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Benchmarking critical success factors in construction projects utilizing 3D printing technology

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ABSTRACT

3D printing, an automated production process with layer-by-layer control, has undergone rapid development in recent years, but without the desired momentum. There has been no research to address the adaptation rate of 3D printing technology in the construction industry collectively, which is why the success factors of projects using 3D printing technology have been developed. The observed factors were Relative advantage, Complexity, Trialability, Compatibility, Absorptive capacity, External pressure, Uncertainty, Supply – side benefits and Demand – side benefits. Research questions are reconsidering how success factors are applicable through case studies of 3D printing and how the same factors behave in the context of conventional construction. These factors were verified through two different case studies (only shells of the construction - one 3D printing technology construction and one conventional construction, both in Germany). In this paper, the 7-step methodology was implemented to answer the research question. The contribution of this study is to supplement the body of knowledge by validating the above success factors as a credible tool for assessing the success of construction projects using 3D printing technology and as a possibility of application to future construction projects before deciding on the method of construction. Factors showed relative similarity in performance in both cases with certain differences and specifics for 3D printing technology. Both technologies have demonstrated specific advantages and disadvantages when compared to each other. It is important to establish a mechanism for evaluating these factors. This will serve as a decision-making tool for future investors in determining which construction method to choose. Nevertheless, it can be said that, in some views, 3D printing of buildings will never be profitable without combining it with conventional construction.

Keywords: 3D printing technology, success factors, conventional construction, future application.

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1. INTRODUCTION

3D printing, an automated production process with layer-by-layer management, has experienced quick growth in recent years (Wu et al., 2016). A systematic review shows that 3D printing technology can be used to print large-scale architectural models and buildings after years of development (Wu et al., 2016). Even though the C3DP technology readiness level for small and medium-size project execution is quite high

(Ma et al., 2022), the capacity of the technology is limited by the lack of large-scale implementation, building data modelling development, mass customization requirements, and life cycle costs of printed projects (Wu et al., 2016). Although 3D printing technology has significant potential, the rate at which it is being adopted is not quite as fast as the market expects (Yeh and Chen, 2018). The idea scales, but the processes and materials are unlikely due to several factors including material properties, cost, and availability (Buswell et al., 2008).

Ghaffar et al. (2018) described not only process- and product-related issues that hinder the widespread use of 3D printing in mass production, but also potential legal issues (policies/regulations that still need to be adapted to this technology) and the process of certifying new components. Wu et al. (2018) examined the influence of other factors on the adoption of 3D printing technology implementation in the construction industry: readiness for the technology, effectiveness of 3D printing, organizational support for print production manufacturing, and policy and regulatory considerations related to 3D printing in construction. Management challenges have been identified in previous research related to large-scale, extrusion-based digital construction, such as distance to ready-mix plants, transportation, and on-site setup of a 3D printer and its adaptability to different applications requiring different product geometries, access levels, and underlying materials (Camacho et al., 2018; Mechtcherine et al., 2019). Various authors apply complex approach for the influential factors investigation on 3D printing technology adaptation by collecting industry experts' opinions (Aghimien et al., 2020; Won et al., 2022). Industrial field research involved various technology acceptance theories to strengthen factors identification (e.g., Zhao et al., 2021; Almahamid et al., 2022; Ukobitz and Faullant, 2022). In contrast, construction field do not provide factors list based on the robust theories and collect construction industry experts' opinion neglection 3D printing experts' opinion.

Regarding the 3D construction printing, only theories that focus on technology and the outcomes of using 3D printing can be considered and analysed (Besklubova et al., 2021). Accordingly, the technology acceptance model (TAM) (Davis, 1989), innovation diffusion theory (IDT) (Rogers, 2003), technology readiness (TR) (Başgöze, 2015), and contingency theory (CT) (Donaldson, 2001) are considered to be the most suitable theories in light of conceptual model development (Besklubova et al., 2021). Factors from the aforementioned theories of technology adaptation were compared to determine their similarity and to create a list of factors that influence 3D printing technology adaptation in the construction (Besklubova et al. 2021). The observed factors are named as follows: (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). To measure the influence of the relevant factors and measurements, the structural equation modelling technique was utilized (Besklubova et al. 2021). The results suggest that the top significant factors in ensuring the success of 3D printing technology in construction are "technology compatibility," "supply-side benefits," and "complexity." Based on these outcomes, present and upcoming 3D printing project managers may utilize the results of this study to guide their efforts in adapting this technology to produce high-value construction components and related products and to generate new business opportunities (Besklubova et al., 2021).

The focus of this paper is to verify the success factors of construction projects that use 3D printing technology, as defined in a previous study by Besklubova et al. (2021), through a case study. Research questions are defined in such a way as to answer how success factors are applicable through case studies of 3D printing and how the same factors behave in the context of conventional construction. The relative similarity of the application of factors in both cases and the relatively equal ratio of advantages and disadvantages of both methods are shown. This implies the need to develop a decision-making tool for potential investors which method to choose, but also relatively confirms the fact that 3D printing technology will never be fully meaningful without merging it with traditional construction.

2. LITERATURE REVIEW

Numerous studies have been conducted to identify and analyse the factors that impact the adoption of 3DP technology, as evidenced by a comprehensive review of the related literature. Yeh and Chen (2018) examined the factors that influenced the adoption of 3DP in Taiwanese manufacturing enterprises using the Technology-Organizational-Environment (TOE) framework. They found that the most significant factor from an organizational perspective was the cost, specifically the cost of materials. In a study conducted by Tsai and Yeh (2019), which built on the work of the authors mentioned above, the TOE framework and rough set theory were combined to derive a set of factors for 3DP adoption. The study found that the top four determinants are environment, technology, cost, and organization. Chaudhuri et al. (2019) used the TAM to identify several challenges, including creating a business case, optimizing processes for specific parts, using different materials, insufficient training and educational support, lacking ready-made solutions from equipment manufacturers, poor product quality, and high costs associated with machine breakdowns, repairs, and maintenance. Zhao et al. (2021) conducted a study on how a company's sustainability orientation affects the adoption of 3D printing technology during the acquisition and application stages. The study involved collecting expert opinions through interviews and questionnaire surveys in the United States and India. The data was then analysed and compared between the two countries. In a study by

Almahamid et al. (2022) on the adoption of 3DP technology by manufacturing companies in the Gulf Cooperation Council context, an integrated model combining TOE and TAM was developed. The study found that the most influential factors affecting the spread of 3DP technology were its technological usefulness and ease-of-use.

Efforts have been made in the construction industry to explore the integration of 3D printing. Wu et al. (2018) conducted a survey of Australian construction professionals to propose a framework for adopting 3D printing technology. The survey identified factors, subfactors, and hypotheses related to 3D printing adoption. Notably, the survey found that the top three subfactors with the most influence on adoption were "building codes and regulations", "top management commitment", and "liability for 3D printed components". A study by Aghimien et al. (2020) investigated the potential benefits and challenges of implementing 3D printing technology in housing delivery in South Africa. The study collected opinions from construction professionals through a questionnaire survey and identified several benefits of 3D printing such as better cost delivery, socio-economic benefits, creative designs and new market opportunities, increased productivity and stakeholder satisfaction, and quality and speed of project delivery. The study also identified several barriers to 3D printing adoption, including operational issues, organizational and personnel issues, and limited understanding of the technology among stakeholders. In a survey conducted by Won et al. (2022), construction practitioners in Singapore were asked about the drivers, challenges, and strategies for 3DP technology. The results of the survey showed that the three biggest challenges to integrating 3DP technology were limited production size, reluctance to invest in 3DP, and high upfront cost.

The preceding discussion highlights that studies on the adoption of 3DP technology in the construction industry often overlook widely accepted technology adoption theories and focus solely on gathering opinions from professionals in a single country. However, it is essential to obtain a global perspective from 3DP practitioners, who play a key role in technology adoption. Recently, Besklubova et al. (2021) conducted a questionnaire survey to collect expert opinions and identify factors that influence 3DP technology adoption. They used a systematic approach to identify factors and determine their prioritization by combining several technology adoption theories, including the TAM, Innovation Diffusion Theory, Technology Readiness, and Contingency Theory. However, there is a lack of verification of identified factors in the context of real 3D printed projects. This paper is a logical continuation of Besklubova et al. (2021), which explores the applicability of success factors through case studies of 3D printing. To make the study more robust, the same factors were assessed in the context of conventional construction. It is important to demonstrate in practice how the factors can be applied and discussed for wide industry and academic use, in order to strengthen the position of the technology in the market.

3. MATERIALS AND METHODS

3.1. Materials

An explanation of factors affecting 3D printing technology adaptation (Table 1) and their measurements that served as a basis for case studies was implemented from study called “Factors Affecting 3D Printing Technology Adaptation in Construction” (Besklubova et al., 2021).

3.2. Methodology

Methodology is represented by four major steps, as depicted in Fig. 1, and discussed in detail below.

3.2.1. Case Studies Selection

To select the case studies, the following criteria were applied: (1) a real example to generate a demonstration of the applicability of the model in the real world; (2) the case studies had to be from the same country and use comparable practices and policies; and (3) the data used in this case study cover a variety of factors.

One of the selected case studies is the first legally and fully 3D-printed house in Germany, located in the town of Beckum (Peri, 2022). It is a high-level quality house with a living area of 160 square meters. Another case study represented traditional construction methods. It is building of a 172 square meter house, constructed in Berlin, but with the use of many innovative engineering solutions. In both cases, the focus of the analysis was on the building shell, as it was determined that only that (regarding the current limitations of 3D printing technology) could provide the possibility of a more consistent benchmark.

3.2.2. Case Studies Data Collection

A comprehensive data set is obtained by utilizing a three-step data collection approach that relies on the triangulation of evidence from three interconnected methods. (Yin, 2009). To begin with, a thorough search and meticulous review of reliable open-source documents and articles pertaining to the case studies were conducted. The data collection process encompasses the utilization of diverse sources including published reports, previous studies, and official websites (Ahmed and Zhang, 2021). Subsequently, the extracted information is utilized in the development of a survey form specifically designed for operative level employees. This survey form consists of concise and technical questions aimed at gathering project data and technical details. Certain technology-related questions are omitted since the information is available in reliable sources or formulated in a manner that corroborates the published data. The survey form consists of three sections, which are as follows: (1) Background information on the low-rise building construction project, including inquiries about its size, location address, and the roles and locations of participating parties, among others; (2) Construction process and logistics-related questions, such as the quantity of materials per structure and the number of workers involved; (3) Queries pertaining to costs associated with the project. Lastly, a comprehensive interview is carried out with high-level management, building upon the responses provided in the completed survey form. This interview aims to gain a more profound understanding of the construction process logistics and address any gaps or missing information that may have arisen during the survey.

3.2.3. Expert Selection

Two interviewers were selected for the final stage of the data collection, the interview. The 3D printing case study was represented by a managing director of PERI who holds a doctoral degree and has more than 10 years of extensive experience in the construction industry. Additionally, he leads the R&D and execution of 3D printing projects. Therefore, his broad knowledge in both conventional and 3D printing construction contributes to obtaining a comprehensive vision on the adaptation of 3D printing.

The traditionally built project was represented during the interview by a civil engineer with over 20 years of professional experience in construction. He has participated in the project across various countries and has experience in applying various technologies in construction. With his extensive experience in diverse technology applications in construction, he has a robust background. This expertise allows him to provide insightful perspectives on the adoption of advanced technologies.

Table 1. Factors affecting 3D printing technology adaptation and their measurements (adopted from Besklubova et al., (2021)

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
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)

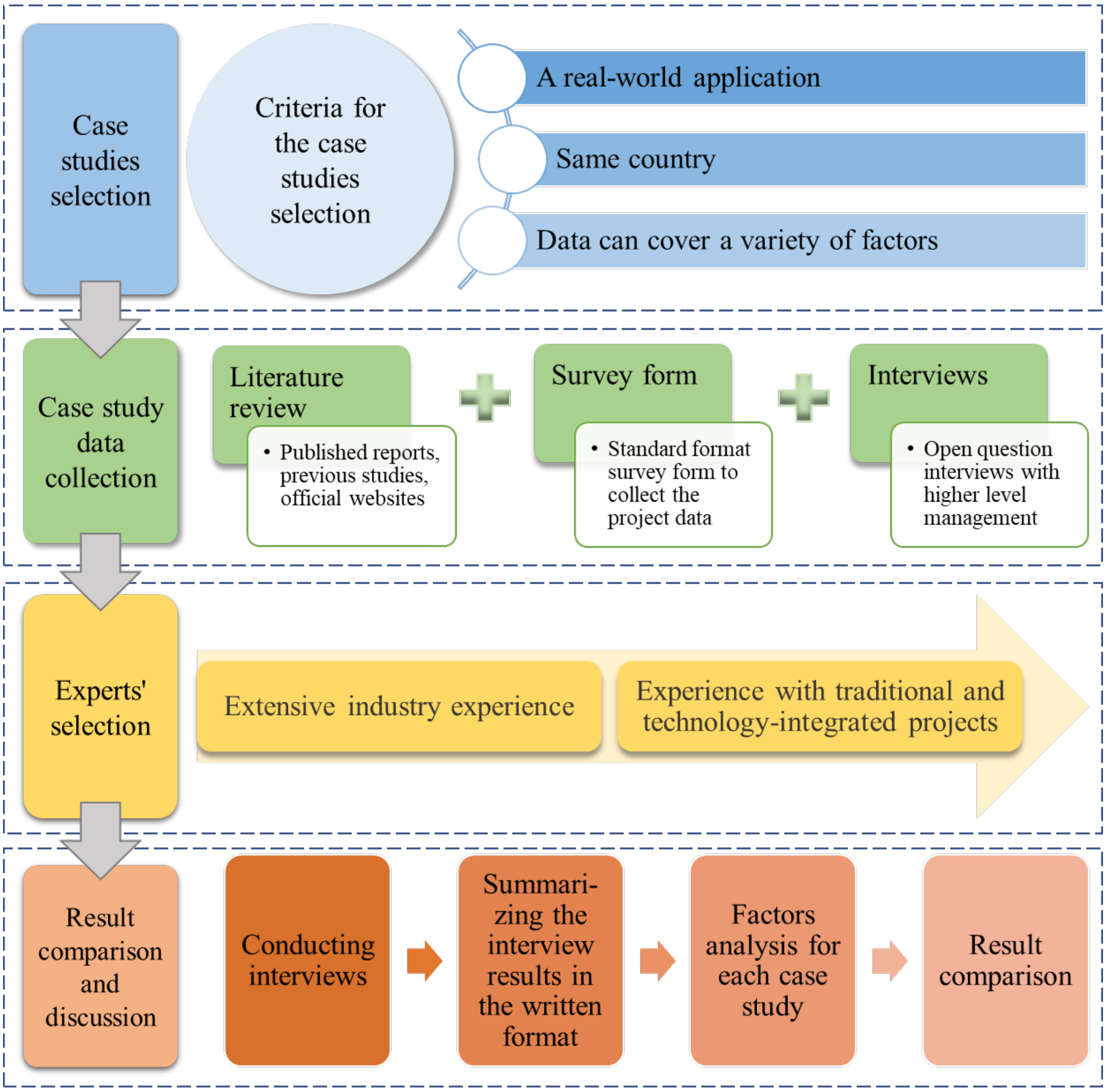

Fig. 1. Methodology diagram

3.2.4. Result Comparison and Discussion

The interview responses were summarized in written English format. Since both interviews followed the same structured list of factors, a table was created to compare and summarize their responses. The table includes the conclusions regarding the similarities and differences for each factor.

4. RESULTS AND DISCUSSION

The survey form was sent to the Peri organization to obtain project data and technical details and based on the returned form an interview was conducted with the head of 3D construction printing to get comments regarding factors. The same procedure was repeated with conventional construction in Berlin. Completed survey forms and the ensuing interviews results for 3D printed and conventional projects were compared with the intention of determining the differences and similarities between them. The cross-comparison of case studies is summarized in Appendix A.

4.1. Case Study 1

The first case study deals with 3D printing of a house in Beckum (Germany), with a living area of 160 m^2, which currently serves as an exhibition space, and tenants are expected to move in by the end of 2022. The 3D printing process, as a method of construction, in this case was incomparably shorter due to the complexity of the design and the comprehensiveness of the project compared to the speculative example of traditional construction. The amount of material and the cost of machinery probably lie in the same range as in classical construction as the cost of labour. Additional tools with a 3D printer were almost not needed, and rest of the building materials was used in the conventional way (insulation, window, plaster etc.). The aspiration was to achieve free forms which still have a function. That is why it was desired to build economically in terms of materials, more sustainable, cheaper and to simplify the whole construction process. A shortage of skilled workers and a shortage of resources was noted. Therefore, there was need to build automatically, and this is something that 3D Print promises. Such a design and comprehensiveness would not be possible with traditional construction. As a result, the customer has a completely distinct, individually arranged house.

4.1.1. Relative Advantage

It is concluded that material waste can definitely be reduced. Freedom of design was achieved, but with extra cost. Additional costs for free design are significantly lower than in conventional construction, but free forms are also associated with additional costs in 3D printing. Optimization has been accomplished in almost all segments by, by all means (e.g. printing at dam level, leaving the openings free, printing the tub foundation, etc.). It is definitely possible to print in in harsh and aggressive environment. Manpower requirement was absolutely reduced, which is also the point / background of the whole topic. In respect of reducing cost of construction component/structure, technology just hasn't gotten that far today. Costs are not yet cheaper than with conventional construction (approximately 20 percent more expensive than conventional construction but with the tendency to change the trend). Construction time was reduced which is also one of the most important backgrounds for doing this. A machine must be built in such a way that it is safe. In this case, an extremely large machine that moves a lot was used and making such a large machine safe is logically associated with great effort. Also, it is important to have a relatively clean construction site, and a clean construction site means a safe construction site. Therefore, the estimated level of human intervention was approximately 3. Regarding quality problems, the standard in Germany is already at an extremely high level. And to raise that standard even further is extremely challenging. It should be satisfactory to achieve the same quality, and that should be the requirement here.

4.1.2. Ease of Use (Complexity)

Computer-generated design process was described as easy and someone who understands CAD will be successful without problems. Managing the digital construction process was also not a big effort. To operate the printer itself was relatively easy but experience is required to adjust the material appropriately. This is not always trivial, especially when it comes to different environmental conditions. Maintenance is again labelled as pretty simple.

4.1.3. Trialability (Divisibility)

3D printed material properties were only partially predictable because that knowledge is still lacking. Also, different weather conditions (wind, rain, sun, whatever) play a role. It was simply not as reliably predictable as in conventional construction processes. Since it is a relatively new technology, there are still many open questions and there is simply no possibility of retrospective analysis for already printed buildings. The tests were performed in a laboratory environment (static analysis, stability, and vibration analysis). Tolerances were definitely respected and are lying in the area of conventional building tolerances.

4.1.4. Compatibility

Flexibility was unquestionably present (at least with the machinery used here because it is modular). Particular machine used needs some space around buildings, other machines do not need that space. It is important to mention is that in the future there will definitely be many more different machines for different projects, but 3D printing is globally compatible with different construction site environments. Printing conventional design elements was described as simply financially unprofitable and completely meaningless for the time being (except for research purposes). 3D printed materials can be compared very well with their equivalent in traditional construction. After all, it's just concrete. With a dose of caution, it can be said that, in some views, 3D printing of buildings will almost certainly never be profitable without combining it with conventional construction.

4.1.5. Absorptive Capacity

It was worked successively with several different companies and universities, so the calculation of company capital expenditure devoted to R&D is not so simple. Most of employees in this case had tertiary level education. A wide range of knowledge, i.e., from mechanical engineering, electrical engineering, construction, materials science was needed. The fact that this is an interface technology is also a special aspect of 3D printing. Due to the same fact that this is an interface technology means that a great and big cross-functional teams are needed. Project holder company as a family business believe in this technology, because otherwise they wouldn't even be doing it. In general, the whole company was described as open-minded to innovation and disruption. Resources of the project holder company have been there and ready from the beginning for all aspects of 3D printing.

4.1.6. External Pressure

The pressure of competition is kept within normal limits. However, the pressure will soon come, that is unquestionable and certain, and this is the fact that doesn't allow the company to rest. There are no right technical standards today and that's good and bad at the same time. For example, the printing company can design own quality assurance standards. They are not affiliated with old standards and can bring in new materials and certification accordingly. Sceptical attitude was described as quite normal. This is for most customers probably the biggest investment of their lives and then the healthy scepticism is not entirely wrong. Lack of information on technical and economic benefits arising from innovation and restrictions imposed by regulations, contractors and consultants isolated from one another are the objects that make things a little harder for the customer. But, again, this is quite normal for such a young technology.

4.1.7. Uncertainties

No significant side effects associated with innovation were seen. Innovation is always good for the image. And image is again crucial to find skilled workers. Resistance to environmental influences and failure with exposure to high stress is the task that should always be set to in such projects. The profitability is also still an open point, so it's important to prove it to customers accordingly.

4.1.8. Supply-Side Benefits

The work becomes much easier on the construction site, e.g., for electricians. Pre-assembly and assembly activities become less if one print on the construction site (the question of profitability remains). Transport was not described as being easier / reduced. It probably doesn't change that much. Perhaps it will be worse because of the size of the printer, but this reduces the need to transport material. Everything was simpler to transport and unload. The number of suppliers should not change significantly. This will remain relatively constant. Regarding increasing collaboration among stakeholders (architects, engineers, constructors, suppliers, etc.), "Increasing" might be the wrong word, but this technology makes sure that happens sooner. Accordingly, more in the planning phase and less in the execution phase.

4.1.9. Demand-Side Benefits

Customized production of printed components is a point that is wanted by the “margin”, but it is a relatively small point. So, customization is always expensive, and the market rarely asks for expensive. That is always just a niche, regardless of the type of construction. “Demand" is for faster and cheaper, as banal as it sounds. Faster, cheaper, more sustainable is the most important matter.

4.2. Case Study 2

The second case study represent a conventionally built house in Berlin (Germany) with a living area of 172 m2, where the family of the construction manager will be both the owners and tenants of the house. Compared to the potential alternative (3D print technology), approximately 200 tons of material were used, and the cost of machinery was approximately 200 thousand euros. Additional tools needed were slightly more then by potential 3D printing, and building materials were in the same range. Labour cost per day (in EUR) was also in the same range. It was never even considered anything else but the conventional way, since the first day of planning. The problem detected that would emerge with 3D printing is the plastering (to achieve the same aesthetic levels), which was not needed to be done at all - with Sand-Limestone blocks done clean. The only question mark was whether to use prefab concrete stairs or not but was quickly dismissed as it was expensive and had a long waiting list. Benefits that the customer received from the implementation of conventional construction method were described as perceived reliability and durability, good transparency, easy oversight, and quality control. Ability to do last minute smaller geometry adjustments on the site/on the »fly« and ability to do parts of construction by oneself. No computer-generated design was done. Minor problems were noted related to the maintenance of the conventional method machinery (e.g., the saw for the sand-limestone blocks was not well maintained which caused excess dust on the site until properly cleaned). In the management of the digital construction process no problems since all the planning was done by one person with deep knowledge of the process.

4.2.1. Relative Advantage

Since the project was planned to an exact block in BIM, there was almost no waste with the wall blocks. Concrete excess from the pours was also not wasted but used to pour pathways to be utilized later. It was designed for “freedom of use”, instead of “freedom of design”. No free forms were needed, but instead a house was built with almost complete freedom to build interior walls. The structure itself only has one staircase and one smaller inner wall. The freedom of arranging the space, rooms, or leaving it completely open is 100%. Almost no construction waste worth mentioning was noted. Practically no partitions offer flexible and interchangeable functionality as well. Using conventional construction methods and being built by hand means exposure to weather until the shell is done, and this cannot be avoided, as with almost any method. The construction was planned around the weather and with daily adjustments, where necessary. This is probably an advantage of building everything by hand, since it costs almost nothing for the workers to change position or not come the next day, and meanwhile some other work instead could be done (installation, ground works, insulation, piping…). With good communication and planning for weather, there was not effectively any stops of the build process due to external conditions. Since it was only 2 people on site on average, and it was a small site, reducing manpower requirement factor is not very applicable because one cannot go much lower than that. When it comes to qualification, it´s a low qualification work and they were experienced, so it would be a hard win to get from a 3D printer, since the education of the user on site would need to be substantially higher than that of bricklayers. It was noted that in reducing cost of construction component/structure, the experts in favour of conventional building method will still be able to beat it personal with good structural planning for a good while, but on large scale projects, it´s impossible to have all the high-end planning done properly. Another risk to be mitigated is the time to design versus time to build. There are a lot of errors which first come to view on the site in the build process. If the structure is optimized with generative design, and then printed with 3D printers, there needs to be room for changes and errors. With a dose of reserve, it is concluded that the factor of reducing construction time does not play a big role on a small project such as this and estimated level of human intervention was also probably Level 3. Quality problems were generally elegantly avoided / reduced.

4.2.2. Ease of Use (Complexity)

Real computer-generated design was still described as an area of high knowledge that even some experts and "ordinary engineers" cannot do it. Managing digital construction process was not easy by a long shot. The tools today and of the near future are not nearly as good as they need to be in terms of "talking to each other" and ease-of-use. Just a "simple" clash detection requires a high level of expertise and knowledge of the project and multiple disciplines in order to be done properly. Operating traditional machinery was easy for most people with experience using modernised machinery. Maintenance of traditional machinery was not always easy as it can clash with the production schedule, especially in the case of breakdowns and machines needed to be sent away for repairs.

4.2.3. Trialability (Divisibility)

In the case of reinforced concrete and sand-limestone blocks-built material properties were predictable. Structural analysis tests conducted for structural behaviour prediction were only unofficial (there were concrete pours of the extra concrete on the side of the paths, which were broken with a hammer after 1 day, 3 days and 7 days, just to see if they behave as expected, according to the experience). Precision of the built components was absolutely within acceptable tolerances.

4.2.4. Compatibility

Flexibility to build various sizes of components for different construction industry needs was absolutely noted in this project as well as compatibility of construction site environment with machinery and suitability of building conventional design elements. Matching available alternative materials with the characteristics of legacy construction processes was not stated on this project.

4.2.5. Absorptive Capacity

Significant share of company capital expenditure devoted to R&D was none because the whole R&D was the owner itself. Predominantly low education of workers but high engagement of the owner in preparation (oversight/engineer) was noted (high skill leadership (owner) + low skill workers). The owner was described as a very motivated and versatile engineer that knows the process inside and out. The subcontractors favourably evaluated owners' attention to detail and pre-planned working schedule. It made it easy for them to have no planning on their side, and no site engineer or oversight present. Adequacy of company's resources to produce, test or implement conventional building method was described as high.

4.2.6. External Pressure

Almost non-competitive pressure was noticed. Lack of technical standards, standards for quality control and product certification issues was also not noticed in private single-family housing. The detailed and well thought out plans and drawings had great acceptance overall. It could not be concluded that there was a lack of information. In fact, in this case, the analysis of all this available information ruled in favour of the conventional method of construction.

4.2.7. Uncertainties

Involved people had an initial impression that it was easy to prepare a project so well and that it doesn´t take a huge amount of knowledge and experience. This was later described as misapprehension. Resistance to environmental influences and failure with exposure to high stress was described as not too resistant, because traditional method has it´s pace and is only influenced by extreme weather. Uncertainty in conventional building method profitability was labelled as not clear as most of it had to do with price rises due to Covid-19. The work cost was the same as in contract (separate from materials).

4.2.8. Supply-Side Benefits

Reducing and/or simplifying construction tasks was described as not applicable. It was planned from the start to be reduced and simple. First the method and the tools were selected, then the materials, and then the geometry was planned to align with that. None pre-assembly/ assembly activities were needed. Timely planning and understanding of the logistics and vehicle capacities already optimized transport from the start. Buying locally made it efficient as well. They were only 4 suppliers included: one for concrete, one for reinforcement steel, one for the timber construction, and one for the sand-limestone blocks and all the other materials. Regarding collaboration among stakeholders (architects, engineers, constructors, suppliers, etc.) it was only the owner (1 person) dealing with all the suppliers directly.

4.2.9. Demand-Side Benefits

Customized production of built components was described as probably negligible factor in total construction costs. Faster reaction to changing customer needs was not much possible, as the owner was the planner and the site manager, and has planned everything to the smallest details, starting backwards. This mitigating circumstance also applies to production in collaboration with the customer and supplier (e.g., customers integrated in product development).

5. DISCUSSION

Research on the acceptance of 3DP technology in construction largely ignore the commonly recognized theories of technology acceptance, compared to industry practice. For that reason, the factors from aforesaid theories of technology adaptation were evaluated to verify their correspondence and to generate a list of factors that affect 3D printing technology acceptance in the construction. Regarding contributions of this study, a plausible extension of the identifying of success factors of construction projects that use 3D printing technology was to verify them through a case study. Through explanatory, descriptive case study of the first legal, complete 3D printed house in Germany and by comparing this case with an example of a house built with more conventional method (also in Germany), this research increases the knowledge base by validating these success factors as a reliable instrument for measuring the success of construction projects using 3D printing technology. Moreover, it gives a prospect of application in decision-making tool for future construction projects before deciding on the method of construction. Therefore, beyond the theoretical insights, these findings also have ramifications on organizational decision makers. Precisely this is considered to be the most significant contribution of this research.

In this paper, project success factors, specifically designed for construction projects using 3D printing technology, are tested. They are compared within one case study (3D printed house – Beckum) with another case study, building completed by conventional construction method (sand-limestone blocks - Berlin).

In the section on Relative Advantage, both buildings showed similar characteristics in terms of reduction of construction waste, reduction of labour needs and the possibility of performance even in bad weather. 3D construction technology has shown advantages in free form construction (especially exterior walls), but at the same time it is still approximately 30 percent more expensive than traditional construction. The estimated level of human intervention required was Level 3 in both cases. Quality issues were also avoided in both cases. Conventional construction has, as expected, shown greater resilience to errors while in the case of 3D printing the planning phase must be almost perfect.

Regarding Ease of use (complexity), by 3D printed house, computer-generated design process was described as easy and someone who understands CAD should be successful without problems. In the conventional construction project, there was an interesting discussion about what computer-generated design entails and real computer-generated design was still described as an area of high knowledge that experts and “ordinary engineers” cannot do. Managing the digital construction process was also not a big effort for 3D printing, but a enormous problem for conventional construction (a more complex understanding of the same is taken into account). To operate the printer itself was relatively easy, but experience is required to adjust the material appropriately while the same can be concluded for the operating of traditional machinery. The same goes for printer / machinery maintenance.

3D printed material properties, as a part of section Trialability (divisibility) were only partially predictable because that knowledge is still lacking. In conventional construction, in the case of reinforced concrete and sand-limestone blocks, built material properties were very predictable. Also, different weather conditions (wind, rain, sun, whatever) play a great role by 3D printing. It was simply not as reliably predictable as in conventional construction processes. Since it is a relatively new technology, there are still many open questions and there is simply no possibility of retrospective analysis for already printed buildings. The tests were performed in a laboratory environment (static analysis, stability, and vibration analysis) for 3D printing and unofficially for conventional building. Tolerances were definitely respected in both cases.

In domain of Compatibility, flexibility was definitely present in both cases, again noting that the process is much easier with 3D printing (due to process automation). It is important to mention is that in the future there will definitely be many more different machines for different projects, but 3D printing is globally compatible with different construction site environments. 3D Printing conventional design elements was described as simply financially unprofitable and completely meaningless for the time being (except for research purposes). 3D printed materials can be compared very well with their equivalent in traditional construction (concrete, but also other materials). With a dose of caution, it can be said that, in some views, 3D printing of buildings will never be cost-effective without mixing it with traditional construction.

Regarding Absorptive capacity, on 3D printed house, it was worked successfully with several different companies and universities, so the calculation of company capital expenditure devoted to R&D is not so simple. On the other hand, in conventional construction, a significant share of the company's capital expenditure devoted to R&D was none, because the whole R&D was the owner itself. Most of the employees in this case had tertiary level education for 3D printing, while the workers in conventional construction had a lower level of education. A wide range of knowledge, i.e., from mechanical engineering, electrical engineering, construction, materials science was needed for 3D printing as well as a great and big cross-functional teams. In conventional construction, the owner was a very motivated and versatile engineer that knows the process inside and out. The subcontractors loved owners’ attention to detail and pre-planned working schedule. It made it easy for them to have no planning on their side, and no site engineer or oversight present. Adequacy of company resources to produce, test or implement conventional building method was described as high.

On External pressure, the pressure of competition is kept within normal limits by 3D printed house and almost none was noticed by conventional building. However, the pressure will soon come for 3D printing technology. It is noted that there are no right technical standards today and that's good and bad at the same time (designing own quality assurance standards). The scepticism associated with the lack of information, technical standards and quality control in 3D printing is marked as very high, but also healthy and expected. On the other hand, with conventional construction, with good preparation and planning and the expertise of the owner, it was almost non-existent.

In chapter Uncertainties, no significant side effects associated with innovation were seen by 3D printing. Innovation is Resistance to environmental influences and failure with exposure to high stress is marked as the task we should always set to ourselves in such projects. The profitability is unfortunately still an open point, so it's important to prove it to customers accordingly. Traditional method has it´s pace and is only influenced by extreme weather. Uncertainty in conventional building method profitability was not clear as most of it had to do with price rises due to Covid-19. The work cost the same as in contract (separate from materials).

As for Supply-side benefits, in 3D printed process, the work becomes much easier on the construction site, e.g., for electricians. Pre-assembly and assembly activities become less if one print on the construction site (the question of profitability remains). Transport was not described as being easier / reduced. The number of suppliers should also not change significantly. "Increasing" of the collaboration among key participants might be the wrong word, but this technology makes sure that happens sooner. Accordingly, more in the planning phase and less in the execution phase. On the other hand, with conventional construction, reducing and/or simplifying construction tasks was described as not applicable. It was planned from the start to be reduced and simple. None pre-assembly/ assembly activities were needed. Timely planning and understanding of the logistics and vehicle capacities already optimized transport from the start. Buying locally made it efficient as well. They were only 4 suppliers included. Regarding collaboration among stakeholders (architects, engineers, constructors, suppliers, etc.) it was only the owner (1 person) dealing with all the suppliers directly. They all knew him by name by the middle of the project.

On Demand-side benefits customized production of printed components is a point that is wanted by the “margin”, but it is a relatively small point. So, customization is always expensive, and the market rarely asks for expensive. That is always just a niche, regardless of the type of construction. “Demand" is for faster and cheaper, as banal as it sounds. Faster, cheaper, more sustainable is the most important matter. By conventional building, customized production of built components was described as probably negligible factor in total construction costs. Faster reaction to changing customer needs was not much possible, as the owner was the planner and the site manager, and has planned everything to the smallest details, starting backwards. This mitigating circumstance also applies to production in collaboration with the customer and supplier (e.g., customers integrated in product development).

The actuality that the research involves no more than two construction cases, both in the same country, as well as the fact that two buildings with almost similar size and style have been studied, is an evident deficiency which limits the level of generalization of the conclusions. As an illustration, 3D printing might have greater value for smaller structures, or constructions in different countries, etc. The assumption is that both projects represent reference representatives of their construction method (especially 3D print as the first house of its kind on German soil).

The recommendation for the further studies is, therefore, to do more case studies in other countries all over the world where the comparison would be even more radical and interesting. Also, it is necessary to develop a scale / mechanism for assessing these factors as a basis for the decision-making tool of future investors which construction method to choose.

6. CONCLUSION

3D print, although a potentially good alternative to the conventional construction method, in this context is faced with the example of conventional construction, performed with engineering expertise and innovation of the future owner in the success factor test. 3D print has shown an advantage in the production of free forms, while in other elements such as material reduction, reduction of labour demand or reduction of construction waste has shown the same results as conventional construction. The need for human intervention in both cases was assessed at Level 3. 3D printing requires a higher level of planning in advance, a higher level of education of workers as well as a higher share of funding for research and development. Conventional construction, on the other hand, has shown greater resilience to errors and a greater ability to adapt planning in the construction phase. Operating and maintaining machinery is in both cases marked as simple as well as compatibility with the construction site environment. In 3D printing, healthy scepticism associated with a lack of reference projects, a lack of standards, and relatively unpredictable material behaviour has been observed as a new technology. In the domain of supply side & demand side benefits, it was concluded that there is no major difference. It is necessary to develop a scale / mechanism for assessing these factors as a basis for the decision-making tool of future investors which construction method to choose. Nevertheless, it can be said that, in some views, 3D printing of buildings will never be profitable without combining it with conventional construction.

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APPENDIX A. THE RESULTS OF THE INTERVIEWS

Factors	Code	Factor measurement	Case study 1 - 3D printing of a house in Beckum (Germany) 3D printing companies' vision	Case study 2 - a conventionally built house in Berlin (Germany) Conventional construction companies' vision	Conclusions: Differences and similarities between conventional and 3D printing construction
Relative advantage	RA1	Optimize and integrate more functionality into components/ structures	-Optimization has been achieved in almost all areas, such as printing at dam level, leaving openings free, and printing the tub foundation -It is certainly possible to print in harsh and aggressive environments	-Other technologies, such as BIM, enable a significant reduction in waste. -Most partitions lack flexible and interchangeable functionality.	Differences: While optimization of conventional structures can be achieved through proven technology, they are missing out on the potential advantages of 3D printing.
	RA2	Reduce manpower requirement	-The manpower required for the project was reduced by decreasing the construction time, without significantly reducing the number of workers.	-This factor does not palay a crucial at the small-scale project (low storey building) as it cannot go much lower than minimum required workers (2 people) -Education of the user on site would need to be substantially higher for 3D printing use than that of bricklayers.	Differences: Reducing manpower in small-scale projects may not be critical when considering just one project. However, in terms of overall project time, it can make a significant difference. Education on the use of 3D printing technology should be prioritized.
	RA3	Reduce cost of construction component/ structure	- Currently, technology has not progressed far enough to significantly reduce the cost of construction components/structures. However, there is a tendency for this trend to change in the future.	-The cost of 3D printing may be high due to the requirement for qualified workers. In conventional construction, low-educated, low-wage immigrants are willing to do the work by hand. -There are many errors that become apparent on the site during the build process. If we optimize the structure using generative design and then print it using 3D printers, we need to allow for flexibility to accommodate changes and errors. -With precise printing at a low cost and with minimal environmental impact, 3D printing still appears to be a plausible future technology.	Similarity: At the current stage of 3D printing technology development, the cost of constructing components and structures is comparatively high with the potential to the situation change in the future
	RA4	Reduce construction time	Reducing construction time is one of the most important reasons for doing this.	Construction time does not play a big role in a small project like this. A difference of 4-6 weeks instead of 2-3 months is not significant for a single-family house.	Differences: Traditional construction experts do not consider time reduction through 3D printing as a decisive factor.

	RA5	Reduce safety hazards	Safety can be achieved through: - Making large machines that move frequently safer, even if it requires great effort. - Providing a clean construction site, which means a safe construction site. - The estimated level of human intervention was approximately 3.	- The estimated level of human intervention was approximately 3.	Similarity: At this stage of 3D printing development, the level of human intervention is similar to that of conventional construction. Difference: Safety can be improved by keeping the space clean and tidy.
	RA6	Reduce product quality problems	Raising the product quality in countries where it is already at an extremely high level is very challenging. However, in some countries, 3D printing can definitely help to raise the quality.	Quality problems are generally avoided / reduced.	Similarity: Structural elements must meet high standards.
Ease of use (complexity)	CX1	Computer-generated design process is easy	The computer-generated design process was described as easy, and someone who understands CAD will be successful without facing any problems.	Computer-generated design is still considered a highly specialized area of knowledge that even some experts and "ordinary engineers" may not be able to undertake.	Difference: The differences in opinion highlight the gap between the traditional construction industry and 3D printing experts' perceptions of the technology. This emphasizes the need for more educated workers to lead the design process for 3D printing. Additionally, more advanced preparation should be done compared to traditional process requirements.
	CX2	Managing digital construction process and operating machinery is easy	- Managing the digital construction process was not a difficult task. - Operating the printer itself was relatively easy, but it does require some experience to adjust the material appropriately.	Managing the digital construction process is not an easy task by any means. The current and upcoming tools are not nearly as effective as they need to be in terms of communication and ease-of-use.	Difference: These differing opinions highlight the gap between the perceptions of traditional construction industry professionals and 3D printing experts regarding the technology. This gap emphasizes the need for significant changes in terms of worker re-education to fully embrace 3D printing technology. Alternatively, new specialties may need to be developed within the 3D printing industry

	CX3	Maintaining machinery is easy	Maintaining a 3D printer is relatively simple.	Operating traditional machinery is generally easy for those with experience using modernized machinery. However, maintenance of traditional machinery can be challenging as it may conflict with the production schedule, especially when breakdowns occur, and machines need to be sent away for repairs.	Agreement: Maintaining either a 3D printer or traditional machinery requires relative experience. It can be easy to handle for experts.
Trialability (divisibility)	TA1	Construction material properties are predictable	The properties of 3D printing materials were only partially predictable due to a lack of knowledge. Additionally, various weather conditions such as wind, rain, and sun can also have an impact. As a result, it was not as reliably predictable as in conventional construction processes.	The material properties of reinforced concrete and sand-limestone block-built structures were predictable.	Difference: Properties of traditional construction materials are quite predictable from a lifespan perspective. 3D printing materials, especially newly developed mixtures, are not yet well understood.
	TA2	Behavior of built product from a long-term perspective (e.g., length of the product life cycle)	As it is a relatively new technology, there are still many unanswered questions, and there is simply no possibility of retrospective analysis for already printed structures. The standard tests conducted were in a laboratory setting, which included static analysis, stability, and vibration analysis.	The structural analysis tests conducted to predict structural behaviour were only unofficial.	Difference: The behaviour of 3D printed components is currently limited by laboratory testing, but there is still room for further study. This contrasts with traditional construction with well-known material behaviour and structural tests.
	TA3	Precision of the printed objects is within acceptable tolerances	Tolerances were definitely respected and fall within the range of conventional building tolerances.	The precision of the built components was well within acceptable tolerances.	Similarity: This parameter is the construction norm that should be reached.
Compatibility (CP)	CP1	Flexibility to build various sizes of components for different construction industry needs	Printing conventional designs of various sizes can be achieved, but it is impractical and entirely pointless given the current stage of 3D printing technology development.	The flexibility to build components of various sizes to meet the different needs of the construction industry was a notable advantage in conventional construction projects.	Similarity: From an economic perspective, there is no need to print conventional design elements. Instead, challenging tasks in conventional construction can be solved by integrating 3D printing technology.

	CP2	Compatibility of construction site environment with machinery (3D printing for case 1) technology	A 3D printer is globally compatible with various construction site environments. Two meters around the building on the site is sufficient space. Additionally, the printer can produce countless different sizes, making it a highly flexible tool.	N/A The compatibility of the construction site environment with machinery was a crucial consideration in conventional construction projects.	The construction site environment should be compatible with machinery, including 3D printers.
	CP3	Matching available alternative materials (3D printing materials for case 1) with the characteristics of legacy construction processes	3D printing materials can be compared very well to their equivalent in traditional construction, such as the well-known concrete.	N/A	3D printing materials should be 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 technology	Various companies and universities were involved in research and development (R&D) and technology integration.	None of the company's capital expenditure was devoted to R&D, as the owner itself was responsible for all R&D activities.	Difference: Research and development for 3D concrete technology requires cross-disciplinary experts. This is due to the technology being newly emerged, in contrast to traditional construction that may integrate the technology (e.g., BIM), but is not necessarily required for low-story buildings.
	AC2	Major share of employees educated at tertiary level	Most employees in this case had tertiary-level education.	The study noted that workers had predominantly low levels of education, but the owner exhibited high engagement in preparation, including oversight and engineering tasks. This suggests a high-skill leadership by the owner paired with low-skill workers.	Disagreement: Integrating new technology requires tertiary level education for employees. This is in contrast to traditional construction, where workers have low skill levels that can be levelled with knowledgeable management.
	AC3	Knowledge, expertise, talent, creativity, and skills of the company workforce	A wide range of knowledge, including mechanical engineering, electrical engineering, construction, and materials science, is required	The owner was described as a highly motivated and versatile engineer who knows the process inside and out.	Difference: Expertise from various fields is required for integrating 3D printing technology in projects. However, experienced management is sufficient to execute traditional construction.
	AC4	Increasing collaboration among stakeholders (integrating a cross-functional team, suppliers, etc.)	The fact that this is an interface technology is also a special aspect of 3D printing. Due to the same fact that this is an interface technology means that a great and big cross-functional teams are needed.	The subcontractors favourably evaluated owners' attention to detail and pre-planned working schedule.	Difference: Compared to traditional construction, integrating 3D printing requires larger cross-functional teams.

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	AC5	Company team attitudes toward selected construction method in general	Project holder company as a family business trust in this technology, because otherwise they wouldn't investing so many efforts in doing it. In general, the whole company was described as open-minded to innovation and disruption.	Adequacy of company's resources to produce, test or implement conventional building method was described as high.	Similarity: Both types of engineering are being embraced by companies/project teams with both enthusiasm and the requisite expertise.
External pressure (EP)	EP1	Competitive pressure	The pressure of competition is kept within normal limits. However, the pressure will soon come, that is unquestionable and certain, and this is the fact that doesn't allow the company to rest.	Almost non-competitive pressure was noticed.	Similarity: Competition pressure is kept within normal limits for both conventional and 3D printing construction companies.
	EP2	Lack of technical standards, quality control standards and product certification issues	There are no right technical standards today and that's good and bad at the same time. For example, the printing company can design own quality assurance standards. They are not affiliated with old standards and can bring in new materials and certification accordingly.	Lack of technical standards, standards for quality control and product certification issues was also not noticed in private single-family housing.	Difference: Conventional construction follows existing technical standards, quality control standards, and product certification. However, there is room for 3D printing to introduce new materials and corresponding certifications.
	EP3	Skeptical attitudes/ psychological barriers of consumers in relation to 3D printing technologies/ conventional building method and product implementations	A sceptical attitude is quite normal when making what is likely the biggest investment of one's life. Customers may lack information on the technical and economic benefits of innovations, and face restrictions imposed by regulations, contractors, and consultants who operate independently of each other. All of these factors make things a little harder for the customer, but this is quite normal for such a young technology.	The detailed and well-thought-out plans and drawings were widely accepted. After analysing all available information, the conventional method of construction was deemed favourable.	Similarity: Traditional construction is more understandable and acceptable to customers compared to new technology-based construction.
Uncertainty (UC)	UC1	Perceived side effects associated with innovation.	No significant side effects associated with innovation were seen. Innovation is always good for the image. And image is again crucial to find skilled workers.	Involved people had an initial impression that it was easy to prepare a project so well and that it doesn´t take a huge amount of knowledge and experience. This was later described as misapprehension.	Difference: Greater reluctance to innovate was found when using the traditional construction method.

	UC2	Resistance to environmental influences and failure with exposure to high stress	Resistance to environmental influences and failure with exposure to high stress is the task that should always be set to in such projects.	Resistance to environmental influences and failure with exposure to high stress was described as not too resistant, because traditional method has it´s pace and is only influenced by extreme weather.	Similarity: In both cases, construction is limited only by extreme weather conditions.
	UC3	Uncertainty in 3D printing technical/economic benefits arising from regulatory restrictions and isolation of contractors and consultants from one another	The profitability is also still an open point, so it's important to prove it to customers accordingly.	Uncertainty in conventional building method profitability was labelled as not clear as most of it had to do with price rises due to Covid-19. The work cost was the same as in contract (separate from materials).	Difference: While the main cause of uncertainty for 3D printing technology was the lack of similar projects, uncertainty for the traditional method depended on temporary factors (e.g., prices due to the Covid-19 situation).
Supply-side benefits (SS)	SS1	Reducing and/or simplifying construction tasks and need for pre-assembly/ assembly activities	Pre-assembly and assembly activities become less if one print on the construction site (the question of profitability remains).	Reducing and/or simplifying construction tasks was described as not applicable.	Similarity: The relationship between cost and time determines the need for pre-assembly and assembly activities.
	SS2	Reducing the need for transportation services	Transport was not described as being easier / reduced. It probably doesn't change that much. Perhaps it will be worse because of the size of the printer, but this reduces the need to transport material. Everything was simpler to transport and unload.	Timely planning and understanding of the logistics and vehicle capacities already optimized transport from the start. Buying locally made it efficient as well.	Similarity: Similar factors play a role in the shaping of the transport concept.
	SS3	Reducing the number of suppliers involved in construction process	The number of suppliers should not change significantly. This will remain relatively constant. Regarding increasing collaboration among stakeholders (architects, engineers, constructors, suppliers, etc.), "Increasing" might be the wrong word, but this technology makes sure that happens sooner. Accordingly, more in the planning phase and less in the execution phase.	Regarding collaboration among stakeholders (architects, engineers, constructors, suppliers, etc.) it was only the owner (1 person) dealing with all the suppliers directly.	Similarity: It is worth noting that collaboration in the earlier stages allows for greater certainty of performance in the later stages.
Demand-side benefit (DS)	DS1	Freedom of design and customization of printed components at no extra cost	Customized production of printed components is a point that is wanted by the “margin”, but it is a relatively small point. So, customization is always expensive, and the market rarely asks for expensive.	Customized production of built components was described as probably negligible factor in total construction costs.	Similarity: Unusual shapes are only an exception in the market and not significant enough to mention in these examples.

DS2	Faster reaction to changing customer needs	In construction this is also just a niche (anything that has a large deviation from the standard).	Faster reaction to changing customer needs was not much possible, as the owner was the planner and the site manager, and has planned everything to the smallest details, starting backwards.	Similarity: In both cases, the definition of objectives in the earlier phases provided certainty for the subsequent phases.
DS3	Production in collaboration with the customer and supplier (e.g., customers integrated in product development)	That's also more of a niche. “Demand" is for faster and cheaper, as banal as it sounds. Faster, cheaper, more sustainable is the most important matter.	This mitigating circumstance also applies to production in collaboration with the customer and supplier (e.g., customers integrated in product development).	Similarity: In both cases, simplicity was a greater consideration.