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A framework for the acceptance of 3D printing technology in construction

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ABSTRACT

Although there is an increasing interest in construction 3D printing, skepticism persists due to the scarcity of supporting data. To address this concern, this paper presents a conceptual framework that aims to evaluate the viability of 3D printing (3DP) projects and facilitate the adoption of this technology. The study formulates hypotheses regarding the interrelationships among nine key factors. A questionnaire survey was conducted to gather expert opinions from the 3DP industry, followed by the application of Structural Equation Modeling and interviews for hypothesis testing and validation. In order to demonstrate the practicality of the suggested framework, a case study was undertaken on a full-scale residential building constructed using 3D printing in Germany. The results demonstrate that the finalized conceptual framework can assist in strategic decision-making to enhance the implementation of 3DP technology in specific projects and across the construction industry. Additionally, it provides a decision-making guideline for industry practitioners regarding the incorporation of 3DP technology in construction projects.

Keywords: Additive manufacturing, conceptual framework, construction 3D printing, structural equation modeling, technology adoption.

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1. INTRODUCTION

Additive Manufacturing (AM), commonly known as 3D printing (3DP) or rapid manufacturing, is an innovative technology with the capacity to propel the industry toward digitalization (El-Sayegh et al., 2020). In 2020, the global market for 3DP experienced significant growth, reaching an estimated value of $12.6 billion, which represents a substantial 21% increase compared to the previous year (Munir and Kärki, 2021). The advent of 3DP technology brings forth the possibility of replacing a significant portion of the human workforce with robotic machines, i.e., 3D printers. This substitution can eliminate worker fatigue, physical stress, and other human-related factors that often result in rework, idle time, and similar challenges.

3DP technology offers a range of advantage, including the reduction of a design

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errors and development cycles, as well as the ability to facilitate customer co-design for customized products that align with their specific demands. Furthermore, this technology enables the execution of complex designs and allows for quick design changes (Berman, 2012; Ghaffar et al., 2018). Additionally, by reducing the number of suppliers, 3DP can enhance material and tool management, mitigating issues associated with supplier coordination and collaboration. Research suggests that 3DP has the potential to significantly reduce material usage by up to 60%, time requirements by 50% to 70%, and labor costs by 50% to 80% (Hossain et al., 2020; Souza et al., 2020). Moreover, 3DP can contribute to waste reduction and add value to the construction industry through the utilization of multifunctional building components that eliminate the need for formwork and enable optimal material utilization in complex geometries (Bedarf et al., 2021).

The construction industry has acknowledged the significance of 3DP technology, leading industry practitioners to explore its adoption. While previous studies have extensively discussed notable 3DP projects by renowned companies like WinSun (Chinese houses), Dubai (UAE) (office buildings), Apis Cor (round-shaped buildings), the first 3D printed castle in Minnesota (USA), and the MX3D bridge in Amsterdam (Netherlands) (Al Rashid et al., 2020; Ali et al., 2022), new companies have entered the 3DP technology market and achieved successful outcomes. For instance, PERI group, in collaboration with Danish printer vendor COBOD, has 3D printed a residential building in Germany that is currently occupied by tenants (Weger et al., 2022). Alquist (2022) has initiated a project to 3D print 200 homes across the state of Virginia (USA), and the completion of the first two 3D printed homes took place in April 2022. In Madagascar, a 700-square foot 3D printed school is addressing educational shortcomings (Steffen, 2022). Inspired by NASA's "Mars Ice House" projects, Serendix has become the first Japanese manufacturer to build a 3D printed house in less than 24 hours, showcasing ongoing interest in developing habitats for extreme environments (Serendix, 2022).

Numerous academic researchers have dedicated significant efforts to incorporating 3DP technology into the construction industry. For example, TU Dresden University introduced the CONPrint3D concept, which focuses on on-site printing aligned with global architectural norms, design codes, prevalent concrete types, and economic constraints (Mechtcherine et al., 2019). Lim et al. (2020) outlined a cable-driven parallel 3D printer specifically designed for application in spacious work environments. Researchers have also been working on developing concepts for fabricating non-homogeneous materials, such as integrating metallic reinforcement automatically during the printing process (Mechtcherine et al., 2020; Wang et al., 2021). The study of various material designs and their suitability for C3DP is ongoing. For example, sustainable 3D printed mortar, which utilizes recycled powder as a partial cement replacement, has been explored (Hou et al., 2021). Additionally, investigations are being conducted into high-strength lightweight concrete compositions (Inozemtcev and Duong, 2020), combinations of fly ash and slag to expand the range of geopolymer materials (Xia et al., 2019), alkali-activated geopolymer as an environmentally friendly alternative (Rehman and Sglavo, 2020), and 3DP foam concrete (Markin et al., 2021). New applications of 3DP technology have also emerged, such as the potential for producing concrete foundation piles (Hoffmann et al., 2021), designing and manufacturing post-tensioned concrete structures using 3DP (Vantyghem et al., 2020), and printing curved concrete panels by combining 3DP technology with a membrane formwork (Lim et al., 2020).

Despite the rapid advancement of knowledge and interest in C3DP technologies, the rate of adoption in the construction industry remains slow in comparison to the manufacturing sector (Pan et al., 2021; Won, et al., 2022). While 3DP technology holds significant potential for enhancing the construction process, several challenges need to be addressed, including technological feasibility, cost and time benefits, user training, and safety considerations. Moreover, the adoption of 3DP technologies entails critical risk implications, compliance with contractual and standard requirements, and departure from conventional practices (Despeisse et al., 2017). These concerns create doubts among potential adopters regarding whether the implementation of 3DP technology is worthwhile, particularly if it does not lead to higher profits (Yeh and Chen, 2018). Therefore, it is crucial to identify the primary reasons behind the limited adoption rate and establish a framework that assists the construction industry in making informed decisions regarding the adoption of 3DP technology.

While previous studies have attempted to identify the factors influencing the adoption of 3DP technology in the construction field (Wu et al., 2018; Aghimien et al., 2020; Won et al., 2022), most of them neglect a systematic approach for identifying these factors. They primarily rely on expert opinions from conventional construction projects to determine the perceptions of influential factors, without incorporating the perspectives of 3DP practitioners who are the primary actors in technology integration and can provide valuable insights into the challenges and issues related to technology integration. To bridge this gap, this paper develops a comprehensive conceptual framework of 3DP technology adoption. The framework is based on technology acceptance theories and has been refined and validated through surveys and post-survey interviews conducted with construction 3DP experts. The majority of the respondents represent traditional construction companies actively involved in 3DP projects, possessing a deep understanding of the acceptance of 3DP technology. The framework explores the interrelationships among various factors as a progressive step in 3DP adoption, considering that one factor can depend on another and addressing dependent factors without addressing the initiating ones may prove challenging. To demonstrate the practicality of the proposed framework, a case study is presented that illustrates its application in making informed decisions regarding the implementation of 3DP technology for a specific project.

The organization of this paper is outlined as follows: Section 2 provides a thorough examination of the current literature regarding the adoption of 3DP. In section 3, the theoretical background and research hypotheses are discussed. Section 4 outlines the research methodology employed, whereas section 5 presents the findings obtained from the study. Section 6 engages in a detailed discussion of the research findings and demonstrates their practical application through a case study. Lastly, section 7 encompasses the study's conclusions and highlights potential directions for future research.

2. LITERATURE REVIEW

A comprehensive examination of the literature indicates that researchers have been actively exploring the factors that impact the adoption of 3DP technology. Yeh and Chen (2018) employed the technology-organizational-environment (TOE) framework to prioritize the factors influencing the adoption of 3DP in manufacturing companies based in Taiwan. Their findings indicated that the most significant organizational factor was "cost", specifically the "material cost". Building upon this research, a subsequent study conducted a year later by Tsai and Yeh (2019) combined the TOE framework with rough set theory. The results of this study identified the top four determinants for 3DP adoption as the environment, technology, organization, and cost. Chaudhuri et al. (2019) employed the technology acceptance model (TAM) to provide insights into the primary challenges linked to the adoption of 3DP. These challenges include the need to create a business case, the utilization of different materials, the optimization of processes for specific parts, the lack of readily available solutions from equipment manufacturers, inadequate training and educational support, the production of low-quality products, and the high costs associated with machine breakdowns, repairs, and maintenance. Zhao et al. (2021) examined how firms' sustainability orientation impacts the adoption of 3DP from a managerial standpoint. This investigation was conducted in two stages: acquisition and application. The researchers conducted interviews and administered a questionnaire survey in the United States and India to collect expert opinions, which were subsequently analyzed and compared between the two countries. Ukobitz and Faullant (2022) conducted a study examining the effects of institutional pressures on the organizational adoption of 3DP technology within a footwear cluster in Mexico. Their research provided evidence that the perceived value of the technology plays a significant role in influencing the adoption decisions driven by institutional forces. In a different context, Almahamid et al. (2022) developed an integrated model that combined the TOE framework and the TAM to investigate 3DP adoption among manufacturing companies in the Gulf Cooperation Council. The results of their study revealed that factors such as "technological usefulness" and "ease-of-use" had the most significant influence on the adoption and diffusion of 3DP technology in this context.

In the construction industry, a questionnaire survey was conducted among Australian construction professionals, the aim of which was to propose a framework for adopting 3D printing technology (Wu et al., 2018). This framework encompasses various factors, subfactors, and hypotheses. The survey results revealed that the top three influential subfactors for technology adoption were "top management commitment", "building codes and regulations", and "liability for 3D printed components". Similarly, Aghimien et al. (2020) conducted a study to explore the advantages and obstacles of 3DP in housing delivery within South Africa. They gathered input from construction professionals through a questionnaire survey. Through factor analysis, the study highlighted several benefits, including improved cost delivery, increased productivity, enhanced stakeholder satisfaction, socio-economic advantages, opportunities for creative designs and new markets, and improved quality and speed of project delivery. On the other hand, the study also revealed obstacles to the adoption of 3DP. These barriers encompass operational issues, challenges related to organizational structure and personnel, as well as a limited comprehension of the technology among stakeholders. Won et al. (2022) undertook a survey targeting construction practitioners in Singapore to evaluate their viewpoints regarding the drivers, challenges, and strategies associated with the adoption of 3DP technology. The survey results unveiled three major challenges hindering the incorporation of 3DP technology, namely: limited production size, high upfront costs, and hesitancy to invest in 3DP.

Based on the preceding discourse, it becomes apparent that studies focusing on the adoption of 3DP technology in the construction industry frequently neglect the importance of a systematic approach in identifying pertinent factors. A systematic approach, rooted in widely recognized technology acceptance theories, would furnish a robust foundation for comprehensive analysis. Furthermore, while existing studies have primarily emphasized gathering insights from professionals within the traditional construction industry within a specific country, it is imperative to incorporate the perspectives of 3DP practitioners worldwide. As key players at the forefront of technology adoption, their viewpoints on the most influential factors carry significant weight in comprehending the field.

Besklubova et al. (2021) have taken a step forward by conducting a comparative analysis of factors derived from various technology acceptance theories, including the Innovation Diffusion Theory, Technology Acceptance Model, Technology Readiness, and Contingency Theory. Their study has contributed to the development of a systematic approach for identifying factors associated with the adoption of 3DP technology, resulting in the creation of a comprehensive list of these factors. The researchers prioritized these factors by collecting opinions from worldwide experts in the field of C3DP through a questionnaire survey. While prior studies have focused on assessing the relative significance of factors that influence the adoption of C3DP, they have overlooked the interrelationships between these factors. Achieving successful adoption of 3DP in the construction industry necessitates a holistic consideration of multiple factors, rather than solely addressing individual factors in isolation. Hence, it is crucial to establish and evaluate the interconnections among the factors that impact the 3DP technology adoption. Modeling these interrelationships is essential for providing a comprehensive overview and understanding the dependencies between the factors. Failing to adequately address the initiating factors can impede progress in addressing the dependent factors effectively.

This study expands upon the research conducted by Besklubova et al. (2021) by introducing a conceptual framework that proposes hypotheses concerning nine key factors that influence the 3DP technology adoption in the construction industry. These factors were identified by comparing various technology acceptance theories and their corresponding factors. To validate the proposed hypotheses, a questionnaire survey was conducted, followed by interviews with industry experts specializing in 3DP construction. The framework establishes connections between these factors, offering insights into proactive measures that can be undertaken to enhance the adoption rate of 3DP technology in the construction industry. It serves as a foundation for developing strategies to promote the uptake of 3DP technology in specific projects and the construction industry as a whole. Additionally, the framework can serve as a guideline for industry practitioners to assess the feasibility of implementing a 3DP project.

3. THEORETICAL BACKGROUND AND RESEARCH HYPOTHESES

3.1. Research Model Development

The development of the C3DP technology acceptance framework initiates with an exploration of existing technology acceptance theories to identify the key factors that influence its adoption. Unlike the technology-push model, where market needs drive adoption, the adoption of C3DP technology is primarily driven by developers' initiatives (Baumers et al., 2016). Hence, only acceptance theories that specifically focus on technology and its usage outcomes are considered in this framework. To ensure a comprehensive understanding of the factors influencing C3DP adaptation, multiple widely used technology acceptance theories have been taken into account, rather than relying on a single theory. This approach was chosen due to the absence of a systematic framework for factor selection. The reviewed theories include the Technology Readiness (TR) (Başgöze, 2015), Innovation Diffusion Theory (IDT) (Rogers, 2003), Contingency Theory (CT) (Donaldson, 2001), and the Technology Acceptance Model (TAM) (Davis, 1989). Each theory encompasses various factors that influence technology adoption. For instance, according to the IDT, the factors include complexity, relative advantage, compatibility, trialability, and observability (Rogers, 2003). While previous research has established similarities between certain technology acceptance theories, Besklubova et al. (2021) conducted a comparative analysis of the aforementioned theories (IDT, TAM, TR, and CT) specifically focused on identifying factors that influence the adoption of 3DP technology in construction. In the process, factors with similar meanings but different names across the theories were consolidated into one all-inclusive term. For example, the concept of "complexity" found in both IDT and CT refers to the extent to which an innovation is considered as challenging to comprehend and utilize (Rogers, 2003). Similarly, the "discomfort scale" from the TR theory captures the negative consumer attitude towards a new technology based on the consumer's understanding of its usage complexity (Parasuraman, 2000). Moreover, the TAM theory introduces the concept of "ease-of-use" as the opposite of complexity. To ensure consistency and clarity, these terms from the four different theories were unified under the inclusive term "complexity". Besklubova et al. (2021) followed a similar process for all factors. In addition to the factors identified in the technology adoption literature, such as "absorptive capacity", "supply-side benefits", and "demand-side benefits", were also included. Table 1 illustrates the process of matching factors from various theories, resulting in a comprehensive list of nine factors (column 1) (Besklubova et al., 2021): relative advantage, complexity, absorptive capacity, trialability, uncertainty, compatibility, external pressure, supply-side benefits, and demand-side benefits.

Due to the abstract nature of these nine factors, direct measurement presents challenges. To address this, a thorough literature review was conducted to identify thirty-two measurement items. Experts then assessed the significance of these items through a questionnaire survey (Besklubova et al., 2021). The Kaiser-Meyer-Olkin (KMO) test, which evaluates the adequacy of the survey sample, yielded a value of 0.693, surpassing the threshold of 0.5. Bartlett's test of sphericity indicated significant correlations among the variables, with a p-value below the threshold of 0.05. Exploratory factor analysis (EFA) was subsequently employed to verify the number of factors (nine) that accounted for the correlation patterns among the identified measurement items. Through EFA, four measurement items were eliminated, resulting in nine factors and twenty-eight measurement items for this study, as presented in Table 2.

3.2. Theory and Hypotheses

The nine proposed factors are interconnected with each other. Therefore, this section presents a discussion of multiple hypotheses that highlight the interactions between these factors and present them within a conceptual framework. Since no previous studies have specifically identified relationships among these factors in the context of 3DP adoption in construction, relevant relationships are extracted and adapted from research conducted in other fields, such as additive manufacturing in industry, information technology and environmental technology.

Table 1. Technology acceptance theories factor's comparison

All-inclusive factor	IDT	TR	TAM	CT	Additional factors
Relative advantage	Relative advantage	Optimism dimension	Perceived usefulness	-	-
Complexity	Complexity	Discomfort scale	Perceived ease-of-use	Complexity	-
Trialability	Trialability	-	-	-	-
Compatibility	Compatibility	-	-	-	-
Absorptive capacity	-	-	-	-	Absorptive capacity
External pressure	-	Insecurity dimension	-	-	-
Uncertainty	Observability	-	-	Uncertainty	-
Supply-side benefits	-	-	-	-	Supply-side benefits
Demand-side benefits	-	-	-	-	Demand-side benefits
References	Rogers (2003)	Başgöze (2015)	Davis (1989)	Donaldson (2001)	Ofori (2000)

Table 2. Factors affecting 3DP technology adoption and their measurements

Factor	Code	Measurement items
Uncertainty (UC)	F1	Resilience against environmental factors and resistance to failure under high-stress conditions
	F2	Competitive pressure
	F3	Side effects perceived to be associated with innovation
External pressure (EP)	F4	Regulatory restrictions and the lack of collaboration between contractors and consultants contribute to the uncertainty surrounding the technical and economic benefits of 3DP
	F5	The absence of technical standards, quality control standards, and challenges related to product certification
	F6	The skeptical attitudes and psychological barriers exhibited by consumers towards the implementation of 3D printing technologies and products
Absorptive capacity (AC)	F7	A majority of employees have received tertiary education
	F8	The expertise, knowledge, and skills of the company's workforce
Complexity (CX)	F9	Operating a 3D printer and effectively managing the digital construction process are straightforward tasks
	F10	The maintenance of a 3D printer is straightforward
	F11	The computer-generated design process is easy
Trialability (TA)	F12	The usage of materials can be improved by making their properties more predictable
	F13	Considering the long-term perspective, aspects of 3DP product behavior, such as the duration of the product life cycle
Relative advantage (RA)	F14	Reduce construction time
	F15	Reduce the cost of construction components/structures
	F16	Reduce safety hazards
	F17	Reduce manpower requirement
	F18	Reduce product quality problems
Compatibility (CP)	F19	Suitability of printing conventional design elements in various sizes
	F20	Matching the characteristics of available 3DP materials with those of legacy construction processes
	F21	The compatibility between 3DP technology and the construction site environment
	F22	The printed objects exhibit precision that falls within acceptable tolerances
Supply-side benefits (SS)	F23	Minimizing the requirement for transportation services
	F24	Minimizing the participation of multiple suppliers in the construction process
	F25	Streamlining construction tasks and minimizing the need for pre-assembly/assembly activities
Demand-side benefits (DS)	F26	Production in collaboration with the customer and supplier
	F27	Reacting faster to changing customer needs
	F28	Freedom to design and customize printed components without any additional cost

3.2.1. Uncertainty

In the context of 3DP technology, "uncertainty" pertains to the disparity between the information needed for the production and utilization of 3D printed structures, their performance, and the existing knowledge held by organizations concerning this technology (Grenyer et al., 2019). When consumers are uncertain, their acceptance of technology is hindered by their diverse and often contradictory beliefs (Jalonen, 2012). Previous research has indicated that as the level of uncertainty increases, consumers tend to exhibit skeptical attitudes, encounter psychological barriers, and become reluctant to take risks in adopting the technology (Hofstede, 2016; Sugandini et al., 2018). In other words, when uncertainties associated with 3DP technology decrease, the external pressure it faces also diminishes. Building on this, we propose the following hypothesis: *Hypothesis 1 - Uncertainty significantly influences external pressure.*

The existence of a knowledge gap, or uncertainty, regarding 3DP technology poses challenges when it comes to understanding specific technical aspects of this innovation. For example, these complexities encompass factors such as the computer-generated design process, which involves challenges like selecting an optimal printing path with multiple stop/start operations (Zhang and Khoshnevis, 2013; Khoda, 2014; Gosselin et al., 2016). Additionally, complexities arise in digital construction management, as well as in operating and maintaining the 3D printer, which can include issues with surface finish, resolution, accuracy, and repeatability (Hague et al., 2004; Barnett and Gosselin, 2015). Furthermore, problems related to material extrudability and flowability contribute to the overall complexities (Chianrabutra et al., 2014; Barnett and Gosselin, 2015; Perrot et al., 2016). The relationship between uncertainty and complexity has been emphasized as a common link in construction projects (Thunberg et al., 2017), thereby supporting the following hypothesis: *Hypothesis 2 - Uncertainty has a significant effect on complexity.*

The uncertainty raises concerns about the compatibility of new technology in the traditional construction site environment. This uncertainty is due to the lack of information regarding the behavior of 3D printed components, including their resistance to environmental pressures and potential side effects. In addition, questions arise about the technology's suitability under specific conditions. This includes its compatibility with existing systems and processes, applicable values, legacy, and past experiences. These aspects collectively fall under the term "compatibility" (Harrison et al., 2007; Greenhalgh et al., 2018; Sugandini et al., 2018; Eastwood and Renwick, 2020). Considering the interdependence between uncertainty and compatibility, we propose the following hypothesis: *Hypothesis 3 - Uncertainty significantly influences compatibility.*

3.2.2. External pressure

In this study, "External pressure" is defined as the influence exerted by external entities on an organization, ranging from pressure to encouragement, which can include incentives or penalties (Kamal, 2006). Government regulations have been identified as a crucial environmental factor that affects the adoption of innovative technologies (Kaufman, 2009). Governments can encourage the adoption of new technologies by formulating regulations that support their integration within organizations (Jaeger, 2007; Best et al., 2008; Ali et al., 2020; Ali and Osmanaj, 2020). The impact of social influence on shaping organizations' attitudes towards technology adoption has also been acknowledged as a significant factor (Abbad et al., 2009; Al-Ammary et al., 2014; Al-Gahtani, 2016; Kemp et al., 2022). Moreover, market uncertainty associated with technological innovations can create internal tensions within firms that need to be managed effectively (Bauer et al., 2014; Prause, 2019). Considering the impact of external pressure, we propose the following hypothesis: *Hypothesis 4 - External pressure has a significant effect on the absorptive capacity.*

3.2.3. Absorptive capacity

"Absorptive capacity" denotes an organization's capability to identify, integrate, and utilize the value of novel information for commercial purposes. To ensure the acceptance of technology, it is crucial for organizations to demonstrate strong commitment and allocate adequate resources, creating a supportive context for the adoption of 3DP (Park et al., 2012). Organizational support has been found to have a positive correlation with reduced complexity (McFarland and Hamilton, 2006; Kim et al., 2007). Previous research has highlighted that educated employees with extensive knowledge about an innovation tend to encounter fewer challenges and complexities when adopting new technologies (Gargiulo et al., 2018; Prause, 2019; Ali et al., 2020; Eastwood and Renwick, 2020). Highly educated employees within an organization are more likely to adopt new technologies earlier as they have easier access to the necessary information for making informed decisions and managing complexities (Ugochukwu and Phillips, 2018). Based on these arguments regarding "absorptive capacity", we propose the following hypothesis: *Hypothesis 5 - Absorptive capacity significantly influences complexity.*

To encourage the adoption of technology, organizations are motivated to explore potential benefits and advantages (Ali et al., 2015; Ali et al., 2020). Previous studies have demonstrated a positive relationship between organizational support and the perception of relative advantages (Lewis et al., 2003; Aziz and Wahid, 2020) Based on this literature, we propose the following hypothesis: *Hypothesis 6 - Absorptive capacity significantly influences the perception of relative advantages.*

3.2.4. Complexity

In the context of innovation, complexity refers to the degree to which it is perceived challenging to comprehend and implement (Rogers, 2003; Ali et al., 2022). Existing research has presented compelling empirical evidence regarding the correlation between complexity and the perception of "relative advantages" (see, for example, Khajavi et al. (2014), Bos et al. (2016), Xia and Sanjayan (2016), Karahoca et al. (2017), Alamri et al. (2020)). "Relative advantage" denotes the extent to which an innovation is perceived as superior to the concept it supersedes (Rogers, 2003). Building upon this discussion, we propose the following hypothesis: *Hypothesis 7 - Complexity has a significant effect on relative advantage.*

When it comes to entirely new ideas, complexity acts as a significant barrier to adoption. However, innovations with lower complexity are more compatible with existing practices (Rogers, 2003; Levison and Oehme, 2017). Previous studies have provided robust empirical evidence for the relationship between complexity and compatibility (see, for example, Karahoca et al. (2017), Alamri et al. (2020)). Based on the relationship between complexity and compatibility, we propose the following hypothesis: *Hypothesis 8 - Complexity significantly influences compatibility.*

3.2.5. Compatibility

"Compatibility" can refer to the consistency between the values or norms of potential adopters and existing practices (Tornatzky and Klein, 1982; Sugandini et al., 2018; Ugochukwu and Phillips, 2018). In the event of any concerns regarding compatibility with existing work practices, preferred work style, prior experience, or established values and norms (Karahanna et al., 2006), these issues will have an impact on the supply of materials, equipment, and other resources (Dainty et al., 2007; Gustavsson et al., 2012; Thunberg et al., 2017). Bankvall et al. (2010) discuss the intricate interrelationships between construction site processes and the supply chain, which are inevitably intertwined. Based on these considerations regarding compatibility, the following hypothesis is put forth: *Hypothesis 9 - Compatibility has a significant effect on supply-side benefits.*

Past studies have demonstrated a connection between compatibility and the intention to adopt innovative technology (Hsu et al., 2007; Park et al., 2012; Joo et al., 2014). Before fully adopting, prospective users frequently express a desire to test an innovation and evaluate its alignment with their specific criteria (Zolkepli and Kamarulzaman, 2015; Karahoca et al., 2017). This testing phase allows users to evaluate the innovation without committing fully or incurring significant costs (Nguyen et al., 2004; Lin and Bautista, 2017). Drawing from these findings, we put forward the following hypothesis, highlighting the relationship between trialability and compatibility: *Hypothesis 10 - Compatibility has a significant effect on trialability*.

3.2.6. Trialability

In the context of utilizing 3DP technology, result trialability refers to a user's attitude towards the tangible nature of the technology (Son et al., 2012). Previous research on technology adoption has indicated that conducting trials of new technology before full integration is a crucial factor in determining perceived relative advantages (Venkatesh and Bala, 2008; Lefievre, 2012; Al-Gahtani, 2016; Zhang et al., 2019). Visible outcomes of the technology play a role in helping potential customers understand the benefits of integrating the technology into their work (Mun et al., 2006; Rezaei et al., 2020). This relationship between trialability and relative advantage has been emphasized in both the healthcare and agriculture industries (Karahoca et al., 2017; Rezaei et al., 2020). Based on the impact of trialability on relative advantage, we propose the following hypothesis: *Hypothesis 11 - Trialability has a significant effect on relative advantage.*

3.2.7. Supply-side benefits

The supply-side refers to the supply chain that extends from machine vendors to technology purchasers (Mellor et al., 2014). Several authors have emphasized the reduction of the construction supply chain (Chen, 2016; Kothman and Faber, 2016; El-Sayegh et al., 2020) due to the elimination of various logistical processes and entities through on-site structural element printing (Kothman and Faber, 2016; Besklubova et al., 2021). This, in turn, can result in a decrease in factors such as human labor (F17) and construction time (F14) (Gibb and Isack, 2003). Essentially, as changes in the supply chain (supply-side) have a positive impact on "relative advantages", we propose the following hypothesis: *Hypothesis 12 - Supply-side benefits have a significant effect on relative advantage.*

The adoption of 3DP technology occurs at the intersection of two supply chains. Firstly, there is a supply chain that connects machine vendors to technology purchasers. Secondly, there is a supply chain that links the purchasers to their users and suppliers. These two components are closely interrelated and have been acknowledged as crucial factors in the implementation of 3DP (Mellor et al., 2014; Monyei and Adewumi, 2018). Numerous studies have focused on the process of interaction between users and suppliers (e.g., Bragagnolo et al. (2020), Chicot and Matt (2018), Georghiou et al. (2014)). Considering the supply-side benefits, we propose the following hypothesis: *Hypothesis 13 - Supply-side benefits have a significant effect on demand-side benefits*.

3.3. Conceptual Reference Framework of 3DP Technology Acceptance by Construction Professionals

The "causal path diagram" is employed to present the interconnected causal relationships between the various factors proposed in the aforementioned hypotheses. A causal path diagram is a visual representation that organizes the causal relationships within a process or sequence of events, utilizing arrows to indicate the direction of causality (McCrudden et al., 2007). In these diagrams, one-way arrows are utilized to demonstrate the direction of influence (Duncan, 1966). Fig. 1 depicts an initial framework for understanding the acceptance of 3DP technology by construction professionals. However, this preliminary framework requires further refinement and validation.

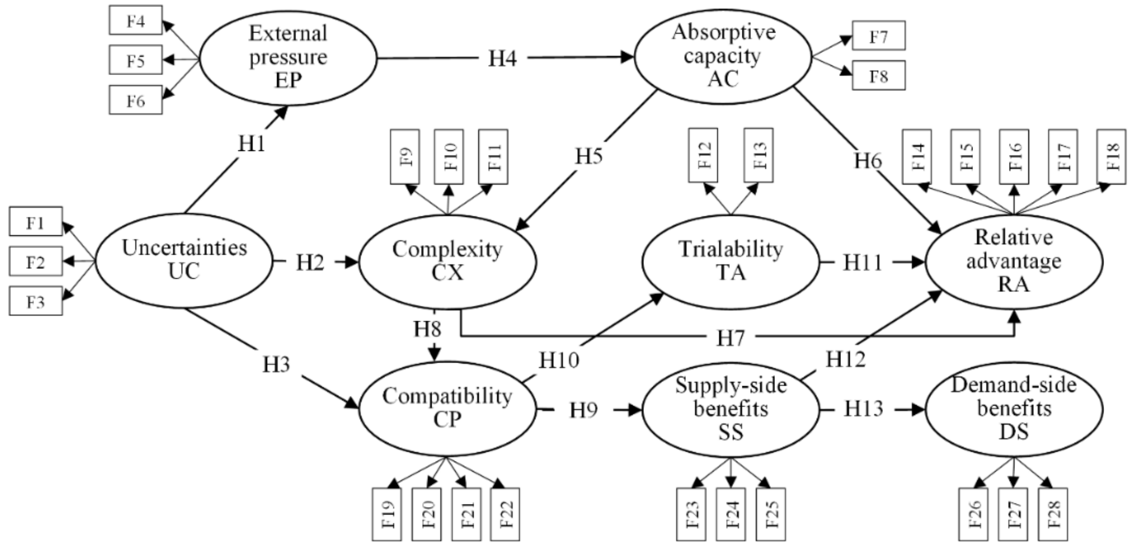

Fig. 1. Initial conceptual reference framework of 3DP technology acceptance by construction professionals

4. RESEARCH METHODOLOGY

The research methodology follows a systematic procedure to quantify the relationships among different factors that impact the acceptance of 3DP technology by field professionals (Fig. 2). The procedure consists of four main steps: (1) conducting a questionnaire survey, (2) testing the formulated hypotheses, (3) evaluating model-fit indices, and (4) validating the refined framework through interviews with 3DP experts in the construction industry.

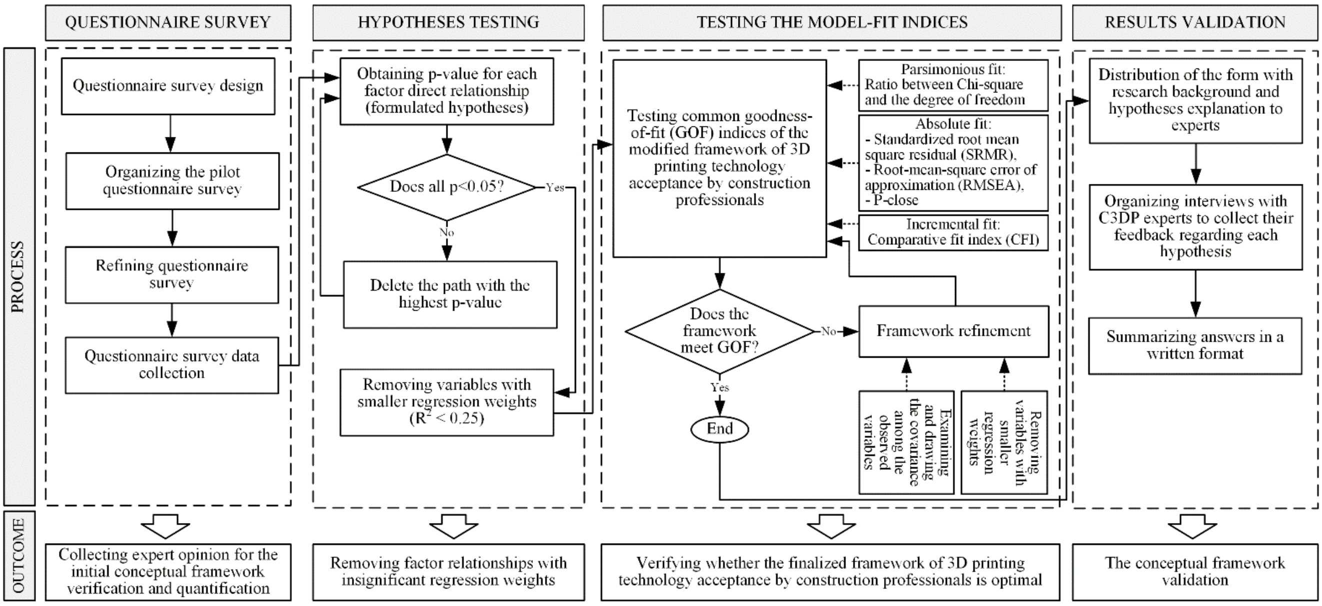

Fig. 2. Research Methodology

4.1. Questionnaire Survey Design and Distribution

The present study implements an online questionnaire survey technique to collect C3DP expert opinions for further testing of the initial framework of 3DP technology acceptance by construction professionals. There are various advantages inclined to favor using the questionnaire to access the following information: unique populations existing in cyberspace (e.g., the co-operative network of building researchers, ASCE); individuals with health issues (e.g., covid-19 pandemic); individuals in other countries; the advantage of automated data collection that reduces time, cost and research effort (Wright, 2005).

The questionnaire survey included three main sections. In section 1, research background and survey purposes were explained; in section 2, regarding 3DP construction adoption, respondents were requested to assess the importance of each proposed factor measurement item, totaling 28 in number. A five-point scale was adopted, from 'very low importance' (equal to 1) to 'extremely important' (equal to 5). In section 3, respondents' professional background and institutional identity information were collected. Before the main survey was launched, a pilot questionnaire survey was organized.

C3DP expert opinions around the world were collected via the online survey on the Qualtrics® online platform (Barnhoorn et al., 2015). A database has been previously developed, comprising potential respondents who participated in 3D-printing projects worldwide. The respondents consisted of individuals from academic institutions and a variety of firms involved in designing, producing, consulting, or installing 3D printed components for construction projects, or those with an interest in these activities. Various sources were utilized to acquire the contact information of the respondents. Contact information for researchers and scholars was gathered from journals and relevant papers, while the names and email addresses of academic professionals were obtained from institutional websites. The contact details of industry professionals were sourced from company websites, the ASCE webpage, the Co-operative Network of Building Researchers (CNBR), and LinkedIn postings. Upon identifying these professionals, the survey was subsequently disseminated to them.

4.2. Hypothesis Testing

In order to test hypotheses and verify the proposed initial framework, the covariance-based Structural Equation Modeling (CB-SEM) as a strong, highly multivariable analysis technique was employed (Gunduz et al., 2017). As applied to this study, CB-SEM can evaluate the following parameters: (a) testing hypotheses through the estimation of a path's significance; (b) checking whether the proposed model configuration is optimal through model-fit indices, and (c) evaluating the strength of the factor causal relationships by obtaining path coefficients in the finalized model.

Hypothesis testing was conducted through the 'Stata/SE 15' software package by checking whether all identified direct factor relationships are significant (Zubair and Zhang, 2020). For this purpose, the p-value obtained for each direct factor relationship (formulated hypothesis) should be lower than 0.05 to make a relationship significant. Insignificant paths were deleted one by one starting from the paths with the highest p-value. An iteration to obtain direct relationship significances was made after each deletion to check whether the significance of other direct factor relationships had changed. Iterations were continued until all insignificant direct relationships were determined and excluded from the path diagrams. Also, factor standardized regression weights (squared multiple correlations) were obtained to confirm that nine considered factors are meaningful for the proposed framework. The variables with a value below 0.25 ($R^2 < 0.25$) can be deleted (Zahoor et al., 2017).

4.3. Testing the Model-Fit Indices

The proposed framework ought to satisfy the necessary model-fit indices (Doloi et al., 2012), for which the following tests were conducted (Xiong et al., 2015): (1) 'parsimonious fit' indices (Chi-sq/df), which aim to prevent excessively complex models in the pursuit of improved GOF; (2) 'absolute fit' indices (SRMR, RMSEA, and P-close) which assess the degree to which an a priori model fits the sample data and indicate which proposed model fits best; (3) 'incremental fit' indices (CFI) which is a group statistic obtained by comparing a proposed model with a baseline model. Model-fit can be enhanced by (1) by removing the variables with low squared multiple correlations; and (2) by examining and drawing the covariance among the variables (Hair et al., 2011). Covariance can be drawn among variables within one or different groups. Drawing covariance among the observed variables begins with the identification of the variable's pairs with the larger correlation value.

4.4. Results Validation

In order to verify the reliability of the findings, interviews with 3DP industry experts were conducted. Previous studies recognized the interview as a proper method for testing findings from a questionnaire survey, which is commonly used in construction and engineering management research (Liao et al., 2021; Ali et al. 2022; Won et al., 2022). Earlier research indicated that the size of an expert panel started from a low of three members (Besklubova et al., 2021). Six experts involved in 3DP technology development and application were interviewed for the current study. Selected 3DP practitioners represent a diverse geography: the United States, Australia (2 experts), Switzerland, China, and Hong Kong. Their work outcomes have also been published in reputable peer-reviewed journals and most of them have over 6 years' experience in the construction managerial process (Besklubova and Zhang, 2019).

Prior to the interview, a form that contains research background and finalized framework figure was distributed. Table with the finalized hypotheses and their explanation was also included. Participants were asked to express their agreement/disagreement with the hypotheses by marking 'yes' or 'no.' Based on the completed forms, the interviews were organized according to a semi-structured framework to obtain expert feedback on disagreements (answers marked as 'no'). Most importantly, all participants were encouraged to develop ideas based on actual experiences related to each hypothesis.

5. RESEARCH FINDINGS

Of the 5,242 surveys that were disseminated, only 270 were returned. From these, 82 were deemed valid and incorporated into the analysis, while the other 188 were discarded due to being incomplete or inaccurately filled out. The response rate was low primarily because the contact information used was obtained from 3DP organizations' websites. Given that only a small subset of these contacts would have had experience with trialing construction 3DP technology and could provide valuable input, the questionnaires were sent to all extracted emails to improve the odds of reaching individuals with pertinent expertise. It should be noted that some organizations opted not to participate in the survey due to concerns about the confidentiality of information.

5.1. Demographic Characteristics

The questionnaire survey involved participants from 28 countries, with the majority of respondents (29) originating from the USA. The remaining respondents came from various countries, including Australia, China, Germany, Spain, The Netherlands, UAE, and others (refer to Fig. 3). Although the number of respondents from each country is limited, each one represented a party involved in a well-known 3D printing project. The total number of construction 3DP initiatives remains limited, particularly within an individual country. Therefore, these responses, tied to specific acclaimed projects, reflect the widespread interest in construction 3D printing technology across various geographic locations.

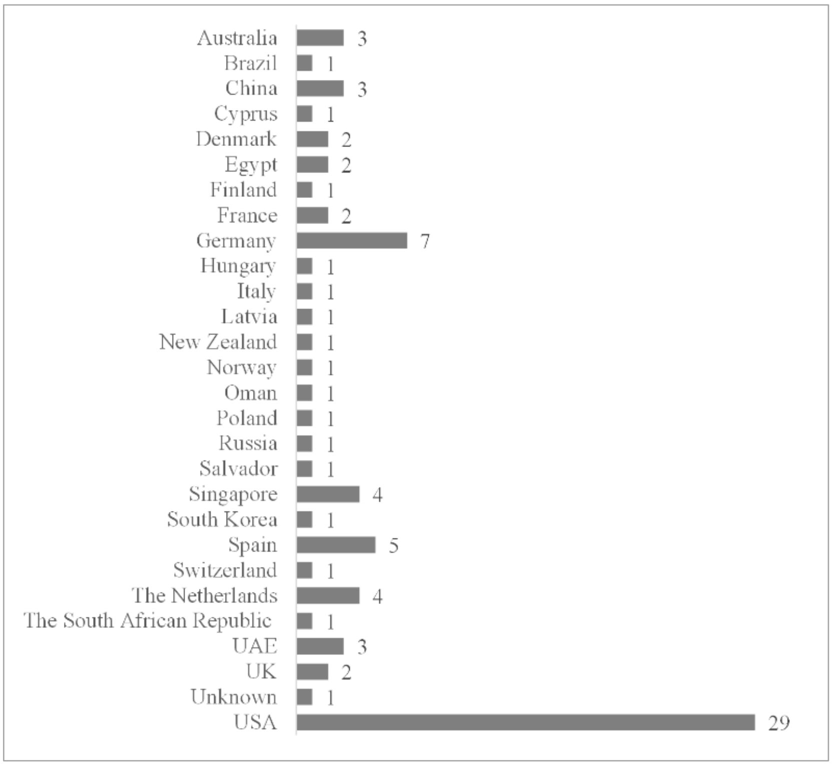

Fig. 3. Distribution of respondents by country

Regarding the primary area of practice, the study received responses from diverse groups, including 3DP practitioners from research labs and companies engaged in 3DP projects, engineering consulting firms, manufacturers and suppliers, government organizations, contractors, and other unspecified areas, as depicted in Fig. 4(a). Analyzing the distribution of respondents based on their construction industry experience and education level, as shown in Fig. 4(b-c), it is evident that a significant proportion (45%) of respondents possess extensive experience of over 11 years. Regarding the respondents' educational background, it was found that 40% of the participants hold a doctoral degree, 38% possess a master's degree, and 16% have a bachelor's degree. The remaining 6% reported other types of degrees, including diplomas, associate degrees, or technical college diplomas. These figures indicate that the majority of the respondents have pursued postgraduate education.

5.2. Hypothesis Testing

The summary of the path coefficients obtained for each diagram can be found in Table 3. The results indicate that the relationships between factors EP and AC, AC and RA, and CX and RA are insignificant (p-value higher than 0.05) and were consequently deleted from the diagram (Zahoor et al., 2017). Additionally, all obtained standardized regression weights of the factors indicate the insignificance of the factor "absorptive capacity" with a value below 0.25 ($R^2 = 0.056$). Therefore, this factor was excluded from the framework.

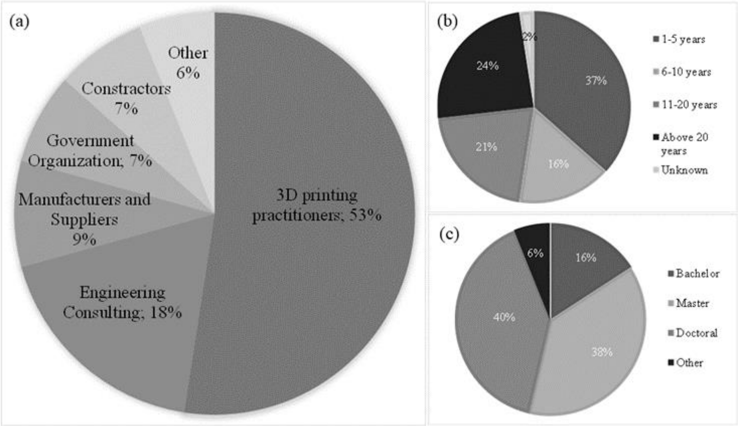

Fig. 4. Distribution of respondents by (a) primary area of practice; (b) years of construction industry experience and (c) education level

Table 3. Testing hypotheses

New numbers	Relationship	Path significance	Result/ Decision
H1	UC → EP	0.000	Supported ($p < 0.05$)
H2	UC → CX	0.007	Supported ($p < 0.05$)
H3	UC → CP	0.001	Supported ($p < 0.05$)
H4	EP → AC	0.150	Not supported
H5	AC → CX	0.008	Supported ($p < 0.05$)
H6	AC → RA	0.207	Not supported
H7	CX → RA	0.666	Not supported
H8	CX → CP	0.000	Supported ($p < 0.05$)
H9	CP → SS	0.000	Supported ($p < 0.05$)
H10	CP → TA	0.000	Supported ($p < 0.05$)
H11	TA → RA	0.011	Supported ($p < 0.05$)
H12	SS → RA	0.001	Supported ($p < 0.05$)
H13	SS → DS	0.000	Supported ($p < 0.05$)

5.3 Model Fit Indices

Following the removal of non-significant direct factor relationships and the exclusion of factor (AC), the conceptual framework was further analyzed using the Stata/SE 15® software package. However, even after the elimination of these factors, the conceptual reference framework did not achieve the desired goodness-of-fit (GOF) indices, as illustrated in Table 4. Thus, the model fit was improved by drawing correlations between variables F14 and F15, and F16 and F18. However, the acceptable GOF indices still were not reached by framework. Therefore, correlation among variables F23 and F27 under the different factors were detected and drawn at the second iteration. Variables F23 and F27 show correlation as they are same nature, both represent supply chain issues. Also, reducing the complexity of the supply-side (F23); demand-side, as a continuation of the chain, can provide a faster reaction to changing customer needs (F27). The conceptual reference framework then achieved the acceptable model fit indices with a statistically significant confidence interval (95%). All aforementioned iterations are summarized in Table 4, and the final conceptual reference framework of 3DP technology acceptance by construction professionals is depicted in Fig. 5.

5.4. Framework Validation

For validation of the finalized framework, interviews were conducted with six industry experts in C3DP. The responses to the form that was sent prior to the interview are summarized in Table 5, which indicates that some hypotheses were accepted unanimously (H8, H11, and H12). While some experts abstained from expressing their opinion regarding a few of the hypotheses, arguments supporting those same hypotheses were expressed during the interviews (H9 and H13). The remaining hypotheses, on which experts expressed opposing opinions, were discussed during the interviews.

Table 4. Iterations during SEM

GOF	Baseline model (after deletion of AC→RA, EP→AC, AC→RA, and factor AC)	Model It-1 Drawn correlations: (F14-F15, F16-F18)	Final SEM Drawn correlations: (F23-F27)	Recommended level	References
Chi/df	1.31	1.28	1.25	< 2.00	Byrne (2016)
P close	0.00	0.00	0.00	< 0.05	Awang (2012)
RMSEA	0.06	0.06	0.06	≤ 0.10	Durdyev et al. (2018)
CFI	0.87	0.90	0.90	≥ 0.90	Zahoor et al. (2017)
SRMR	0.09	0.09	0.08	≤ 0.08	Lei and Wu (2007)

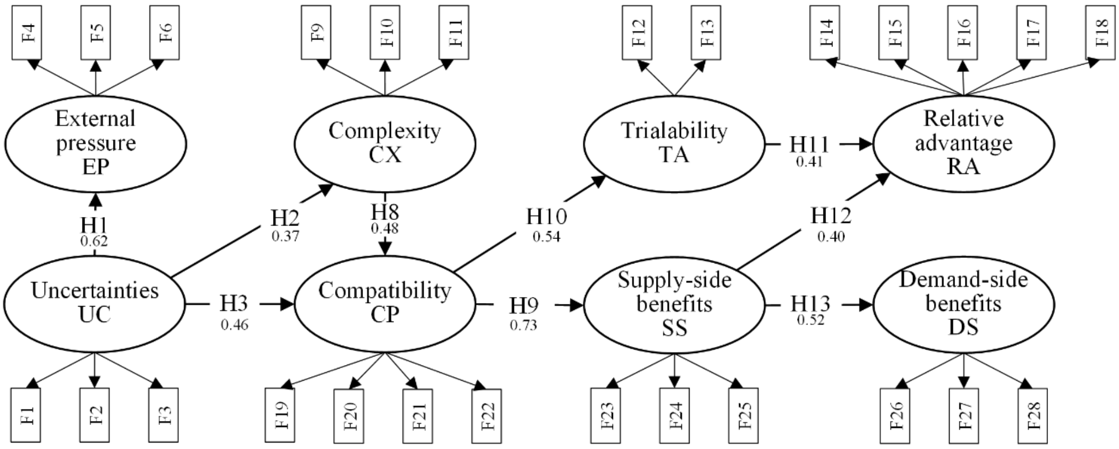

Fig. 5. Finalized conceptual reference framework

Interviewee C does not fully endorse the H1 assertion. He claims that C3DP is at a mature stage with little uncertainty, resulting in minimal external pressure from customers. This viewpoint is supported by the following statement: "3D concrete printing has rapidly developed in both academia and the construction industry over the past ten years. Many innovative construction companies specializing in 3D concrete printing have emerged worldwide in recent years, and concrete structures of different scales have already been successfully manufactured for practical application in different environments. In other words, 3D concrete printing has been gaining increasing popularity in the construction industry". The rest of the experts still held the opinion that "C3DP is a new technology without guidelines or conceptual proof. Although many professionals in the field support the technology's development, few want to risk its implementation at this stage. Building companies, architects, and clients require risk mitigation through standardized certifications of novel building products and processes".

Interviewees A and E did not perceive a connection between the factors 'uncertainties' and 'complexity'. Therefore, they expressed their disagreement with hypothesis H2. However, the rest of opinions supported this hypothesis by stating: "3D concrete printing is essentially a form-free printing process. Whether a concrete structure can be successfully printed or not depends on many factors, such as material properties in a fresh state, printing facilities and parameters, geometrical structure, and local environment. Hence, 3D concrete printing is a very complicated emerging technology, and research is still ongoing to improve its fulfillment in different applications".

Interviewees C and D did not support H3, stating that "the working environment of 3D concrete printing is a combination of a traditional construction site environment and automatic manufacturing (e.g., gantry and robotic arm systems). However, this kind of combination should not be considered a barrier to 3D concrete printing regarding its compatibility with the traditional construction site". Other experts countered that there are remaining questions about material compatibility, such as material properties and strength, which need more experimentation and validation.

Expert D believed that the intention to try new technology is not based on a desire for technology implementation for use in a specific project (H10), but on the opportunity to open entirely new business models with prospective growth for companies. However, the supportive statement for H10 says that "small-scale trial printing can be conducted for newly developed concrete materials to test the printing quality. If the printing goes well, then large-scale printing of practical structures can be conducted. People want to feel comfortable and ready before committing to large-scale projects".

In summary, the interview discussion made clear that there are still numerous questions about technology "uncertainties" deriving from the experts' personal experience. Disagreements on some of the hypotheses were resolved in favor of their approval that consequently proving the proposed conceptual framework of 3DP technology acceptance by construction professionals.

Table 5. Interview results for the framework validation

Interviewees	H1	H2	H3	H8	H9	H10	H11	H12	H13
A	Y	N	Y	Y	Abs.	Y	Y	Y	Y
B	Y	Y	Y	Y	Y	Y	Y	Y	Y
C	N	Y	N	Y	Y	Y	Y	Y	Y
D	Y	Y	N	Y	Abs.	N	Y	Y	Abs.
E	Y	N	Y	Y	Y	Y	Y	Y	Y
F	Y	Y	Y	Y	Y	Y	Y	Y	Y
Summary	5Y/1N	4Y/2N	4Y/2N	6Y	4Y/2Abs.	5Y/1N	6Y	6Y	5Y/1Abs.

Y ("yes") – a hypothesis is confirmed by expert; N ("no") – a hypothesis is not confirmed by expert; Abs. ("abstained") – expert abstains from answering

6. DISCUSSION

6.1. General Discussion on Factors

The finalized causal path diagram, as illustrated in Fig. 5, visually represents the interconnections among the factors that impact the acceptance of 3DP technology among construction professionals. Within the diagram, "uncertainties" emerges as the most crucial factor, as it serves as the catalyst for three direct relationships, two of which subsequently initiate chains of factors. It is not surprising that uncertainties arising from the lack of information about 3DP technology give rise to diverse and often conflicting beliefs (Jalonen, 2012), as well as various concerns related to the technological and economic benefits, resilience under different environmental conditions and high-stress scenarios, and potential technological side effects (Berman, 2012; Hoeffler, 2003). Huffman (2020) also suggests that uncertainty plays a central role in the context of innovation.

Furthermore, "compatibility" emerges as the most impacted factor, as it exhibits connections with four other factors. A smooth integration with existing systems and practices is essential for the successful implementation of 3DP technology in the construction industry. Therefore, 3DP technology should align with established work practices, previous experiences, and the dominant value system of construction stakeholders (Karahanna et al., 2006). Consequently, ensuring compatibility between 3DP technology and the conventional approach requires a reevaluation of the supply chain and the provision of project simulation (trialability), both of which should address the challenges posed by "uncertainty" and "complexity".

Both chains ultimately lead to the factor of "relative advantage", which represents the technical and economic benefits of implementing 3DP technology. Therefore, to quantitatively and qualitatively determine this factor, all previous aspects (factors in the chains) should be taken into account. Additionally, as illustrated by the framework, the decision to incorporate 3DP into a project relies on two intersections within the supply chain: one between a machine and materials vendor, and another between the company seeking to acquire the necessary tools for 3D printing products (Mellor et al., 2014). Most relationships exhibit "strong" ($x \geq 0.6$) and "moderate" ($0.6 < x \leq 0.4$) causal links, emphasizing a strong causal effect among the factors and the framework configuration.

Hypothesis 4 "external pressure has a significant effect on the absorptive capacity" and hypothesis 5 "absorptive capacity has a significant effect on perceived relative advantages" are not supported. Moreover, factor "absorptive capacity" (AC) shows very low standardized regression weights, which caused its exclusion from the framework. The concept of "absorptive capacity" represents the organization's capability to perceive, integrate, and utilize the value of new information for commercial purposes. In established markets, where knowledge generation and dissemination are high, absorptive capacity is vital for organizations to remain competitive and adapt to shifts in their environments. However, when integrating new technologies, 3DP companies and their collaborators become the originators and sources of new knowledge. In essence, 3DP technology is driven by these companies rather than existing market demands, aligning with the technology-push model of adoption (Baumers et al., 2016). In the technology-push argument, innovation is driven by 3DP organizations, stimulating technological development and integration (Chidamber and Kon, 1994). This idea was supported during an interview with 3D printing industry experts, as documented in a publication by Spicek et al.

(2023). The authors describe the creation of large, cross-functional teams from various companies and universities. These teams collaborated to execute 3DP projects and contribute to the 3DP knowledge database. Hypothesis 7 'CX → RA' is also not supported. Even though direct connections between factors "complexity" (CX) and "relative advantage" (RA) have been described in the literature, but the results of the current study establish their linkage through other factors. The factor "complexity" initiates the factors "relative advantage" through "complexity" and "trialability". Thus, those factor relationships exist, but indirectly.

6.2. An Applicable Case Study

This section illustrates how the proposed framework can be employed to assess the acceptance of 3DP technology in a specific construction project. For this purpose, the case study of a 3D-printed residential building in Beckum, Germany, has been selected. The integration of 3DP technology in residential construction in Germany is motivated by a shortage of skilled workers. Furthermore, compared to traditional methods, the automation of construction through 3DP technology can address various challenges by enabling the construction of more sustainable, cost-effective, and functional structures with increased design freedom, such as the integration of electrical lines. The aforementioned project is the result of collaboration among Peri, COBOD, Michael Rupp Bauunternehmung GmbH, Architekturbüro Mühlich, HeidelbergCement, Fink & Partner BDA, Schießl Gehlen Sodeikat, m-tec mathis technik gmbh and the University of Munich Technischen (PERI, 2020). The residential building consists of five flats spread across three floors, offering approximately 160 m² of living area.

To demonstrate the framework, a three-step data collection approach was employed, utilizing a triangulation of evidentiary sources from three interconnected methods in order to gather a comprehensive dataset (Yin, 1994). The first step involved conducting a thorough search and study of relevant documents and articles pertaining to the case studies, obtained from reliable open sources. The sources of data collection were diverse, including official websites, published reports, previous studies, and online platforms. This information served as the foundation for the subsequent steps. In the second step, a survey form was developed specifically for operational-level employees, consisting of technical questions aimed at acquiring project-related data and technical details. Some questions related to technology were excluded if the information was already available from reliable sources or formulated in a way to validate published data. For instance, specifications of 3D printers could be found on relevant company websites. The survey form encompassed three sections: (1) general project background, including inquiries about project location, size, certification, participating parties, their roles, and locations; (2) questions pertaining to the 3DP process, such as printing time, material quantity per structure, number of workers involved, etc.; and (3) cost-related questions. After receiving completed survey forms, interviews were finally conducted with high-level management personnel. The purpose of these interviews was to address any missing answers and gain a deeper understanding of the 3DP construction process. Each factor was evaluated quantitatively or qualitatively, enabling final conclusions to be drawn regarding project implementation decisions. A summary of the findings can be found in Appendix A (Table A1, columns 1, 3, and 4).

This case demonstrates the potential and applicability of the proposed framework. During the interview, the organization's representative expressed no uncertainty towards the 3DP implementation. On the contrary, they were motivated to implement the technology due to the scarcity of skilled workers and the opportunity for integrating innovative features. This motivation positively influences the external pressure (H1), reflecting progress in the construction industry and the company specifically. However, it's important to note that technology can also serve as a marketing tool to attract more attention to the organization and its products and services.

Given the lack of 'uncertainties' to consider, the 'complexity' was assessed positively (H2). 'Complexity' was evaluated with respect to the computer-generated design process and the management of the digital construction process. Despite high technological proficiency among employees, significant resources were spent on R&D, according to calculations (Table A3). Compared to traditional construction, the R&D for the 3DP project is 19 times greater, indicating that further research on 3DP technology is needed to provide unique solutions to challenges during project implementation. Also, the factor 'uncertainty' should be properly assessed to address different aspects in detail. Once the technology reaches a certain level of maturity, less research effort will be needed, as printers can be purchased for long-term use without requiring significant improvements for each project. Additionally, a library of housing projects with detailed specifications can be created, allowing for project selection, downloading, and printing as needed.

The concepts of 'compatibility' and 'trialability' (H3, H10) were positively evaluated because the project used familiar materials like concrete in 3D-printed structures, which passed all required testing. The Beckum office issued a building permit for the project, demonstrating that it met all necessary criteria.

After assessing the 'compatibility' of the technology, it is essential to evaluate the supply chain, as 3DP materials and equipment may require specialized sourcing. To assess the "supply-side benefits" (H9), the logistics cost of a 3DP project was compared to traditional methods. A detailed logistic cost analysis model, developed by Besklubova et al. (2023), was validated through the same case study. Consequently, the main results from the analysis were borrowed. The results did not demonstrate the feasibility of the 3DP project primarily due to long distances. The materials and equipment cannot be sourced from the nearest conventional suppliers, posing a challenge. However, the sensitivity analysis revealed the potential of 3DP in terms of transportation cost. The transportation cost varies based on factors such as the geographical location of the project and the location of material production plants and should be considered in the final decision. The 3D printing project team should determine the sources for materials and 3D printing equipment to enhance the project's feasibility, as these factors account for a significant portion of the cost.

Based on the logistics evaluation, further calculations can be conducted to assess the applicability of the "relative advantages" (H11). The analysis reveals significant savings in manpower costs, with more than double the savings in favor of the 3D printing (Table A3). Additionally, notable reductions in material waste can be achieved due to the precise placement of printing mortar, design flexibility, feasibility in challenging and hostile environments, and improved safety measures. However, it should be noted that the demand-side benefits are not applicable to this particular case study. The project was initiated and funded by the company, rather than being driven by customer demand.

7. CONCLUSIONS

This paper enhances the existing body of knowledge by examining the interrelationship among factors influencing C3DP technology adoption, as perceived by global experts in 3DP. To this end, thirteen hypotheses were presented that explain the relationships between nine factors, which are combined in a conceptual reference framework. In order to quantify and verify this initial framework, questionnaire survey responses from 3DP industry experts around the world are analyzed by using the SEM technique, which helped to test the hypotheses and model-fit indices followed by interviews with 3DP experts for result validation.

The findings indicate that the factor “absorptive capacity” (AC) is excluded from the conceptual framework, which explains the market situation where 3DP technology is driven by organizations rather than by expressed market needs. The effectiveness of utilizing new information for commercial purposes by an organization is dependent on the company's internal assessment processes. The factor “uncertainties” appears to be the most critical factor at this stage of technology development, which can be explained by the information gap about 3DP technology, which in its turn raises different and often conflicting customer beliefs. The case study serves as evidence for the practicality of the finalized conceptual framework. Data for the case study is collected through interviews with organizations that developed and executed 3DP residential building. Based on the case study analysis, the potential of 3DP technology is promising. However, it is important to highlight the major challenges that need to be addressed. Overcoming these challenges is crucial to make a 3DP project feasible compared to traditional construction methods.

Based on the findings presented in this study, both academic and industry stakeholders have gained a thorough comprehension of the interrelationships among factors influencing the 3DP technology adoption. The proposed framework can serve the following purposes:

1) It can provide a decision-making guideline or feasibility assessment tool for industry practitioners, particularly construction companies, who are considering the introduction of 3DP technology to a specific project.
2) The framework can act as a controlling mechanism by treating each factor, whether initiating or consequent, as a checkpoint. This allows for the identification and prevention of factors that may negatively impact the adoption of 3DP technology.
3) Current and future 3DP project managers can utilize the identified essential factor relationships to develop strategies and proactive measures for the adoption of 3DP technology in specific projects and within the construction industry as a whole.
4) Furthermore, researchers can benefit from the stepwise methodology employed in this study. They can use it as a guide to create similar factor models for other specific technology solutions, thereby expanding knowledge and understanding in the field.

Nevertheless, the results of this work have some limitations. Firstly, a small sample data size of 82 responses is considered for mathematical proof of the proposed framework, which can be explained by the limited number of organizations working on 3DP projects that can participate in the questionnaire survey. Once the 3DP technology gets wide acceptance, further factors and framework investigations should be based on larger sample size. Secondly, the finalized framework's applicability to different scales of 3D printed projects needs to be widely verified.

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DATA AVAILABILITY STATEMENT

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

SUPPLEMENTAL MATERIALS

Appendix A

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Appendix A.

Table A1. Factor reassessment and interview summary

Parameters	Factor reassessment	Factor assessment	Decision
1	2	3	4
Objectives to be satisfied	-	The integration of 3DP technology into residential building construction in Germany is driven by a scarcity of skilled workers.	-
Envisioned work improvement	-	Construction automation, in comparison to traditional methods, can effectively tackle the aforementioned issues by constructing structures that are more sustainable, cost-effective, and functional. It also offers greater design freedom, allowing for innovative features such as the integration of electrical lines within the structure.	-
Proposal for 3DP application			
Uncertainty	The assessment can be conducted by comparing the capabilities of traditional construction methods with those of 3DP for specific task execution.	In contrast to traditional construction methods, the realization of 3D printed projects is driven by the goal of simplifying the construction process, while simultaneously creating more sustainable and cost-effective buildings with the use of free-form materials. The aim is to enhance the functionality of structures. Currently, there have been no identifiable negative effects that hinder the implementation of 3DP technology. Furthermore, innovation has a positive impact on the image of the construction industry, making it more enticing for skilled workers. It is the responsibility of 3DP organizations to conduct thorough testing to ensure that 3D printed structures are resilient to environmental influences. The concrete used in 3DP is a well-understood and predictable material.	This is an argument in support of 3DP selection.
External pressure	The examination can be conducted by comparing the current stage of existing technology with that of 3DP technology, specifically by comparing the capabilities of existing robotic systems with those of 3DP technology	The scarcity of skilled workers and resources in Germany has necessitated the adoption of automated construction methods, which is precisely what 3DP technology offers. As a result, alternative technologies like modular integrated construction have not been considered, as they do not provide the same level of fully automated construction. It is the responsibility of construction organizations to address any skepticism from customers by showcasing the capabilities of this innovative new technology.	This is an argument in support of 3DP selection.
Supply-side benefits	Represented through the description of the project's geographical location, which is correlated to (a) logistic costs and (b) environmental working conditions.	(a) A decrease in material transportation was observed, but the transportation of the printer itself poses a challenge due to its significant size. (b) There are no adverse environmental conditions that need to be taken into account.	This factor is not applicable to the considered project.

Parameters	Factor reassessment	Factor assessment	Decision
1	2	3	4
Demand-side benefits	Represented through the description of 3DP technology influence on its customer.	The existing customer demands for faster, more cost-effective, and environmentally sustainable construction serve as compelling reasons to consider the adoption of 3DP technology. This technology offers incomparable design freedom and comprehensiveness that traditional construction methods cannot match. Conventional customization in construction often comes with added expenses, which the market strives to minimize. Consequently, the implementation of 3DP provides customers with the opportunity to have uniquely tailored homes, catering to a niche that holds potential for future development.	This is an argument in support of 3DP selection.
Complexity	Can be represented by a 3D printing process feasibility assessment, extending from a computer-generated design to realization on the construction site	The process of computer-generated design, maintenance of the 3D printer, and management of the digital construction process all require relatively minimal effort. The project architects are familiar with working with 3D models, making the implementation process relatively straightforward. As this project utilized the most advanced and efficient generation of 3D printers, there were no unforeseen incidents that caused delays in the printing execution.	This is an argument in support of 3DP selection.
Compatibility	Can be represented by a 3D printer system configuration selection for specific task execution and technology suitability for integration into the conventional construction process (e.g., material suitability, site environment).	The utilization of the gantry printer BOD2 clearly demonstrates the project's adaptability in printing components of various sizes to meet the diverse needs of the construction industry. Being a modular machinery, this type of printer does not impose any limitations on component length. The dimensions of the printed components in this project were as follows: height - 9m, length - 16m, and width - 11m. The implemented 3D printer, BOD2, requires a relatively small amount of space, approximately 2 meters, around the printed building. The 3D printed material, which is predominantly concrete, exhibits comparable properties to its traditional construction counterpart. Deviations in the printed structure from the intended design are less than 10mm, meeting the tolerances typically expected in conventional building practices.	This is an argument in support of 3DP selection.
Trialability	Introduces a simulation of a 3D printer system encompassing the following aspects: (a) Projected hardware performance; (b) Digital development, involving The design of an optimal printing path, accurate determination of build direction, orientation, and positioning, and control of deposition flow rate to ensure a	(a) The initial generations of 3D printers encountered certain issues that necessitated improvements. However, the next-generation 3D printer chosen for this project exhibited significantly enhanced performance and operated smoothly, without encountering significant problems such as broken seals. (b) The project architects' familiarity with 3D models facilitates a relatively smooth implementation process. (c) A BOD2 gantry printer with the following features was implemented: Max printing length has no limit; Max printing width is 14.6 m;	This is an argument in support of 3DP selection.

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Parameters	Factor reassessment	Factor assessment	Decision
1	2	3	4
	continuous flow of concrete throughout the printing process. (c) Features of the 3D printer, such as its degrees of freedom, printing area, vertical access reach, movement capabilities, power requirements, speed, and other relevant specifications. (d) Material properties, including considerations of extrudability, flowability/ductility, bearing capacity, adherence between adjacent layers, setting time, and other relevant characteristics.	Max printing height is 8.1 m (plus the height of the concrete feet onto which the printer is mounted); Max printing speed is 1 meter/s (1 square meter of a double-skin wall in under five minutes); Max aggregate size is 10mm; Power supply is 32 A, 400 V, 3 phase. (d) No significant concerns were identified regarding material properties. However, expertise is necessary to properly adjust the material properties, particularly when dealing with varying environmental conditions. Structural tests, including static analysis, stability assessments, and vibration analysis, were conducted in a controlled laboratory setting.	
Relative advantage	Can be represented by showing: (a) 3DP technology implementation technical benefits; and (b) 3DP technology implementation economic benefits.	Technical benefits: – Notable reduction in material waste: Precise placement of the printing mortar allows for a decrease in material usage for walls, compared to other large-scale wall construction methods. – Design freedom can be achieved, albeit at an additional cost during this stage of technology development. Nevertheless, the extra cost is significantly lower compared to conventional construction. – Feasibility in challenging and hostile environments: Previous 3D printed projects have demonstrated successful performance in snowy conditions, deserts, and other harsh environments. -Continuous machinery development is necessary to enhance safety measures, such as automated detection of hazards and real-time response. However, the current project execution observed a relatively clean construction site, contributing to overall safety. A clean construction site is synonymous with a safe construction site. Additionally, as the construction progress was primarily monitored remotely through computers, there were fewer workers present on the site. Economic benefits: For the purpose of representing economic benefits, the relevant calculations have been	This is an argument in support of 3DP selection. However, the strategy should be provided to reduce R&D costs for the 3DP project.

Parameters	Factor reassessment	Factor assessment	Decision
1	2	3	4
		done only for the wall structures as other parts (e.g., roof) were built in a conventional way (see Table A2 and A3). The results were calculated by: (a) accounting for 3M: manpower, material, and machinery (variable T3M in Table A3), and (2) accounting for 3M by adding project preparation expenses (variable TT in Table A3). The roles of 3DP project personnel in R&D and Architecture, Construction and Engineering (ACE) are merged and considered as the same personnel for calculation as these involved parties were required to take non-standard approaches for new technology integration. However, only ACE roles were considered for traditional project computing.	

Table A2. Data for the comparison of the 3DP case study with equivalent traditional construction

Parameter	Code	3DP	Traditional construction	Data source
Manpower for R&D including ACE (people)	RD	5	-	From the interview
Average salary for R&D in Germany (Euro/month)	SL1	6 700	-	SalaryExpert (2022a)
Project preparation period (months)	PP	10	2	Ozdemir (2021)
Manpower at design stage (people)	DS	Included in R&D	2	From the interview
Architect's salary in Germany (Euro/month)	SL2	-	4 500	SalaryExpert (2022b)
Labor required to execute construction process (workers)	WR	4	5	Interview, COBOD (2020) and Ozdemir (2021)
Labor cost per day (Euros / day)	SL3	55	55	From the interview
Time required for each operation (days)	OT	24	171	From the interview and ApisCor (2017)
Amount of material per structure (tonnes)	MA	160,0	176,0	From the interview and Bekr (2014)
Cost of one tonne of material (Euro/tonne)	MC	93,6	93,6	COBOD (2020)
3D printer cost (Euro)	EC	500 000	-	From the interview
Equipment rental cost for traditional construction (Euro/day)	REC	-	-	

Table A3. Calculations for the comparison of the 3DP case study with equivalent traditional construction

Parameter	Code	3DP	Traditional construction	Equation
Total labor cost for the wall construction	TLC	5 280	47 025	$\mathrm{TCL} = \mathrm{OT} \times \mathrm{SL3} \times \mathrm{WR}$
Total material cost	TMC	14 976	18 000	$\mathrm{TMC} = \mathrm{MC} \times \mathrm{MA}$
Total equipment cost	TEC	2 400	-	For 3Dprinting: $\mathrm{TEC} = (\mathrm{EC}/\mathrm{EL}) \times \mathrm{OT}$, EL - Life of equipment (8 years) In conventional construction, only hand tools were used.
Total (manpower, material, machinery – 3M) cost (Euro)	T3M	22 656	48 825	$\mathrm{T3M} = \mathrm{TLC} + \mathrm{TMC} + \mathrm{TEC}$
Total transportation cost	TC	78 639	23 507	Detailed calculation provided in (Besklubova et al., 2023)
Project preparation expenses (ACE) (Euro)	PPE	335 000	17 867	For 3Dprinting: $\mathrm{PPE} = \mathrm{SL1} \times \mathrm{PP} \times \mathrm{RD}$ For conventional construction: $\mathrm{PPE} = \mathrm{SL2} \times \mathrm{PP} \times \mathrm{DS}$
Total cost (Euro)	TT	436 295	90 199	$\mathrm{TT} = \mathrm{T3M} + \mathrm{PPE}$