities (except with great efforts, and additional efforts are associated with additional costs). **Zagreb**: In case an investor comes to our office and asks us to provide the building permit documentation for a 3D-printed building, we are not confident about what the price would be, and we would probably reject it. Now, if we had to quote for this type of documentation, the price would be roughly doubled from the normal price for conventional documentation. The reasons we would justify this is the fact that it takes a lot more time to create the documentation in a non-traditional manner, and it also requires a lot of time to determine all of the necessary standards.
10) What kind of future do you expect for 3D printing in the construction industry, and do you think it may play a more significant role in the real estate market in the near future (by 2025)?	**Augsburg:** Reinforced concrete is the least sustainable building material. Therefore, we hope that the construction industry will find a way better. 3D printing could be more cost-effective from an economic point of view if it is used repeatedly, as is the case with modular constructions. **Zagreb**: Until 2025, we don't anticipate that it will have a considerable impact in Croatia, but perhaps one day it will be standard in our country due to the faster construction.

Annex B: Project Organization Structure

Case studies – 3D printing process questionnaire

1) What are the advantages and future potential for 3D printing based on conclusions from this case study?	**Leipzig:** The 3D-printed formwork panels have become even better embedded in the process sequence than traditional formwork. Digital creation of the data enables functional integration, such as screw holes, tongue-and-groove joints, and so forth. Even more time is saved when the formwork is being assembled. Formwork for the most complex part of the staircase was put together in a half of hour. Between the formwork and the panel, a joint gap of only 1 mm was achieved, which is not usually achievable. Considerably less rework was needed (joint is siliconized in a single step). Due to the fact that the casting quality was so good, there was no discernible distinction between traditional and 3D printed formwork panels. **England:** Mass adjustment of building structures (e.g. structures with optimized topology, etc.) **Arizona:** Albeit still very theoretical, automation is extremely critical as there are less and less qualified workers on the construction site. From first-hand experience, there are increasingly fewer "usable" workers on the construction site, both in labourer and management roles and perspectives. Absent the tools of automation, the shortage of housing is going to become an insurmountable issue. Solving this problem is the future promise of 3D printing technology.
2) What are possible further research & development steps based on this case study?	**Leipzig:** Optimization of the casting preparation process, infiltration – grinding – painting. **England:** Upcoming evolution of 3D printing technology will be based on product quality control, including material rheological control, geometric and dimensional conformance, structural output, etc., so as to realize customized mass manufacturing with more reliable and predictable qualities. **Arizona:** R&D in all aspects and in all senses is necessary (software, materials, hardware, etc.).
3) Overall, what were the biggest challenges in this project?	**Leipzig:** Design of the triple curvature of the stairs without discoloration of the concrete. Installation at the construction site.

	England: Assure that the geometry and the dimensions of the single elements are inside the tolerances and that the whole assembly is accomplished. **Arizona:** Most challenging was to think outside the box, because here again we are dealing with a classic example of new technology and existing/old paradigms, naturally resulting in a weaker-than-expected outcome.
4) For which application areas can 3D printing be recommended based on conclusions from this case study?	**Leipzig:** Complicated formwork components. **England:** 1) Any fields that demand adaptation of forms, such as urban furniture, the infrastructure, optimized structures etc; 2) Remote-controlled building in extreme environments such as outer space. 3) Building affordable housing on site **Arizona:** Each unique/complex concrete form that will necessitate unique/customized formwork should strongly consider 3D printed concrete as an excellent alternative.
5) What are the greatest strengths and the greatest weaknesses of 3D printing for concrete casting based on this case study?	**Leipzig:** Huge cost and time reduction. It would not have been possible to reproduce the triple curvature with this level of precision using traditional methods. Furthermore, the printed formwork elements are weather-resistant and could be exposed to wind and bad weather conditions without altering their characteristics. And the surface is scratch-resistant, so no deformation arises when concrete is poured (during compression). No weaknesses worth mentioning were identified here. **England:** Strength: Free-form, economical on materials. Weakness: surface finish, early capital investment in high-quality equipment and specialists (operators). **Arizona:** The automation sought is a strength (potentially a solution to the manpower deficit issue), while the current degree of automation is a weakness (it is merely not sufficiently high). To summarize, automation is invariably a strength, whereas any level of human input is a weakness. However, the balance between these two factors is here still comparatively disadvantageous.

Case studies – Project organization structure responses

9) How should the example of ideal project team for construction projects that use 3D printing technology look like and what is the ideal composition of the project team members?	**Leipzig:** During the realization, the main role is shared between the concrete technologist in cooperation with the structural engineer and the printer operator/manufacturer. The boundary between 3D printing and traditional construction is delineated by these three. A concrete technologist in relation to the performance of the material, a structural engineer in relation to the requirements / load-bearing capacity of the component to be printed, and the "printer" in relation to what it can achieve from a construction logistical and machine engineering point of view. Together, they form the nucleus of the team. **England:** Discussing about successfully marketed concrete printing firms, it can be deduced that a proper project team should be formed by experts with various backgrounds, covering materials, civil engineering, CAD/CAM/robotics, mechanical and production engineering, building services engineering, construction management, etc. **Arizona:** Again, the issue is that we can only make assumptions. Given the particularities of the individual projects and the absence of benchmark cases, it is hard to reach any overall conclusions.
2) What is the main difference between the role of the client / the investor in projects that use 3D printing technology compared to the conventional method of construction?	**Leipzig:** An investor makes an investment in a property. His primary interest ultimately consists of the economic creation of the product and the added value that can be attained as a result. **England:** Fewer subcontractors are involved, and managing a project is more straightforward because one 3D printing company most likely handles the entire job. **Arizona:** It differs in the fact that in this case the investor has to buy or rent a 3D printer, which obviously is the main component of such a project. Nevertheless, in this case it is not a project for profit, but a clear learning target was followed, which is different from the common objectives of traditional construction projects.
3) What is the main difference between the role of the project	**Leipzig:** Will have less margin to improvise. Clearly defined procedures exist (see above) which necessitate more extensive

manager / construction manager in projects that use 3d printing technology compared to the conventional construction method?	pre-planning. Planning during the construction phase will also most likely not be possible anymore. **England:** Depending on two sets of circumstances: 1) In-situ printing project on-site – more managing of machinery and equipment than people management. 2) Offsite printing + onsite assembly – more emphasis on supply chain and logistics in this case. **Arizona:** The project manager's role is usually to coordinate, only in this case in addition to coordinating the aspects of engineering that some of the subcontractors are likely to have not seen previously. Moreover, almost each company participating in this worksite has its own project manager, so it is very hard to generalize their role.
4) What is the main difference between the role of the architect in projects that use 3D printing technology compared to the conventional way of building?	**Leipzig:** More research will be required of the architect up front than just designing and drafting. There will be a significant increase in the extent of pre-planning. The outcome will have to be ready (including feasibilities) before tendering. There will be more need for advance feasibility and state of the art expertise to be integrated into designs. **England:** "Design for Manufacturing/Printing" is the key distinction. In fact, the architects may be dominant of a whole project, as their design should already incorporate the realization of the printing procedure, or rather, architects are actually part of a "manufacturer/constructor". **Arizona:** Being aware of the printer's capabilities, the architect must be able to translate them into practice by using them on his rendering. However, not every axis could be printed precisely to our imagination/designs. So, in this instance, the architect needs to be conscious of the physical boundaries of 3D printers right from the beginning.
5) What is the main difference between the role of the structural engineer in projects that use 3D printing technology compared to the conventional	**Leipzig:** The structural engineer will still need to prove the structural stability. He will however require precise data from the concrete technologist and cannot rely on normal reference values in the same manner. If necessary, he will determine the bedding strengths that the concrete technologist needs to reach in the formulation of the additives.

method of construction?	**England:** Most likely, there would be no significant distinction. Anyway, all the requirements for the mechanical strength and stability of the construction have to be satisfied. **Arizona:** There is presently no distinction in the manner in which a structural engineer treats a 3D-printed house as opposed to a traditionally constructed building, as all projects will always involve some sort of conventional structural design (e.g., vertical loading, column load capacity calculation, etc.). Thus, structural engineers do not pay much attention to the load-bearing capacity of the printed walls itself, since in this case they serve only as "formwork" for everything else. This "formwork", however, must fulfil all the technical specifications as well as the concrete in the conventional formwork (together with the reinforcement). That role should be customized, nonetheless, and there should be a new way of checking structural adequacy; the basic cylinder testing that structural engineers typically perform is just not enough. This is another area where there is a cry for a paradigm shift that has yet to take place, and the question remains as to when it will occur.
6) What is the main difference between the role of the quantity surveyor / project supervision in projects that use 3D printing technology compared to the conventional method of construction?	**Leipzig:** Logistics and construction operations are going to be impacted considerably. The supply and traffic areas related to the different elements, i.e., what is printed and what is traditionally constructed, will necessitate more planning of construction sequences and construction workflows. Regarding the construction process, the printer will affect the conventional building procedure by obstructing the traffic routes for its own material supply, etc. As a result, it will be more challenging to alter the workflow. So, the importance of project supervision is much more important than in traditional construction. **England:** Much like the answer to question 3) above. The management of machinery and equipment is more important than the management of people, and the emphasis is placed more on the supply chain and logistics, as reflected in the duties of project control. **Arizona:** No particular difference is observed. All risks, precautions and methods that should be observed in any other case must also be considered in this case.

7) What is the main difference between the role of the contractor / main contractor in projects that use 3D printing technology compared to the conventional method of construction?	**Leipzig:** There are two areas of additive manufacturing that are relevant to the contractor here: 9) Printing of structures (3D printing of concrete or related compounds): In this case, it is assessed that the contractor will need to considerably extend his skills and area of specialization or externally acquire this know-how. The contractor will become more of a machine operator and will also take on sub-tasks (installation of lintels, etc.). The traditional construction process in connection with site logistics is going to be completely changed. An essential point will be that times will have to be divided into printing times and hand-operated postprocessing. For example, printing periods could take place at night with an operator, while the required finishing work is carried on during the day. Example: 3D printing is applied to generate walls one floor at a time. The wall height is then printed at night, while installations and insulation work are performed in the daytime. System downtime is not an option, considering the high cost of the printer, to guarantee an economically viable building operation in the end. 2) The printing of construction tools and prefabricated parts: There are basically no longer any limitations here as far as the design of geometries is considered. Merely the expertise is transferred from the person performing the work to the designer, who engineers the prefabricated parts in 3D. Various craft skills are thus no longer as relevant. High efforts for low-proportion detailed solutions (see also Pareto principle) must no longer be carried out in a handicraft work in a time-consuming manner, rather they can be purchased or manufactured on a project-specific level. Among these is, for example, the entire area of so-called integrated formwork: printed prefabricated concrete components that are traditionally casted and that are left in the building structure. **England:** Main contractor's role won't fundamentally shift – he will still be in charge of project design and construction management. Yet the substance of his job may alter through the use of 3DP methods, e.g., by subcontracting to a 3D printing

	company or by purchasing (buying/renting) equipment or services from a professional 3D printing company for the execution of the activities. **Arizona:** As a matter of fact, the contractor's role is in many respects quite like that of the project manager. The distinctive feature, again, is that it is a specific and singular type of structure for which even the contractor, regardless of his general level of expertise, is unlikely to have any referential knowledge of those specific set of conditions.
8) Regardless of the project team, what is the impact of changing the construction method from a standard method to projects that use 3D printing technology in the context of the manpower necessity?	**Leipzig:** The job qualification transforms from skilled construction worker/assembler to machine operator/service mechanic. **England:** There will be an acceleration of the transformation of the profession and/or the employment of the laborers on the construction site. **Arizona:** 3D printing's true potential is not yet adequately specified nor sufficiently materialized, so it's also only guesswork to speak of what will occur with the demand for workforce. Though the tendency is to automatize the whole procedure, we are far from achieving that yet.
9) What is the difference in terms of project team costs, manpower costs and suppliers' costs in projects that use 3D printing technology compared to standard construction?	**Leipzig:** Costs are going to transfer from construction manpower to suppliers and project management. Since planning walls will be considerably larger, this is also probably the field where the biggest growth will occur. **England:** Increased costs for the project team, but decreased costs for manpower and suppliers. **Arizona:** Getting an exact figure of the costs is not possible, as firms in such cases are still fighting to attract investors. Besides, this project utilized many volunteers and laborers who were working unpaid, which makes it impractical to get an exact sense of the costs on the scale of a conventional construction site. To summarize, there is no accurate cost for a 3D-printed house as there is no possibility to buy one at a specific price from a company using the default method, rather it is invariably a unique experiment. Apart from that, the price of selling or buying such house is also always significantly higher (about 30-40%) than the price of a conventional building.

Annex C: "Construction 5.0".

Impact Dimension	**Code**	**Measurement items**	**Reference**	**Clarification**	**Case study 1 – Stairs Leipzig**	**Case study 2 – Bridge Tianjin, China**	**Case study 3 – Smart Slab**	**Case study 4 – Integrated Funicular Slab**
Increased Environmental Sustainability	ES							
	ES1	Reducing CO_2 emissions	(Hajek et al. 2011, 13)	In comparison with traditional construction and to what degree.	*Opinions and explanation:* No comparable data were provided. **(3)**	*Opinions and explanation:* Not recognized. **(3)**	*Opinions and explanation:* Reduction of incorporated CO_2 through functional hybridization, i.e., the structural concrete slab is also the finished slab surface. See: Agusti-Juan et al. „Environmental assessment of multifunctional building elements manufactured with digital	*Opinions and explanation:* Reduced total emissions through functional hybridization, use of recycled and biodegradable materials, efficient building systems, etc. **(5)**

							fabrication technology." **(5)**	
	ES2	Reducing Carbon Footprint	(Hajek et al. 2011, 13)	In comparison with traditional construction and to what degree.	*Opinions and explanation:* No comparable data were provided. **(3)**	*Opinions and explanation:* Not recognized. **(3)**	*Opinions and explanation:* Similar as above, comparable carbon footprint to a conventional ceiling, but the carbon footprint is reduced when a suspended ceiling is being contemplated. **(4)**	*Opinions and explanation:* Reduced carbon footprint by using recycled aggregates and cement, biodegradable bio-based formwork, potentially inorganic foam, etc. **(4)**
	ES3	Reducing energy consumption	(Hajek et al. 2011, 13)	In comparison with traditional construction and to what degree.	*Opinions and explanation:* No comparable data were provided. **(3)**	*Opinions and explanation:* Not recognized. **(3)**	*Opinions and explanation:* Zero reduction in operating energy. **(3)**	*Opinions and explanation:* Reduced operating energy thanks to an improved chilled beam HVAC system incorporated in the ceiling. **(4)**

	ES4	Reducing water use	(Hajek et al. 2011, 13)	In comparison with traditional construction and to what degree.	*Opinions and explanation:* No comparable data were provided. **(3)**	*Opinions and explanation:* Not recognized. **(3)**	*Opinions and explanation:* The decreased w/c ratio for HPFRC may be interpreted as a decrease in water consumption. **(4)**	*Opinions and explanation:* No distinction. **(3)**
	ES5	Reducing construction time	(Hajek et al. 2011, 13)	In comparison with traditional construction and to what degree.	*Opinions and explanation:* Considering the formwork planning, the total time factor could be decreased by a factor of 10 thanks to a continuous digital data chain – particularly for complex freestanding shapes. **(5)**	*Opinions and explanation:* The shortening of construction time commonly includes the elimination of formwork preparation and the reduced construction process in comparison to casting. With offsite 3D printing, time can even be saved by conducting 3D printing of components and foundation work	*Opinions and explanation:* Quicker than conventional cast-in-place concrete construction, yet similar to the less commonly used precast concrete construction technique. **(4)**	*Opinions and explanation:* Comparable to a traditional in-situ cast slab. **(3)**

						in parallel on site. **(5)**		

	ES6	Waste generation reduction	(Hajek et al. 2011, 13)	In comparison with traditional construction and to what degree.	*Opinions and explanation:* The 3D printing is an additive process in which the material is applied exactly where it is required. Traditional production methods are mostly subtractive and therefore generate waste. However, 3D-printed formwork is presently being used for complex free-form geometries, usually only required for the production of a single concrete casting.	*Opinions and explanation:* With 3D printing, the material can be perfectly positioned and formed into lightweight shapes. **(5)**	*Opinions and explanation:* Much like a traditional construction technique for a singular concrete component. **(3)**	*Opinions and explanation:* Reduced costs compared to a traditional tailored ceiling, as the formwork and concrete are both recyclable. The insulation material might also be advanced by the application of non-organic foams. **(4)**

					Repeated usage of printed formwork is a possibility, but after being used, the printed formwork components are hazardous waste in the actual method of manufacturing. **(4)**			

	ES7	Using local materials	(Morel et al. 2001, 1119).	In comparison with traditional construction and to what degree.	*Opinions and explanation:* The "voxeljet" open-source manufacturing approach enables clients to use their locally produced sand material for printing once it has been properly specified. **(4)**	*Opinions and explanation:* On-site 3D printing of structures enables the utilization of local materials (e.g., sand, gravel, etc.) as aggregate for the printing formulation, which is especially beneficial for isolated, under-developed regions. **(4)**	*Opinions and explanation:* Comparable with a traditional method. **(3)**	*Opinions and explanation:* Better than traditional new concrete. Recycled aggregates were obtained from locally demolished projects. **(3)**
Impact Dimension	**Code**	**Measurement items**	**Reference**	**Clarification**	**Case study 1 – Stairs Leipzig**	**Case study 2 – Bridge Tianjin, China**	**Case study 3 – Smart Slab**	**Case study 4 – Integrated Funicular Slab**
Increased Construction Safety	CS							
	CS1	Reducing biological hazards	(Tamrin and Yussof 2014, 55).	Viruses, bacteria, insects, animals, etc., which could have harmful impacts on health. E.g.,	*Opinions and explanation:* No comparable data were provided. **(3)**	*Opinions and explanation:* Not recognized. **(3)**	*Opinions and explanation:* No distinction. **(3)**	*Opinions and explanation:* No distinction. **(3)**

				mold, blood and other body fluids, noxious plants, sewage, dust, and vermin.				
	CS2	Reducing chemical hazards	(Tamrin and Yussof 2014, 55).	Hazardous substances that can cause both health and physical consequences, such as skin irritation, respiratory irritation, blindness, corrosiveness and explosions.	*Opinions and explanation:* No comparable data were provided. **(3)**	*Opinions and explanation:* Not recognized. **(3)**	*Opinions and explanation:* No distinction. **(3)**	*Opinions and explanation:* No distinction. **(3)**
	CS3	Reducing ergonomic hazards	(Tamrin and Yussof 2014, 55).	A result of physical factors that can lead to musculoskeletal injuries. E.g., a badly arranged workplace in an office, bad	*Opinions and explanation:* No comparable data were provided. **(3)**	*Opinions and explanation:* Not recognized. **(3)**	*Opinions and explanation:* No distinction. **(3)**	*Opinions and explanation:* No distinction. **(3)**

				body posture and handling manually.				
	CS4	Reducing psychosocial hazards	(Tamrin and Yussof 2014, 55).	Repetitive motions, inappropriate workplace setup, inadequate equipment design, workplace (posture) or workflow, handling by hand, etc.	*Opinions and explanation:* No comparable data were provided. **(3)**	*Opinions and explanation:* Not recognized. **(3)**	*Opinions and explanation:* No distinction. **(3)**	*Opinions and explanation:* No distinction. **(3)**
	CS5	Reducing physical hazards	(Tamrin and Yussof 2014, 55).	Factors that can cause harm to a worker while not necessarily touching them, for example, height, noise, radiation, pressure, slippery floors, objects on walkways,	*Opinions and explanation:* Free-form geometries can be manufactured much more straightforward and to a great degree automated with 3D printing. Nonetheless, post-processing	*Opinions and explanation:* Every physical hazard is specified in relation to the workers on site. Since 3D printing offers an automated manufacturing/construction process, hands-on work has been minimized, except for the	*Opinions and explanation:* Improvement of the reverberation time and the general acoustic quality of a room with no additional suspended ceilings. The room acoustic characteristics may also be	Opinions and explanation: Enhancement of reverberation time and overall acoustic quality of a room eliminating the need for extra suspended ceilings.

				unsafe or misused machinery, poor lighting, fire, etc.	requires a lot of handwork, but altogether 3D printing is likely to be less labour-intensive than traditional formwork manufacturing techniques for free-form shapes. **(4)**	operating the printing machines itself, which leads to a reduction in physical hazards (e.g., related to formwork). **(4)**	additionally improved by custom ceiling designs. **(4)**	Better thermal comfort for the residents through optimization of the chilled beam HVAC (heating, ventilation, and air conditioning) system **(4)**
	CS6	Reducing mental fatigue of workers	(Tamrin and Yussof 2014, 55).	Mental fatigue threats encompass anything that can negatively impact an employee's mental health or well-being. For example, sexual harassment, victimization, workplace stress and violence,	*Opinions and explanation:* 3D printing makes it much simpler to generate free-form geometries, and it's mostly automated. However, there is still a lot of manual work involved in post-processing, but overall, 3D printing is probably less	*Opinions and explanation:* Because 3D printing offers an automated manufacturing/design process, hands-on work (e.g., formwork, casting, foundry, etc.) other than operating the printing machines has been reduced to a minimum, leading to decreased levels	*Opinions and explanation:* No distinction. **(3)**	*Opinions and explanation:* No distinction **(3)**.

				night shifts, etc. **(X)**	labour-intensive than traditional methods of producing formwork for free-form geometries. **(4)**	of mental fatigue. **(4)**		
Impact Dimension	**Code**	**Measurement items**	**Reference**	**Clarification**	**Case study 1 - Stairs Leipzig**	**Case study 2 – Bridge Tianjin, China**	**Case study 3 - Smart Slab**	**Case study 4 - Integrated Funicular Slab**
Increased Compatibility (Technology)	CT							
	CT1	Compatibility with IoT	(Chun et al. 2018, 397; (Darwish et al. 2021, 196).	In comparison with traditional construction and to what degree.	*Opinions and explanation:* As a digital manufacturing technology, binder jetting (3D printing) may be incorporated into an IIoT environment. **(4)**	*Opinions and explanation:* 3D printers and all associated hardware can be fitted with sensors to be integral to the whole IOT construction system. **(4)**	*Opinions and explanation:* No distinction. **(3)**	*Opinions and explanation:* No distinction. **(3)**
	CT2	Compatibility with Big Data	(Chun et al. 2018, 397; (Darwish et al.	In comparison with traditional construction	*Opinions and explanation:* No comparable data were provided. **(3)**	*Opinions and explanation:* Not considered. **(3)**	*Opinions and explanation:* No distinction. **(3)**	*Opinions and explanation:* No distinction. **(3)**

			2021, 196).	and to what degree.				
	CT3	Compatibility with BIM	(Chun et al. 2018, 397; (Darwish et al. 2021, 196).	In comparison with traditional construction and to what degree.	*Opinions and explanation:* This could be feasible, but the formwork components need to be digitally customized to work with 3D printing. Completely digital planning is however a possibility. **(4)**	*Opinions and explanation:* One finalized idea is to use BIM models to generate 3D printing machine toolpaths, which should be the future direction of development, although there are new entities and regions that must be delineated in BIM to reflect the 3D printing system and process. **(4)**	*Opinions and explanation:* No distinction. **(3)**	*Opinions and explanation:* No distinction. **(3)**
	CT4	Compatibility with Cloud Computing	(Chun et al. 2018, 397; (Darwish et al. 2021, 196).	In comparison with traditional construction and to what degree.	*Opinions and explanation:* No comparable data were provided. **(3)**	*Opinions and explanation:* Not considered. **(3)**	*Opinions and explanation:* No distinction. **(3)**	*Opinions and explanation:* No distinction. **(3)**

	CT5	Compatibility with Artificial Intelligence	(Chun et al. 2018, 397; (Darwish et al. 2021, 196).	In comparison with traditional construction and to what degree.	*Opinions and explanation:* In terms of process stability and improvement, AI could conceivably be applied. **(4)**	*Opinions and explanation:* AI is applied to decision making. Thus, there are two stages of 3D printing where AI can be utilized: optimization of tool path planning and on-site collision prevention for 3D printing robots. **(4)**	*Opinions and explanation:* No distinction. **(3)**	*Opinions and explanation:* No distinction. **(3)**
Impact Dimension	**Code**	**Measurement items**	**Reference**	**Clarification**	**Case study 1 - Stairs Leipzig**	**Case study 2 – Bridge Tianjin, China**	**Case study 3 - Smart Slab**	**Case study 4 - Integrated Funicular Slab**
Increased Resilience	RE							
	RE1	Resilience for natural hazards	Bosher et al. 2007, 163).	Geo-risks and hydrometeor ological hazards.	*Opinions and explanation:* Not specified. **(3)**	*Opinions and explanation:* Not recognized. **(3)**	*Opinions and explanation:* No distinction. **(3)**	*Opinions and explanation:* No distinction. **(3)**
	RE2	Resilience by Cyber Security challenges and vulnerability	(Mantha and Soto 2018, 1; CompTIA 2022, 1).	Critical infrastructure security, Application security,	*Opinions and explanation:* Not specified / considered. **(3)**	*Opinions and explanation:* Not recognized. **(3)**	*Opinions and explanation:* No distinction. **(3)**	*Opinions and explanation:* No distinction. **(3)**

				Network Security, Cloud Security, Internet of Things (IoT) Security.				
	RE3	Robustness	(NIAC 2009, 8).	The capability to maintain critical operations and functions in the event of a crisis (the building itself, infrastructure construction - office buildings, power generation, distribution structures, bridges, dams, levees) or in system redundancy and	*Opinions and explanation:* 3D printing enables decentralized production even in labour-intensive industries. Since no tools etc. are required, the necessary formwork can be printed and reprinted whenever needed. **(4)**	*Opinions and explanation:* 3D printing adds efficiency and mobility to the construction process. Printed structures affected by natural disasters can be reprinted anytime, anywhere. **(4)**	*Opinions and explanation:* Like a traditional post-tensioned slab. **(3)**	*Opinions and explanation:* Slightly higher susceptibility to catastrophic failures because of the compression-only system. **(4)**

				substitution (transportation , power grid, communication networks).				
	RE4	Resourcefulne-ss	(NIAC 2009, 8).	The capability to adeptly anticipate, respond to, and manage a crisis or disruption as it develops (planning, training, supply chain management, prioritization of damage control and mitigation actions, and effective communication on decision-making).	*Opinions and explanation:* Not specified / considered. **(3)**	*Opinions and explanation:* Not recognized. **(3)**	*Opinions and explanation:* No distinction. **(3)**	*Opinions and explanation:* No distinction. **(3)**

	RE5	Rapid recovery	(NIAC 2009, 8).	The capability to return to or restore operations to normal as quickly and efficiently as possible after a disturbance (carefully developed contingency plans, competent emergency response, and the ability to move the right people and resources to the appropriate locations).	*Opinions and explanation:* Not specified / considered. **(3)**	*Opinions and explanation:* Not recognized. **(3)**	*Opinions and explanation:* No distinction. **(3)**	*Opinions and explanation:* No distinction. **(3)**

	RE6	Redundancy	(NIAC 2009, 8).	The availability of backup resources to provide support for the original resources in the event of a failure should also be addressed when designing for resiliency.	*Opinions and explanation:* "voxeljet" runs its very own on-demand manufacturing facilities in order to be able to print for clients who have surplus capacity or are experiencing downtime. **(4)**	*Opinions and explanation:* The 3D printing robots can operate both on-site and off-site in a group, so the system offers a level of redundancy if any local entities malfunction. **(4)**	*Opinions and explanation:* No distinction. **(3)**	*Opinions and explanation:* No distinction. **(3)**

Annex D: Benchmarking Critical Success Factors

Case study 1 (Beckum)

Details of the 3D printed components (project guide)

Details of the 3D printed components

Location of project (full address):	59269 Beckum, Germany
Location of 3D printing - for prefabricated elements (full address):	89264 Weissenhorn, Germany
Type of 3D printed component (façade segment, pillar, beam, bridge, wall section/element, slab, whole building/structure*, shafts, prefabricated module of the building):	Whole building
Property type (row house, apartment, multi-family, single unit, etc.):	Detached single family house
Construction year:	2020 (Starting date: 17. 09. 2020)
Key project participants:	PERI, MENSE-KORTE ingenieure+architekten, COBOD, HeidelbergCement, Technical University of Munich, Schießl Gehlen Sodeikat
Number of floors* *(if the printed component is a whole building/structure):*	2
Living area of the property (m2)* *(if the printed component is a whole building/structure):*	160 m2
Basement present (yes or no):	No
Parking space present (yes or no):	Yes
Occupancy date and/or status (rented/unrented):	The lease began in August 2022, until then it was an exhibit space
Source of energy:	Natural gas
Assessed property condition (from very poor to excellent):	Excellent
Energy certificate present (yes or no / if yes, which category):	The KfW 55 Efficiency House Standard
Furnishings quality (from basic to upscale):	Upscale
Heating type:	Gas
Offer price of the asset (in €):	Estimated 600.000 €, calculated on the basis of the construction costs
Dimensions of the component (height / length / width in m):	Approx. 6m / 13m / 10 m

Has the 3D printed component been certified and (legally) put into use? [10] ☒ Yes | ☐ No

If yes, building permit granted by: City of Beckum - Building Permit Procedure Office

Deviation of the printed model from the designed model:	<10	mm
Number of people who participated in the planning phase[8]:	2 – 3	

Number of people that participated in R&D stage[6]:	Numeric data were not obtained during the interview
Number of persons who participated in the 3D printing procedure[8]:	2 – 4 (depending on the stage and the fact whether something else had to be incorporated in the 3D print)

Has it been complicated to build the printed components in the traditional way?[5]

☐ straight-shaped component | ☒ non-standard shaped component

Support structures:

☒ "Without support" **(ground or foundation serves as surface for building)**

☐ Built support, left in place ☐ External support, left in place

☐ Built support, removed afterwards ☐ External support, removed afterwards

3D printing process

Total printing time[2] 50 hours

Climate/environmental conditions[1]:

☒ Uncontrolled environment: | ☐ Controlled environment (e.g., pavilion, lab)

Material characteristics

Materials used for built product (please specify ingredients of cement-based paste)

☒ Natural aggregates such as soil, sand, natural gravel, crushed stone, clay or mud
☐ Recycled aggregates from construction, demolition or excavation waste
☐ Manufactured aggregates such as air-cooled blast furnace slag and bottom ash
☐ Natural fiber, such as cellulose and/or recycled wood fiber
☐ Other ingredients, specify type

From where (location) the materials were delivered to the building location?

All local materials.

Comparison with traditional construction

Comparison with an alternative construction method

Please elaborate the table by providing input for numbers or rates (e.g. "3 times less"):

	3D printing technology	Conventional construction approach
Required total time a) for planning b) for execution	a) unparalleled shorter due to the complexity of the design and the scope of the project b) unparalleled shorter due to the complexity of the design and the scope of the project (7-8 days per floor).	a) see 3D printing b) see 3D printing
Quantity of material per structure (m^3)	About 160 tons of material	Presumably in the same range
Machine cost (in €)	About 500.000 €	Presumably in the same range
Extra tools and construction materials	Extra tools hardly need to be used with a 3D printer, building materials in the traditional manner (insulation, window, plaster etc.).	Extra tools - a little more, building materials - in the same ranges.
Labor cost per day (in €)	50-55 € / h	Presumably in the same range.

Open questions

Questions	Answers
Please outline which issues of conventional manufacturing methods (e.g. structural, technological or assembly issues) are expected to be solved by the application of 3D printing technology in this project.	Free forms are, of course, what we are trying to achieve. But free forms still serve a function. Therefore, we want to build in a material-saving way, more sustainable, cheaper. This means that we want to simplify the entire building procedure, not only the walls, but also the integration of electrical cables, for instance. Ultimately, the tendency is to construct in a more economical way.
Was 3D printing technology compared with other alternative technologies (e.g. modular integrated construction) for project implementation? What were the arguments in support of 3D printing technology?	In a similar way to the previous question. We have a shortage of skilled workers, a shortage of resources. Therefore, we need to build automatically. This is something that 3D printing is promising.
What advantages has the customer obtained through the utilisation of 3D printing technology?	This kind of design and level of completeness would not be possible with a more conventional building approach. Therefore, the customer has a totally unique, individually shaped building.
What problems were encountered in connection with the computer-aided design process?	Hardly anything. The architects who were working on this project are accustomed to 3D models. Therefore it was quite straightforward to implement.

What problems were experienced in relation to the maintenance of the 3D printer?	The machine being used was one of the first generations. So naturally there were some challenges to be resolved. In the projects carried out one year later (2021), things were already a lot improved. But in general, nothing dramatic, e.g. a broken seal.
What problems emerged in connection with the management of the digital construction process?	Much like traditional 3D printing. You have a file, load it into a laser and start printing. So this stage of the whole procedure is pretty simple.

Quality problems during a building process[3]:

☐ Material extrudability issue *(problem related to material passing through small pipes and nozzles at the machinery head)*

☐ Material flowability/ductility issue *(measured by performing the slump flow test)*

☐ Built filaments formed with some deformation or damage (e.g. cavities)

☐ Low material bearing capacity that limits the layers number that can be print at one time

☐ Bonding weakness/adherence between the adjacent layers

☐ Material overspending due to a limited time available during which material must be utilized

☐Others, please specify

____

Examples of quality problems avoided by using traditional construction approach[3]

There were no major issues on site, which is mainly due to the excellent preparation and high level of readiness of the research and development department.

Project remarks and analysis of critical success factors

Project remarks and analysis of critical success factors

Determinant/ factor	Code	Measurement items	Clarifying questions
Relative advantage	RA1	Improved material usage[4]	*Did the 3D printing technology decrease material (concrete) utilization, material waste? Was any rework done throughout the 3D printing process?* Material waste can be reduced for sure. Naturally, the usage of the materials strongly depends on what is being created. All the walls in this case were printed (both load-bearing and non-load-bearing), and so the question arises as to what they can even be comparable to in conventional construction. Extremely complicated. Eventually constructing 3 identical houses in a traditional manner, that would perhaps be sufficient benchmark data for comparison (simply not possible, especially for Beckum

			3D project to be built in a traditional manner).
	RA2	Freedom of design at no extra cost	*Opinions and evaluation.* Only the word "no" is too much in the question and we have the answer. The answer would therefore be: freedom of design- yes, but still with additional costs. The additional costs for free design are considerably lesser than in traditional construction, but free forms also come with extra costs in 3D printing (unlike "repetitive" straight walls, for instance).
	RA3	Optimize components/ structures and integrate more functionality into them	*Examples of optimization done. (e.g., sound-proofing structure [D80], gradient structure, components connections)* Absolutely. It functions perfectly and it's very well made. Whether you choose to print at dam level, leave the openings blank, print the tub foundation, it remains to be individually decided.
	RA4	Construct in harsh and aggressive environment [1]	*Opinions and evaluation.* That is certainly feasible. It has been printed in the event of snow, it was printed in the desert and so forth. It works practically always.
	RA5	Reduce manpower requirement	*Opinions and evaluation.*[8] Absolutely. This is the whole point/background of the entire subject.
	RA6	Reducing cost of construction component/structure	*Opinions and evaluation.* Today, the technology is simply not yet ready. The costs are not yet cheaper than with traditional construction (about 20 percent more expensive than with traditional construction, but with a tendency to reverse the trends).
	RA7	Reduce construction time [2]	*Opinions and evaluation.* Naturally, yes. One of the most significant motivations to do this as well. In case that you cannot do that, it is reduced amount of sense.
	RA8	Reduce safety hazards	*What was the estimated level of human intervention in 3D printing, in handling or gathering simple and small elements? (Level 1 - no human intervention, level 5 full human intervention).* A machine must first of all be built in a way that makes it safe. Here we are dealing with an extremely large machine that moves a lot, and making such a large machine secure is logically associated with a lot of effort.

			Afterwards, however, we have a fairly clean construction site, and a clean construction site equals a safe construction site. Therefore, the estimated level of human intervention is approximately 3.
	RA9	Reduce product quality problems	*Opinions and evaluation.* That depends very much on one's perspective. In America, the response would definitely be "yes", in Germany rather "no". In Germany, the standard is already at an exceedingly high level. And to lift this level even higher is a huge task. We have to be satisfied if we can achieve the same level of quality here. This should be the aspiration in this case.
Ease of use (complexity)	CX1	Computer-generated design process is easy	*Opinions and evaluation.* Indeed. A person who is familiar with CAD will be successful effortlessly.
	CX2	Managing digital construction process is easy[8]	*Opinions and evaluation.*[8] Also, managing the digital building process is not a major task.
	CX3	Operating 3D printer is easy	*Opinions and evaluation.* This is always a debatable issue. The operation of the printer itself is fairly simple, but one requires expertise in order to set the material properly. That's not always straightforward, especially when it comes to different environmental conditions.
	CX4	Maintenance of 3D printer is easy	*Opinions and evaluation.* The maintenance is also fairly uncomplicated.
Trialability (divisibility) [DA23]	TA1	3D printed material properties are predictable[3]	*Explanation if any above (#3) marked* [3] 3D printed materials' properties are only predictable to a certain extent, as this know-how is still absent. Not enough buildings have been constructed as yet. In addition, various weather factors (wind, rain, sun, whatever) still play a role. We have invested a lot of effort and time in order to be able to make a prediction, but today it is simply not as reliably foreseeable as with traditional construction techniques.
	TA2	Behavior of 3D printing product from a long-term perspective (e.g. length of the product life cycle)	*What structural analysis tests were conducted for structural behavior prediction?* As this is a comparatively novel technology, there are still a lot of unresolved issues and there is simply no retrospective analysis possibility for already printed buildings. The tests were conducted in a laboratory setting

			(static analysis, stability and vibration analysis).
	TA3	Precision of the printed components is within acceptable tolerances [6]	*Answered above* [6] The tolerances are absolutely considered and here we are in the range of traditional building tolerances.
Compatibility	CP1	Flexibility to print various sizes of components for different construction industry needs [5]	*Opinions and evaluation.* There is unquestionably plenty of flexibility. Or at least with the machines used here because they have a modular design.
	CP2	Compatibility of construction site environment with 3D printing technology	*Opinions and evaluation.* A particular machinery requires some extra space around the construction, other machines don't need that space. It is essential to note that in the future there will definitely be many more various machines for diverse projects, but 3D printing is universally compatible with different construction site settings. On the construction site, two meters surrounding the structure is sufficient space. Also, a myriad of various sizes are possible to be produced, so we are pretty adaptable.
	CP3	Suitability of printing conventional design elements	*Opinions and evaluation.* Well, it can be printed, but in practice it is not usually done this way when printing a strictly traditional design. The printing of such items is merely unprofitable in financial terms and at present utterly senseless (except for research reasons).
	CP4	Matching available 3D printing materials with the characteristics of legacy construction processes	*Opinions and evaluation.* 3D printed materials can be very well contrasted with their analogues in conventional construction. It is after all merely about concrete. One can say, cautiously, that 3D printing of building will in some views never be economically viable without being coupled with conventional construction.
Absorptive capacity	AC1	Significant share of company capital expenditure devoted to R&D[9]	*Opinions and evaluation.* To the question precisely how much money was spent, it is impossible to provide any specific figures. Also, work was done consecutively with multiple various corporations and universities, making the math not so straightforward.
	AC2	Extensive cooperation with other companies or research institutions in R&D[7]	Responded above [7]

	AC3	Major share of employees has education at tertiary level	*Is education at tertiary level (bachelor or master) required for 3D printing process management and operation?* The majority of personnel in this instance are university graduates.
	AC4	Knowledge, expertise, talents, creativity and skills of a company' workers	*Opinions and evaluation.* The claim is made that a wide range of expertise, i.e. from mechanical engineering, electrical engineering, civil engineering and materials science, is particularly required in the ongoing process of developing a new technology of this kind. Being an interface technology is another distinguishing feature of 3D printing.
	AC5	Integration of a cross-functional team in the building structure planning and design process & construction operations process	*Opinions and evaluation.* Making it an interface technology means it also requires a large and cross-functional collaborative team.
	AC6	Company team attitudes toward 3D printing in general	*Opinions and evaluation.* The project carrier firm, as a family-owned company, has faith in this technology, as otherwise they wouldn't be deploying at all. More generally, the whole firm is receptive to innovation and disruption. As their main activity is the manufacture of formwork and they are aware that formwork-free concrete is already possible, they are not willing to ask themselves where and how to continue in about 10 years. It is also the very fact why they are investing a great deal in the R&D division.
	AC7	Adequacy of company's resources to produce, test or implement 3D printing technology	*Opinions and evaluation.* The project holder's resources were available and prepared for all facets of 3D printing right from the start.
External pressure	EP1	Competitive pressure	*Opinions and evaluation.* Considering certain preposterous advertisements asserting that such houses can be printed in only two days and are 80 percent less expensive than traditional construction techniques, which no one really believes in anyway, the firm that carries the venture has neither fear nor any particular attitude to this topic. As already mentioned, it is a family-owned business from Schwaben (a synonym for frugality). Therefore, when they claim that it cannot be carried out less expensively and more rapidly, this should correspond to the actual state of affairs. Competitive pressure is thus

			within ordinary parameters. However, the pressure will come shortly, that is indisputable and for sure, and that is the factor that does not allow the company to remain dormant.
	EP2	Lack of technical standards, standards for quality control and product certification issues[10]	*Opinions and evaluation.* Currently, the standards are fairly nonexistent, which is both positive and negative simultaneously. For instance, we can draft our own standards for ensuring quality. This means we are not restricted to traditional norms, and we can implement new materials and certifications consequently.
	EP3	Skeptical attitudes/ psychological barriers of consumers in relation to 3D printing technologies and product implementations	*Opinions and evaluation.* Having a sceptical mindset is perfectly understandable. It's up to us to show clients what can be accomplished with this new technology. Moreover, a healthy scepticism is not entirely wrong, as it is evident that for end customers, pretty often, it is the largest acquisition of a lifetime.
	EP4	Lack of information on technical and economic benefits arising from innovation and restrictions imposed by regulations, contractors and consultants isolated from one another	*Opinions and evaluation.* Perhaps those are the factors that make it a tad harder for the client. However, this is quite natural for a technology as young as this. It is up to us to help fix these issues as well.
Uncertainti es	UC1	Perceived side effects associated with the innovation.	*Opinions and evaluation.* There were no noteworthy adverse effects observed. The innovation is invariably beneficial for the company's reputation. And reputation, in turn, is essential for attracting skilled manpower. This direction is a key aspect.
	UC2	Resistance to environmental influences and failure with exposure to high stress	*Opinions and evaluation.* Indeed, it's necessary to have tested it sufficiently well to avoid this happening i.e. to prevent a failure. That is the task always set for itself.
	UC3	Uncertainty in 3D printing technology profitability	*Opinions and evaluation.* Return on investment is still an unsettled matter as well, thus it is our duty to prove it to the clients in a suitable manner.
Supply-side benefits	SS1	Reducing and/or simplifying construction tasks	*Opinions and evaluation.* Absolutely. The work on the building site gets much simpler, e.g. for electricians.
	SS2	Reducing the need for pre-assembly/ assembly activities	*Cases of pre-assembly/ assembly actions lessened in the project.*

			Pre-assembly and assembly operations are reduced by printing on the construction site. The matter of cost-effectiveness still arises.
	SS3	Reducing the need for transportation services	*Opinions and evaluation → Examples of decreased transportation.* As for transportation, it's not something we would see as easier/reduced. That probably won't vary very much. Possibly it's worse on account of the size of the printer, but it reduces the necessity to ship materials. Moreover, everything is much simpler to transport and unload. Thus, it is to be expected that it will be comparatively similar.
	SS4	Reducing a number of suppliers involving in construction process	*Opinions and evaluation.* At this point, we would not say that the number of suppliers will substantially alter. It will stay rather consistent.
	SS5	Increasing collaboration among stakeholders (architects, engineers, constructors, suppliers, etc.)	*Opinions and evaluation.* "Increasing" is perhaps the incorrect term, but it is a technology that is making this occur earlier. In other words, more during the design stage and then less in the implementation stage.
Demand-side benefits	DS1	Customized production of printed components	*Opinions and evaluation.* Naturally, it is a "marginal" desired feature, a fairly minor one. Customization is thus invariably pricey, and the market seldom demands expensive solutions. It is constantly just a niche, irrespective of the style of building.
	DS2	Faster reaction to changing customer needs	*Opinions and evaluation.* The truth is that in the building industry, it is also merely a niche (anything that has a significant discrepancy from the norm).
	DS3	Production in collaboration with the customer and supplier (e.g., customers integrated in product development)	*Opinions and evaluation.* That, too, is more of a niche. The "demand" is for quicker and less expensive, as platitudinous as that may sound. Quicker, less expensive, and more sustainable are the most significant goals.

Case study 2 (Berlin)

Details of constructed component (project guide)

Details of constructed component

Location of project (full address):	Püttbergeweg 47, 12589 Berlin
Location of 3D printing - for prefabricated elements (full address):	No prefabricated elements, everything in-situ
Type of 3D printed component (façade segment, pillar, beam, bridge, wall section/element, slab, whole building/structure*, shafts, prefabricated module of the building):	The entire building. Reinforced concrete: foundation slab, floor slabs, staircases. Sand-lime bricks/blocks; walls
Property type (row house, apartment, multi-family, single unit, etc.):	Detached one-family house
Construction year:	2021-2022
Key project participants:	Property owner, miscellaneous sub-contractors
Number of floors* *(if the printed component is a whole building/structure):*	3 floors (basement, ground and 1st floor)
Living area of the property (m2)* *(if the printed component is a whole building/structure):*	172 m2
Basement present (yes or no):	Yes
Parking space present (yes or no):	Yes
Occupancy date and/or status (rented/unrented):	Planned relocation approx. in the summer of 2022
Source of energy:	Wooden Pellets
Assessed property condition (from very poor to excellent):	Excellent
Energy certificate present (yes or no / if yes, which category):	Excellent, A+ Category, KfW 40 Standard with only 23,67 kWh/m^2a
Furnishings quality (from basic to upscale):	Basic
Heating type:	Floor heating (central heating)
Offer price of the asset (in €):	Not for sale, estimated 800.000 € by the architect
Dimensions of the component (height / length / width in m):	12 m high, 12,5 x 10 meters layout

Has the 3D printed component been certified and (legally) put into use? [10] ☒ Yes | ☐ No

If yes, building permit granted by: District office Treptow-Köpenick, Berlin

Deviation of the printed model from the designed model:	<10	mm
Number of people who participated in the planning phase[8]:	1	

Number of people that participated in R&D stage[6]:	1
Number of people that participated in building procedure[8]:	On average 2 on the site when building at any time. Up to 25 with all the subcontractors and workers included (1-4 at a time)

Has it been complicated to build the printed components in the traditional way?[5]

☒ straight-shaped component | ☐ non-standard shaped component

Support structures:

☒ "Without support" (ground or foundation serves as surface for building)

☐ Built support, left in place ☐ External support, left in place

☐ Built support, removed afterwards ☐ External support, removed afterwards

Building process

Total building time[2]	more then 2000	hours

Climate/environmental conditions[1]:

☒ Uncontrolled environment: | ☐ Controlled environment (e.g., pavilion, lab)

Material characteristics

Materials used for built product

☒ Natural aggregates such as soil, sand, natural gravel, crushed stone, clay or mud
☐ Recycled aggregates from construction, demolition or excavation waste
☐ Manufactured aggregates such as air-cooled blast furnace slag and bottom ash
☐ Natural fiber, such as cellulose and/or recycled wood fiber
☐ Other ingredients, specify type

From where (location) the materials were delivered to the building location?

All local materials.

Comparison with alternative construction (3D printing technology)

Comparison with an alternative construction method

Please elaborate the table by providing input for numbers or rates (e.g. "3 times less"):

	3D printing	Traditional construction method
Required total time a) for planning b) for execution	a) undetermined/unknown, without further detailed analysis b) undetermined/unknown, without further detailed analysis	a) about 70 hours b) structural - about 200 hours
Quantity of material per structure (m^3)	Presumably in the similar range	About 200 tons of material
Machine cost (in €)	Presumably much more	About 200.000 €
Extra tools and construction materials	Additional tools are almost not needed with a 3D printer for the shell, building materials in the traditional way (insulation, windows, plaster, etc.).	Extra tools - a little more, building materials - in the same area.
Labor cost per day (in €)	Preasumbly in the same range	50-60 €

Open questions

Questions	Answers
Please define which problems of alternative manufacturing method (e.g., structural, technological, assembly problems) were attempted to be resolved by executing this project in traditional manner.	Nothing other than the conventional approach has ever been considered from the beginning of the planning process. 3D printing problem that would emerge is plastering, which was here not needed whatsoever - using sand-limestone blocks, which were made neat. Merely a very thin finish (3 mm).
Was traditional approach contrasted to other alternate technologies (e.g., modular integrated construction) for project performance? What were the arguments in favour of traditional construction method?	Wasn't compared. About the only question mark was whether or not to use a precast concrete staircase, but that was dismissed rather rapidly since it was pricey and there was a lengthy wait list.
What advantages has the customer received from the implementation of traditional construction method?	Portrayed reliability and longevity, good transparency, ease of monitoring and quality assurance. Ability to make last minute minor geometry adjustments directly on site as well. Furthermore, the possibility to undertake parts of the design independently.

What problems occurred associated to the computer-generated design process?	The design has not been computer-generated.
What issues were confronted linked to the maintenance of the traditional technique machinery?	The saw for the sand-lime blocks was not maintained properly, resulting in excessive dust on the site until it was adequately cleansed.
What problems were faced linked to the management of the digital construction process?	There were no issues as all the planning was done by an individual with comprehensive understanding of the entire process.

Quality problems during a building process[3]:

☐ Material extrudability issue *(problem related to material passing through small pipes and nozzles at the machinery head)*
☐ Material flowability/ductility issue *(measured by performing the slump flow test)*
☐ Built filaments formed with some deformation or damage (e.g., cavities)
☐ Low material bearing capacity that limits the layers number that can be print at one time
☐ Bonding weakness/adherence between the adjacent layers
☐ Material overspending due to a limited time available during which material must be utilized
☐Others, please specify

___

Examples of quality problems avoided by using conventional building method[3]

On the construction site there were practically no issues, mainly due to the experienced laborers, proper coordination, and the strong dedication of the property owner, who took on the role of construction manager and was present on the site around the clock.

Project remarks and analysis of critical success factors

Project remarks and analysis of critical success factors

Determinant/ factor	Code	Measurement items	Clarifying questions
Relative advantage	RA1	Improved material usage[4]	*Did the traditional construction technique reduce material (concrete) consumption, material waste? Was any rework done during the construction procedure?* Thanks to the fact that the project was designed in BIM with block-by-block precision, there was practically no wastage of wall blocks. Even the surplus concrete from the concreting operations was not being wasted, but rather utilized to pave walkways.
	RA2	Freedom of design at no extra cost	*Opinions and evaluation.* It was conceived to provide "freedom of use" as opposed to "freedom of design." Free forms were not required, but a house

			constructed with virtually total latitude in the design of the internal walls. The building itself only has stairs and a smaller internal load bearing wall. There is 100% freedom to arrange the rooms and the partition walls or to keep it totally open. This allows a great deal of interior creativeness, and if one wishes, the house can be remodeled entirely each year. Also, there is nearly total liberty to put a bathroom, kitchen, or toilet in any part of the building, as the infrastructure has been prepared under the foundation slab with multiple possibilities for the laying of sewage pipes. Moreover, since there are no peculiar shapes, there is no requirement for customized furnishings that could be utilized just once. In addition, freedom of design was not a requirement, as the intention was to construct a straightforward, efficiently designed "engineer's house" featuring four corners. The objective was a great deal of internal separability, cost-effectiveness, and a minimum labor requirement per square meter, which was accomplished. It also implies high quality building, a low running costs and utilizing the interior creatively, rather than constructing "creative forms" with no actual purpose.
	RA3	Optimize components/ structures and integrate more functionality into them	*Examples of optimization done. (e.g., sound-proofing structure [D80], gradient structure, components connections)* Practically no significant construction waste. Nearly no partitions offer flexibility and exchangeable functionality.
	RA4	Construct in harsh and aggressive environment [1]	*Opinions and evaluation.* Employing more traditional methods of construction and building manually means that the structure is vulnerable to the weather until the shell is finished, and as with virtually all techniques, this is inevitable. The construction was scheduled based upon the weather, with day-to-day modifications where required. With good coordination and careful consideration of the weather there were no weather-related disruptions to the construction process. This is probably an advantage of the craftsman construction approach, as it will cost

			practically zero if workmen alter their position or even don't come the following day as other tasks could be completed in the interim (installation, earthwork, insulation, piping, etc.).
	RA5	Reduce manpower requirement	*Opinions and evaluation.*[8] Given that there were on average just 2 people on the construction site and it was a rather small one, this is not very applicable as one cannot go much below that. Machinery and 3D printing would definitely "save" the physical bodies of these laborers, but as long as they are both willing to work and use their bodies in such a manner, there is no high manpower requirement. The property owner was on the site around the clock as the construction manager, but the workers didn't require any of his input as he created easy-to-read blueprints and plans. Concerning the skills, it is a low-skill job, and the laborers were experienced. Thus, it would be challenging to obtain a 3D printer, as the education of the operator on the site would have to be much more advanced than that of the masons.
	RA6	Reducing cost of construction component/structure	*Opinions and evaluation.* As long as we have low educated, low wage immigrants who are ready to do the work manually, it will be hard to win that argument. However, if we begin to lose access to immigrant workforces and wages start to rise, there could quite easily be an argument for 3D printing. Nonetheless, with good structural planning, proponents of conventional construction will be able to personally outperform it for quite a while on such projects, but on larger projects, it's impractical to get all the high-end design correct. Time to design compared to time to build is yet one more hazard to be defused. A lot of mistakes are made that don't become apparent until the construction site is already in the building process. So, if we optimize the structure with generative design and then 3D print it, there has to be margin for modifications and flaws. If we optimize too much, it's not straightforward to make major alterations afterwards in the ongoing

			process. Deciding "on-the-fly" to cut out an opening or not is not a simple task. Again, the design has to be run through the software. All of these are resolvable issues, but they may not give as much flexibility as traditional construction, nor allow us to utilize the machinery after specific segments have already been constructed. This could all incur additional costs in adopting 3D printing technology, but it is an exciting challenge to address and ultimately standardize in the future.
	RA7	Reduce construction time [2]	*Opinions and evaluation.* With a certain reluctance, one might conclude that for a small project such as this, it does not really matter. Taking 4-6 weeks as opposed to 2-3 months is not a huge distinction for a single-family house. In addition, once the workmen are "leveled", they are also pretty rapid in the building procedure.
	RA8	Reduce safety hazards	*What was the estimated level of human intervention in machinery tasks, in handling or gathering simple and small elements? (Level 1 - no human intervention, level 5 full human intervention)* Likely Level 3.
	RA9	Reduce product quality problems	*Opinions and evaluation.* In general, quality problems were smartly eliminated/decreased.
Ease of use (complexit y)	CX1	Computer-generated design process is easy	*Opinions and evaluation.* True computer generated design is definitely still a high expertise area that professionals and " regular engineers" do not master. BIM or CAD designs are not really computer generated designs, they are also not simple and cannot be done by someone "who merely knows CAD". CAD represents Computer Aided Design, not Computer Generated Design. Actually, we are still many years from Computer Generated Design being applied to more mainstream projects, or even from general-purpose design software that can do so with little effort/cost. Answering "yes" to this question does not indicate that it was straightforward, but a total failure to comprehend the subject at stake. A classic "Dunning-Kruger" effect.

			In order to code such a design, one needs skills in programming, coding, structural analysis, in-depth knowledge of materials science etc.
	CX2	Managing digital construction process is easy[8]	*Opinions and evaluation.*[8] By no means. Currently and upcoming tools are not anywhere near as good as they should be in terms of intercommunication and ease of use. Something as basic as a "simple" clash check demands a high degree of skill and understanding of both the projects and the multiple other disciplines to be done accurately.
	CX3	Operating traditional machinery is easy	*Opinions and evaluation.* True, to most people skilled in the operation of advanced machines.
	CX4	Maintenance of traditional machinery is easy	*Opinions and evaluation.* It does not work always, as it can conflict with the production schedule, particularly if there are failures and/or the machinery has to be sent for a service.
Trialability (divisibility) [DA23]	TA1	Built material properties are predictable[3]	*Explanation if any above (#3) marked* [3] For reinforced concrete and sand-lime bricks, yes. In fact, they have been known for a long time and have been studied in detail.
	TA2	Behavior of built product from a long-term perspective (e.g., length of the product life cycle)	*What structural analysis tests were conducted for structural behavior prediction?* Zero. The additional concrete on the edges of the pathways was crushed informally with a mallet after one, three and seven days to see if it performed as anticipated, based on the experience.
	TA3	Precision of the built components is within acceptable tolerances [6]	*Answered above* [6] Yes, definitely.
Compatibility	CP1	Flexibility to build various sizes of components for different construction industry needs [5]	*Opinions and evaluation.* Yes, definitely.
	CP2	Compatibility of construction site environment with machinery	*Opinions and evaluation.* Yes, the land was purchased especially for this reason.
	CP3	Suitability of building conventional design elements	*Opinions and evaluation.* Yes, definitely.
	CP4	Matching available alternative materials with the characteristics of legacy construction processes	*Opinions and evaluation.* Unused in this project.
Absorptive capacity	AC1	Significant share of company capital expenditure devoted to R&D[9]	*Opinions and evaluation.*

			None, because all the research and development was in the hands of the proprietor himself.
	AC2	Extensive cooperation with other companies or research institutions in R&D[7]	*As same as the above (AC1)* [7].
	AC3	Major share of employees has education at tertiary level	*Is education at tertiary level (bachelor or master) required for conventional building process management and operation?* No, fairly minimal education of laborers, yet high commitment of owner in preparation (oversight/engineering).
	AC4	Knowledge, expertise, talents, creativity and skills of a company' workers	*Opinions and evaluation.* Highly skilled management (owner) + comparatively low-skilled labor.
	AC5	Integration of a cross-functional team in the building structure planning and design process & construction operations process	*Opinions and evaluation.* Well, it was there, but the owner was also a very driven and well-rounded professional engineer who knew the process well. It was planned in reverse, beginning with individual blocks of masonry and by setting building dimensions so that it would require as little cutting as possible with virtually no waste or squandered costs.
	AC6	Company team attitudes toward conventional building method in general	*Opinions and evaluation.* The subcontractors appreciated the attention to details and the pre-planned work schedule. Having no planning on their side and even without no civil engineer or supervisor in attendance was straightforward for them.
	AC7	Adequacy of company's resources to produce, test or implement conventional building method	*Opinions and evaluation.* Very much adequate.
External pressure	EP1	Competitive pressure	*Opinions and evaluation.* Practically none observed.
	EP2	Lack of technical standards, standards for quality control and product certification issues[10]	*Opinions and evaluation.* None in private single-family homes.
	EP3	Skeptical attitudes/ psychological barriers of consumers in relation to conventional building method and product implementations	*Opinions and evaluation.* All were wowed by the highly detailed and well designed blueprints and schematics.
	EP4	Lack of information on technical and economic benefits arising from innovation and restrictions imposed by regulations, contractors and consultants isolated from one another	*Opinions and evaluation.* The conclusion could not be drawn that there was a shortage of available data. As a matter of fact, the evaluation of all this existing information was in support of the traditional construction technique.

Uncertainties	UC1	Perceived side effects associated with the innovation.	*Opinions and evaluation.* Stakeholders believed that it is simple to get a project ready so effectively and that it does not require a lot of expertise and know-how. Actually, it is not, and not anyone is able to do that.
	UC2	Resistance to environmental influences and failure with exposure to high stress	*Opinions and evaluation.* The conventional method is not too resistant and is affected only by extreme weather conditions.
	UC3	Uncertainty in conventional building method profitability	*Opinions and evaluation.* Unclear as most had to do with increases in price due to Covid-19. Labor cost was same as in the contract (independent from materials).
Supply-side benefits	SS1	Reducing and/or simplifying construction tasks	*Opinions and evaluation.* Does not pertain. From the beginning it was intended to be minimalist and simplistic. The method and tools were selected at first, then materials, and finally the geometry was designed to fit with that.
	SS2	Reducing the need for pre-assembly/ assembly activities	*Examples of pre-assembly/ assembly activities reduced in the project.* None were required.
	SS3	Reducing the need for transportation services	*Please express your views and interpretation. →* *Examples of reduced transportation.* Thanks to timely scheduling and an understanding of the logistics and vehicle capabilities, the transport was optimized from the very beginning. On-site procurement also rendered it highly operational.
	SS4	Reducing a number of suppliers involving in construction process	*Opinions and evaluation.* There were just 4 suppliers involved: one for the concrete, one for the reinforcing steel, one for the wood structures, and another for the sand-lime bricks as well as all the remaining material. This means that certain reductions are actually inapplicable.
	SS5	Increasing collaboration among stakeholders (architects, engineers, constructors, suppliers, etc.)	*Opinions and evaluation.* Only the owner (one person) negotiated directly with all suppliers. By the midpoint of the process, all of them knew him by name.
Demand-side benefits	DS1	Customized production of built components	*Opinions and evaluation.* Arguably a marginal factor in overall building costs.

	DS2	Faster reaction to changing customer needs	*Opinions and evaluation.* There is no faster way, because the owner was the designer and construction manager, and has mapped out every detail, starting from the back.
	DS3	Production in collaboration with the customer and supplier (e.g., customers integrated in product development)	*Opinions and evaluation.* It was the exact same person, as stated earlier.

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Place: Maryland, USA

Date: 19.07.2023

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