# ABSTRACT

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| Title of thesis | SUCCESS FACTORS FOR 3D PRINTING TECHNOLOGY ADOPTION IN CONSTRUCTION |
| | Pankhuri Pimpley, Master of Science |
| Thesis directed by | Professor Miroslaw J. Skibniewski |
| | Department of Civil and Environmental Engineering |

3D printing or Additive Manufacturing (AM) technology is taking small, slow steps in the construction industry. It is dominantly used for prototyping purposes, and even with the several benefits it can bring to building technology, it is not being adopted on the desired scale. Several inter-organizational and intra-organizational factors play a critical role in determining the extent of 3D printing technology adoption in construction. This dissertation uses various technology innovation theories and studies to identify factors which might affect the 3D printing technology adoption in construction. The research investigates these elements from different stakeholder's perspective and categorizes and analyzes them. The approach includes elaborate literature review, correspondence with professionals, and case studies. The success factors are assessed based on questionnaire responses from organizations and personnel who are interested in or are working with construction 3D printing. This research will help in understanding the implementation of the 3D printing technology in construction and provide a framework to guide efforts in the direction of technology adoption into the construction practice.

# SUCCESS FACTORS FOR 3D PRINTING TECHNOLOGY ADOPTION IN CONSTRUCTION

by

Pankhuri Pimpley

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science
2019

Advisory Committee:
Professor Miroslaw J. Skibniewski, Chair
Professor Qingbin Cui
Professor Gregory B. Baecher

# Acknowledgement

I express my heartfelt gratitude to my advisor Professor Miroslaw J. Skibniewski, for introducing me to the world of innovative construction technology research and the e-Construction Group. His guidance in my academics and invaluable advice on my research have aided me throughout my graduate degree and made me a better student, researcher and individual. I would also like to thank Svetlana Besklubova for being my unofficial guide, for her experience and counsel on research methodologies and support for my thesis work.

I would also thank the e-Construction Group for the discussions, thoughts and suggestions over the numerous research meetings over the past year. They have been a source of constant learning and enthusiasm for me.

I extend my deepest gratitude to Professor Qingbin Cui and Professor Gregory Baecher for taking the time to serve on my thesis defense committee and for their valuable feedback and comments on my work.

To my family, thank you for constantly encouraging me from across the globe and inspiring me to pursue all my goals, big and small. To my friends for the numerous coffees and long group study sessions. This journey would not have been possible without the support I was blessed with for the last two years.

# Table of contents

# List of Tables

## List of Figures

# List of Abbreviations

3D – 3 Dimensional
3DP – 3D Printing
AM – Additive Manufacturing
SM – Subtractive Manufacturing
RP – Rapid Prototyping
2D – 2 Dimensional
UV – Ultraviolet
USA – United States of America
UAE – United Arab Emirates
UK – United Kingdom
IDT – Innovation Diffusion Theory
TR – Technology Readiness
TAM – Technology Acceptance Model
CT – Contingency Theory
AC – Absorptive Capacity
RA – Relative Advantage
CX – Complexity
TR – Trialability
CP – Compatibility
AC – Absorptive Capacity
EP – External Pressure
UC – Uncertainty
SB – Supply-side Benefits
DB – Demand-side Benefits
CC – Contour Crafting
CVR – Content Validity Ratio
R&D – Research and Development
CNBR – Co-operative Network of Building Researchers

ASCE – American Society of Civil Engineers

GRG – Special glass fiber reinforced gypsum board

SRC – Special glass fiber reinforced cement

FRP – Special glass fiber composite material

CAD – Computer Aided Design

CEO – Chief Executive Officer

USC – University of Southern California

FDM – Fused Deposition Modeling

NASA – National Aeronautics and Space Administration

SSS – Selective Separation Sintering

# 1. Introduction

3D printing technology was introduced to the world in the 1980s with the development of 3D printing equipment and material. Also known as Additive Manufacturing (AM), it is the process of creation of products by layer-by-layer formulation and joining of material from the design model. The traditional approach to manufacturing is material removal, or Subtractive Manufacturing (SM). Over the years, AM has found widespread potential in diversified industries such as manufacturing, medical, industrial, socio-cultural sectors and even food and clothing. In spite of being the one of the largest industry sectors in the world, the construction industry merely begun research and development in the direction of 3D Printing (3DP) in 1995. Initially the use of 3DP started for functional or conceptual prototyping in construction (Santos et al., 2006). Hence 3D printing has also come to be known as Rapid Prototyping (RP). The technology is now taking steps in partial printing or printing small components of a building unit, or decorative units of a structure, but RP remains the dominant application for construction (Mellor, Hao, & Zhang, 2014).

## 1.1. History of construction 3D printing

3DP was traditionally introduced to the market as a Rapid Prototyping (RP) technology in the mid-1980s. The first 3D printer was invented by Charles Hull in 1986. Over the years RP found various applications in the manufacturing, automobile, bioengineering, aerospace, food processing and industrial sectors. As technology expanded, attempts were made to use RP for construction-related printing. Construction industry slowly moved on to printing complex ceramic and concrete components, plastic and nylon fixtures and fittings, among other small-scale building elements. The first attempt of cement based 3DP was made in 1997 (Agenda, 2017). During the 2000s, 3D printing was adopted to print architectural models. Over the next decade, with the advancement of technology, construction 3DP made its way into printing of entire small-scale buildings. Vigorous R&D efforts are now being made into large-scale building printing, reducing printing time for structural components and increasing the print accuracy (Wu, Wang, & Wang, 2016).

## 1.2. Printing technology

Five technologies have been commonly used for 3D printing in construction. Stereolithography uses laser to harden liquid polymer and resins and a perforated platform to form and place the multiple layers. Fused-deposition modeling is the process where the printing head is fed with elastomer, wax or metal and the head forms the multiple layers. A similar method of printing head deposition is Inkjet powder printing, which used powdered form of deposited material, polymer or metal. The product obtained is then oven-dried. Selective laser/heating sintering also uses powdered printing material, mostly nylon based, rapid steel or sand form, and each layer is consolidated using a laser beam. Contour crafting technology uses a computer-operated gantry system and a nozzle to deposit ceramic or concrete material (Wu et al., 2016).

## 1.3. Printing process

Similar to general 3D printing, for construction 3DP a digital model of the 3D component is first designed. An algorithm converts the 3D design into 2D slices.

The printer then prints each slice, depositing the material to form the 3D component (Labonnote, Rønnquist, Manum, & Rüther, 2016).

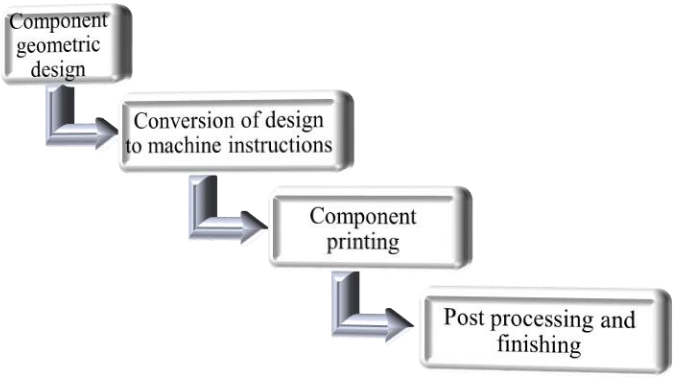


*Figure 1. General 3D printing process (S. Lim et al., 2012)*

3D modeling tools and software are used to develop the construction model. These tools allow the flexibility to design with high precision. Digital modeling allows processing of geometrical as well as material data. (Wu et al., 2016)

*Figure 2. 3DP frame of concrete printing system (Sungwoo Lim et al., 2018)*

## 1.4. Need for 3D printing technology in construction

One of the major evolutions in major industries like manufacturing, medicine, automobile, etc., has been automation. Construction, being one of the largest industries in the world has not been able to fully adopt automation in practice. It is the only job still being done by hand. The construction industry has been slow in adopting new methods and innovations due to deep confidence in the efficiency of traditional processes, materials and codes. Since no change or innovation proposes growth of the sector, the construction industry has one of the lowest productivity-increase compared to other industries. It is even more important to automate construction activities given the risks associated with it. About 400,000 people are injured or killed every year in the USA during construction. These injuries and fatalities eventually translate to costs for society. Construction is also prone to corruption and political feuds. Hence the primary need for 3DP in construction is to reduce or eliminate human involvement in the design and development of the structure. It is also important that 3D printing be considered a standard construction practice by code bodies. Accepting the innovation can help set a common standard for global construction and solve the problem of labor skill variation from demographics and experience. Conventional means of construction being subtractive in nature also generate a lot of construction waste. 3D printing could be an effective way to reduce waste and make construction sustainable and environmentally friendly. Automation can help achieve more precision, design flexibility and complexity of construction. 3D printing is a rapid form of construction and can thus help reduce overall construction time and wait time, eventually reducing construction cost. 3D printing also eliminates the need for temporary formwork on site.

## 1.5. State of practice review

As of 2017 the construction 3D printing market is worth $.07 billion and according to SmarTech Publishing it is expected to produce global revenue of $40 billion in 2027 (Jamie, D., "3D printing: The Future of Construction", January 31st 2018).

Since early 2000s, several construction companies, manufacturing plants, start-ups, research institutions and universities have taken keen steps to implement innovative 3D printing technology. (Laubier R., Wunder M., Witthoft S., Rothballer C., "Will 3D Printing Remodel the Construction Industry?", January 23rd 2018).

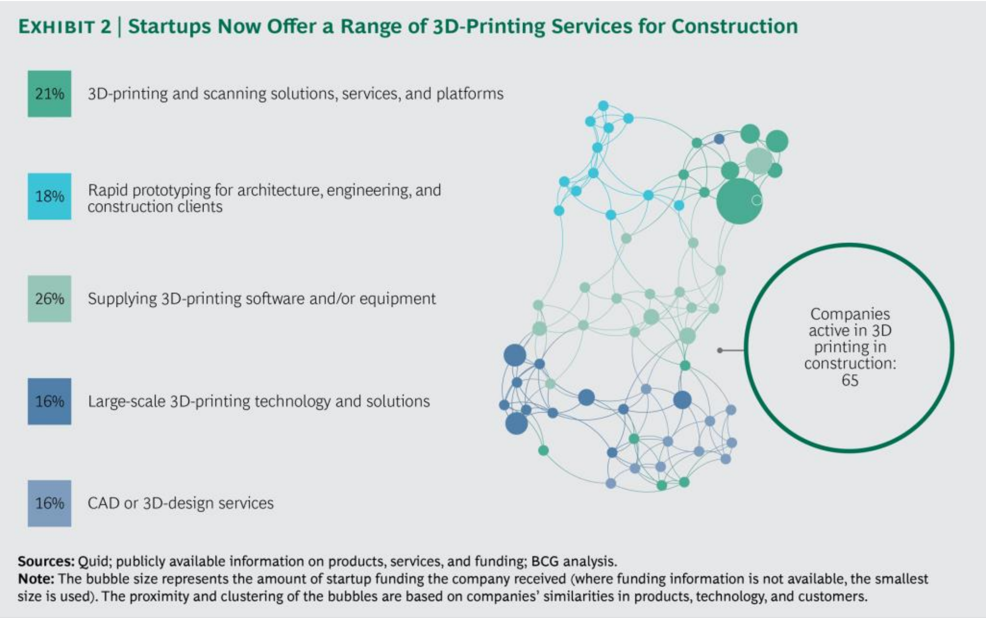


EXHIBIT 2 | Startups Now Offer a Range of 3D-Printing Services for Construction

**Sources:** Quid; publicly available information on products, services, and funding; BCG analysis.
**Note:** The bubble size represents the amount of startup funding the company received (where funding information is not available, the smallest size is used). The proximity and clustering of the bubbles are based on companies' similarities in products, technology, and customers.

*Figure 3. Startups offering range of 3DP services*

Constructions-3D, a French company invented a polar 3D printer which can print from inside the construction unit and once finished can leave through the building's front door. Cazza Construction developed a similar robot, with a mobile crane system which makes printing of higher structures on larger areas, and even whole houses possible. BatiPrint 3D developed a robot to print three layers at once, the middle layer of concrete and inner and outer layers of polymeric foam for insulation (Jamie, D., “3D printing: The Future of Construction”, January 31st 2018).

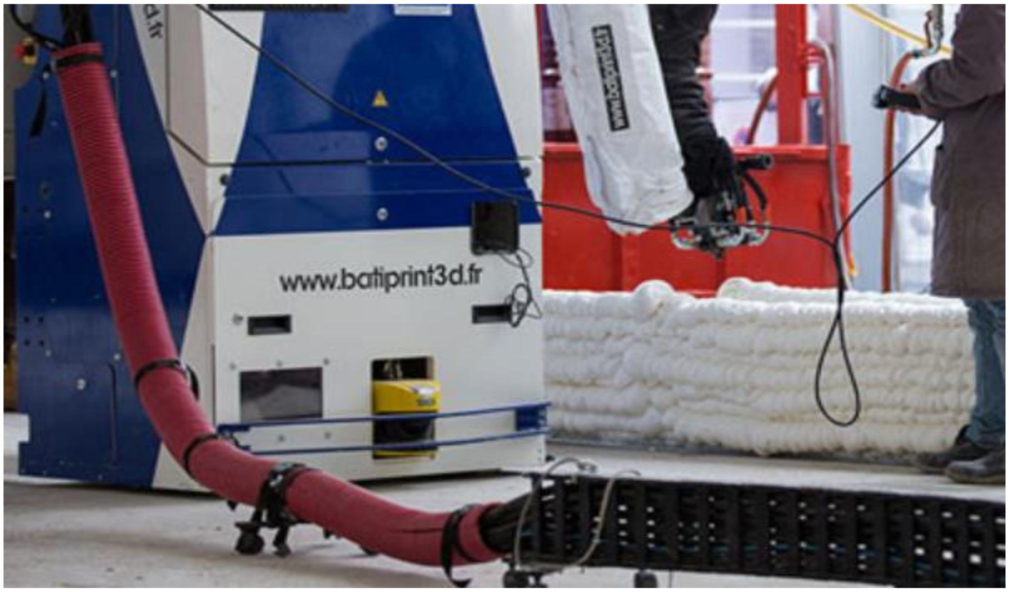


*Figure 4. Batiprint 3D’s invented machine (Jamie, D., “3D printing: The Future of Construction”, January 31st 2018).*

Moscow based Apis Cor built the world’s first 3D printed residential house within 24 hours on site. They use the mobile printer which takes 30 minutes to install. The machine can operate at temperatures as low as -35 degree Celsius. The construction saves 70% compared to conventional methods and claims to last for 175 years in the snow prone area (“Thanks to 3D printing, you can now build a home in just 24 hours”, 2018, February 09).

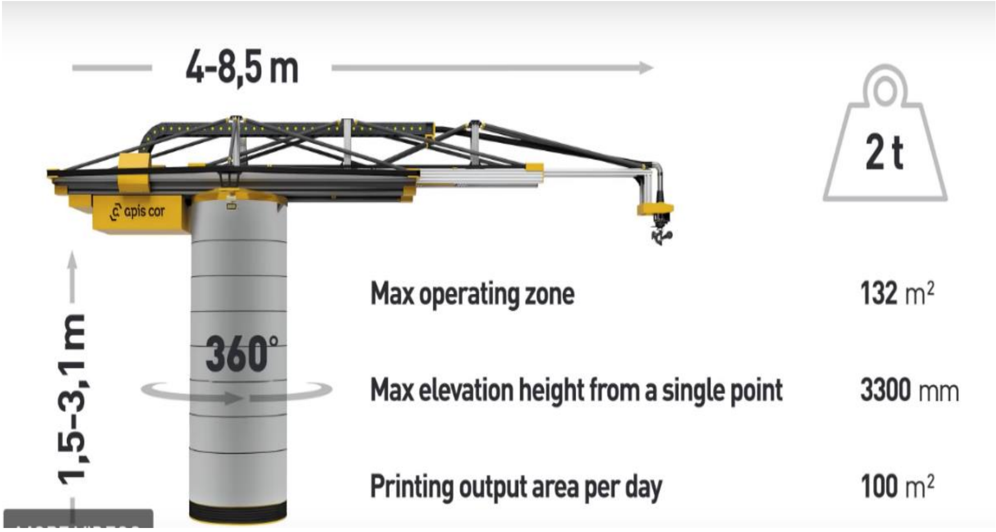


*Figure 5. Apis Cor's 3D printer design and configuration ("Thanks to 3D printing, you can now build a home in just 24 hours", 2018, February 09).*

*Figure 6. Apis Cor's 3D printed building ("Thanks to 3D printing, you can now build a home in just 24 hours", 2018, February 09).*

Italian architect Enrico Dini invented the 'D-shape' printer which relies on a unique binding powder poured onto layers of sand through a print head to harden them. (Jamie, D., "3D printing: The Future of Construction", January 31st 2018).

*Figure 7. D-shape's printer (Jamie, D., "3D printing: The Future of Construction", January 31st 2018).*

Branch Technology, a startup based in Tennessee directed their research towards printing materials and developed a process to print free-form polymer matrices which can be filled with cement or foam (Laubier R., Wunder M., Witthoft S., Rothballer C., "Will 3D Printing Remodel the Construction Industry?", January 23rd 2018).

Icon 3D based in Austin, USA aims to print complete homes in a day as well. They intend to print for under $4,000 using Vulcan construction's 3D printer ("3D Printed Homes – 4 Most Fascinating Projects in 2019", 2019, February 20).

*Figure 8. Icon's printed homes ("3D Printed Homes – 4 Most Fascinating Projects in 2019", 2019, February 20).*

The project by Eindhoven University of Technology in Netherlands plans to print five single story, two-bedroom residences ("3D Printed Homes – 4 Most Fascinating Projects in 2019", 2019, February 20).

*Figure 9. Eindhoven's proposed home design ("3D Printed Homes – 4 Most Fascinating Projects in 2019", 2019, February 20).*

As far as the policies and subsidies are concerned, steps have been taken to encourage 3D printing adoption in construction. The UAE government is aiming to 3D print 25% of its new buildings by 2030 in the Middle East. The UK government has initiated a National Strategy for Additive Manufacturing predicting construction 3DP, creating several new jobs and contributing more than $1 billion to annual GDP by the year 2025. The USA Department of Defense aims to study the idea of using local material to 3D print its military barracks worldwide (Laubier R., Wunder M., Witthoft S., Rothballer C., "Will 3D Printing Remodel the Construction Industry?", January 23rd 2018).

## 1.6. Purpose of the research

3D printing provides innovative, customizable, sustainable, low volume and economical solutions to the construction industry. With the current trends and needs, buildings and structures need more flexibility in design and construction while being economical at the same time (Mellor et al., 2014). Through this research, the socio-economic factors which might affect the scope of 3D printing in construction will be explored and analyzed. Assessing them will help professionals and researchers develop productive ways of utilizing and managing the technology in the future, thus expediting the adoption process.

## 1.7. Framework of the thesis

This introductory chapter is followed by the following sections in this dissertation:

**Chapter 2 Literature review:** The thesis begins with a brief literature review of the proposed factors and the various innovation and technology adaptation theories and concepts they have been derived from.

**Chapter 3 Proposed factors and measurement items for 3D printing adoption in construction:** Nine (9) factors and forty-two (42) measurement items which might affect the 3D printing technology adoption are proposed and discussed, while considering the current and future prospects of construction 3DP. This is the first phase of the research.

**Chapter 4 Research methodology of the thesis:** The second phase of the research elucidates the design and dissemination of the survey questionnaire. The third phase of the study is data collection through the aforementioned questionnaire, personal interview and case study selection.

**Chapter 5 Data analysis:** The fourth phase of the research involves respondent analysis, response analysis by content validity ratio to quantitatively study the data recorded, derivations and comparison of non-USA and USA responses.

**Chapter 6 Case studies:** The quantitative analysis is followed by a qualitative analysis of the factors with three case studies.

**Chapter 7 Results and discussion:** Results obtained and the possible reasons for the observations are discussed.

**Chapter 8 Conclusion and future work:** Contribution of the research and future possibilities are discussed.

# 2. Literature Review

## 2.1. Relative advantage

Relative advantage is one of the major predictors of adaptation which reflects user-attitude about the innovation. It is derived from the characteristics of **Innovation Diffusion Theory (IDT).** Diffusion can be defined as the communication of a new, innovative idea within a social system via certain channels, over a period of time (Everett, 1983). Innovation diffusion theory suggests that there exists a gap in time between the introduction of an innovation and its successful implementation in the industry. This gap is often several years. With this long gap, the innovation needs to reach a critical mass before being able to self-sustain. Therefore, innovation diffusion is considered to be primarily a social, rather than a technical process, since the innovation's reach largely depends on the client orientation of its diffusion channels (Everett, 1983). An idea can be perceived better than the conventional methods not just economically, but also socially (Everett, 1983).

Variables with similar meanings were found in Technology Acceptance Model (TAM) and Technology Readiness (TR) theory (Walczuch, Lemmink, & Streukens, 2007). The **Technology Acceptance Model's** characteristic ‘‘perceived usefulness’’ defines the prospective user's chances of using the innovation to increase job performance within his/her organization (Walczuch et al., 2007). This is the degree to which the user of the technology understands that using the innovation would enhance his or her job performance. **Technology Readiness (TR)** is displayed in the consumer's desire to adopt and use a new technology in order to achieve his/her daily/business goals (Parasuraman, A. 2000). It is a measure of the positive or negative feeling/emotion towards the technology. “Optimism dimension”, related to TR theory, directs the consumer’s assurity in his/her ability to enhance the control, flexibility, and effectiveness in its life and work performance (Walczuch et al, 2007). This helps the individual build confidence and control over their performance (Walczuch et al., 2007).

These terms are similar in their expression that consumers’ work performance can be increased by using the innovative 3DP technology, which replaces existing analogous. The term “relative advantage” is recognized across a variety of disciplines and thus will be proposed and maintained as a factor in 3DP technology adoption in this research.

## 2.2. Complexity

According to the characteristics of **Innovation Diffusion Theory**, the scale to which an innovation is considered difficult to understand by the user is complexity (Everett, 1983). More complex ideas are difficult to comprehend and thus, slower to adopt.

**Technology Readiness** theory’s “discomfort scale” establishes the level of consumers’ negative attitude to the new technology according to their understanding of this technology (Parasuraman, 2000). Discomfort scale is the individual’s belief that their knowledge of the technology is not sufficient and so they may feel restless and uneasy. An antonym to complexity is “ease-of-use” factor deployed in **Technology Acceptance Model** and explained as the scope of the user’s understanding of the new technology to be effortless (Walczuch et al., 2007).

The close relation between these factors becomes obvious as they discuss the same issue from a positive and negative perspective. Aforementioned terms are combined in all-inclusive factor “complexity” for this research.

### 2.3. Trialability

**Innovation Diffusion Theory’s** characteristic “trialability” can be explained as the innovation being experimented on a small-scale prior to its full-scale adoption (Everett, 1983). Trialability helps reduce some uncertainty regarding the innovation and increases chances of acceptance.

### 2.4. Compatibility

According to **Innovation Diffusion Theory**, compatibility is the characteristic of an innovation considered consistent with the existing norms, past experiences and future expectations (Everett, 1983). Based on statistical analysis that combines various studies, Tornatzky and Klein (1982) conclude that an innovation’s compatibility is positively related with its adoption.

### 2.5. Absorptive capacity

Absorptive capacity is the user’s skill to absorb the value of new technology, integrate it, and incorporate it to their work and is positively related to adoption of new technology(SANCHEZ, 2009).

## 2.6. External pressure

**Technology Readiness** theory's "Insecurity dimension" was included as a measurement of external pressure where the consumer does not trust to a technological product and doubts about product fulfillment through its task (Parasuraman, 2000). Hence it will be addressed as "external pressure" to analyze and study as a 3DP technology adoption factor.

## 2.7. Uncertainty

**Contingency theory (CT)** offers the potential to understand better how context (situation, atmosphere) affects innovation adoption (Tidd & Prajogo, 2016). Uncertainty is the contingency defined as the degree to which the consequences and impacts on the management of the work using an innovation cannot be predicted or established (Tidd & Prajogo, 2016). Uncertainty affects technology adoption negatively and will be studied as a factor in this research.

## 2.8. Supply-side benefits

**Supply-chain management** includes the planning, control and execution of a project's flow from procurement of raw material to production and distribution to the final customer. Two channels of supply are formed in any material management process, supply and demand. Supply focusses on the material procurement and product development phase of a project. The purpose of supply-chain management is to ensure that both these channels operate in an organized and effective manner. It is a highly customer-focused business approach. The interest and influence of the people and cross-functionals organizations involved in the process towards innovation can affect both the production and customer channels of the supply-chain. The supply chain from the innovation vendor to the buyer of the technology becomes one crucial factor in 3DP adoption.

## 2.9. Demand-side benefits

Demand focusses on the product distribution or purchase by the customer. The demand chain is where the buyer of the technology will incorporate the technology in their work for their customers (Mellor et al., 2014).

## 3. Proposed success factors and measurement items for 3DP technology adoption

For each proposed factor, several measurement items were ensued by deriving construction 3D printing interpretations from technology innovation theories. These measurement items were then rated by professionals and academics in the field of construction 3D printing on a five-point scale of importance to evaluate the significance of the associated factor in 3DP technology adoption.

### 3.1. Technology-related factors for 3DP technology adoption

Technology-related factors determine the competitive and economic benefits that the 3D printing technology could help develop the business strategy. Three factors are proposed in this category.

#### a. Relative Advantage (RA)

The measure of relative advantage is expected to be metered by parameters such as the improvement or reduction in material usage and wastage by using 3D printing, the freedom of construction component design at no additional cost, the possibility to optimize the components, and the ability to construct in harsh and aggressive environments. Reduction in manpower requirements, overall cost of construction of printed components, construction time, safety issues and product quality problems by using 3D printing instead of conventional building methods were also evaluated.

#### b. Complexity (CX)

Complexity is measured by the ease of processing the computer-generated design and managing the digital construction activity. The effect of this factor was also examined by weighing the importance of ease of operation and maintenance of the 3D printer.

**c. Trialability (TR)**

To rate the importance of trialability, the predictability of 3D printing material, the behavior of 3D printed product from a long-term perspective and the precision of printed objects within acceptable tolerances were proposed as measurement items.

## 3.2. Organization-related factors for 3DP technology adoption

Intra-organizational and inter-organizational influence in the adoption of construction 3D printing technology is critical and thus is measured by the proposed two factors.

**a. Compatibility (CP)**

The importance of compatibility in 3D printing technology adoption was tabled to be measured in terms of the flexibility to print various sizes of objects for different construction needs, the agreement of the construction site with 3DP technology, the suitability of printing conventional design elements, and the need to match the 3D printed material standards with the characteristics of legacy construction processes.

**b. Absorptive Capacity (AC)**

Absorptive capacity is proposed as a measure of the importance of allocating a significant share of the construction 3DP company's capital to R&D and the collaboration with other companies and research institutions for R&D. It is also measured by the importance of having a major share of employees with tertiary level education on the project, their expertise and knowledge about 3DP, integrating a cross-functional team in the planning, design and construction of building product, the team's attitude towards 3D printing technology in general and the adequacy of company resources to produce, test and implement the 3DP technology.

## 3.3. Market-related factors for 3DP technology adoption

Market-related factors affect the organization through external channels. These factors are crucial to inherit an alignment of business, manufacturing and R&D strategies.(Mellor et al., 2014)

### a. External Pressure (EP)

The external pressure will gauged by the significance of competitive pressure from other construction firms, the presence or absence of technical and quality standards or certification issues, the consumers' skeptical attitude and psychological barrier related to 3DP technology and its implementation, their lack of information on the technical and economic benefits of the technology, and the restrictions imposed by regulations, contractors or consultants associated with 3DP innovation.

### b. Uncertainty (UC)

The perceived side-effects associated with 3DP technology, the printed component's resistance to environmental influences and failure from exposure to high stress and the uncertainty of the technology's profitability are the tendered measures of importance of uncertainty in 3DP adoption.

### 3.4. Supply-chain related factors for 3DP technology adoption

Projects are a work of collaboration of several units, and supply-chain management of 3DP in construction is an interaction of two supply chains, giving us two factors to analyze in this category.

#### a. Supply-side benefits (SB)

The importance of reducing and simplifying construction tasks, reducing the need for pre-assembly/assembly activities, transportation services, number of suppliers involved in construction and increasing collaboration among stakeholders involved in the 3DP project are the measures suggested to understand the supply-side benefits of technology adoption.

#### b. Demand-side benefits (DB)

To weigh the significance of demand-side benefits, the measures are the value of customized production of printed components, the company's fast reaction to changing customer needs, and production in collaboration with the customer and the supplier.

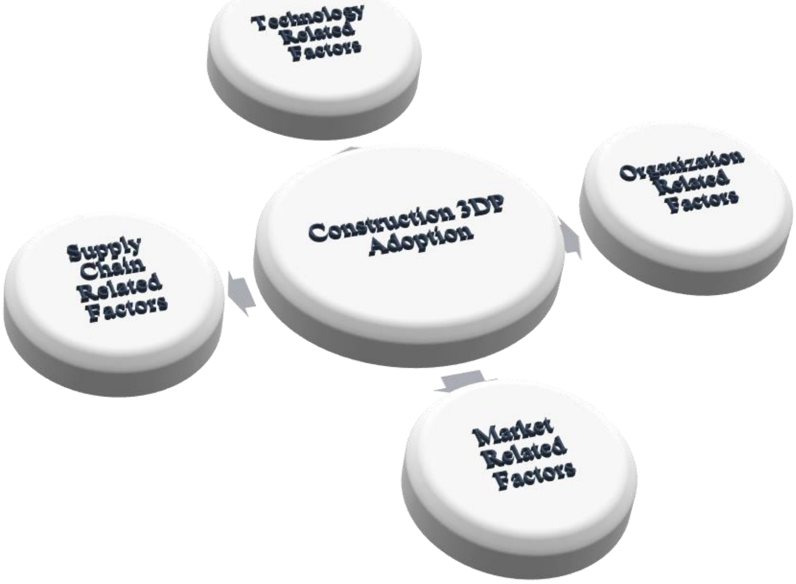
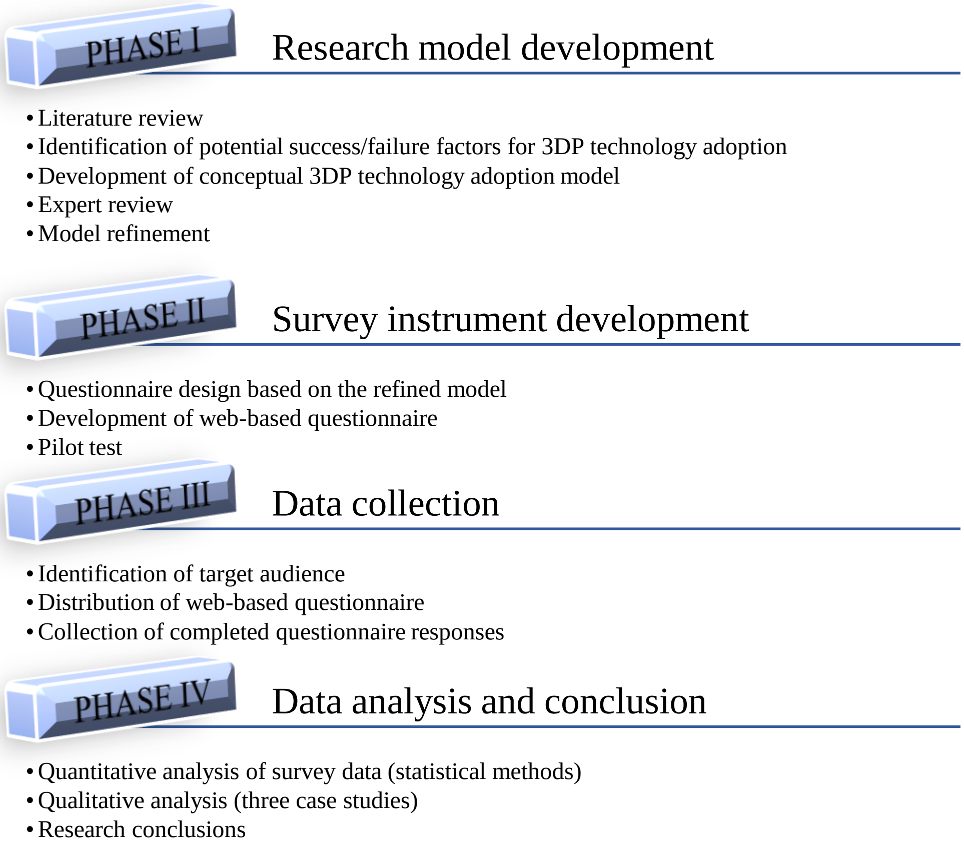


*Figure 10. Conceptual 3DP adoption model*

## 4. Research methodology of the thesis

This research is divided into four phases. Phase I comprises the preceding literature review and development of the 3DP technology adoption model, which is followed by the proposed factors and measurement items.



PHASE I Research model development

- Literature review
- Identification of potential success/failure factors for 3DP technology adoption
- Development of conceptual 3DP technology adoption model
- Expert review
- Model refinement

PHASE II Survey instrument development

- Questionnaire design based on the refined model
- Development of web-based questionnaire
- Pilot test

PHASE III Data collection

- Identification of target audience
- Distribution of web-based questionnaire
- Collection of completed questionnaire responses

PHASE IV Data analysis and conclusion

- Quantitative analysis of survey data (statistical methods)
- Qualitative analysis (three case studies)
- Research conclusions

*Figure 11. Research model*

### 4.1. Organization of questionnaire

Phase II of the research consists of the survey instrument development. The questionnaire was formed on and distributed via Qualtrics. It is divided into two sections. The first section asks the respondents of the survey to rate the importance of each proposed factor in construction 3D printing on a scale of 1-5, where 1 is 'very low importance', 2 is 'low importance', 3 is 'fairly important', 4 is 'very important' and 5 is 'extremely important'. The section has the 42 proposed measurement items classified in 9 groups. The second section collects general information about the respondents such as their organization, their positions in the organization, country, education, primary area of professional practice and years of experience in construction.

## 4.2. Data collection

Phase III of the research is data collection. All responses were collected electronically. Respondents belonged to a wide range of firms capable of, or interested in, designing, specifying, producing or installing 3D printed components for construction projects. Respondents also included academics involved in 3D printing research or with exposure to construction 3D printing.

In order to get access to the respondents' contact information, several sources were used. For researchers and scholars, the contact details were obtained from journals and papers. The names and emails of academic professionals were obtained from institutions' websites. Contact information for industry professionals was retrieved from company websites, Co-operative Network of Building Researchers (CNBR) and American Society of Civil Engineers (ASCE) webpage and LinkedIn postings. These professionals were identified and the survey was dispatched to them.

A total of 5,246 surveys were sent out, out of which 544 responses were returned. The response rate of the survey was 10.37%. Out of these 544 responses, 82 were considered valid and accounted for since the remaining 462 questionnaires were either incomplete or incorrect and were considered void.

## 4.3. Case Selection and Interview

Phase IV involves the analysis of data. For the qualitative analysis, several candidates were considered for the case and interview, based on their level of interest in the research and participation in the steps following the questionnaire survey.

Yingchuang Building Technique (Shanghai) Co. Ltd. Or Winsun, China was selected for the first case study. This construction 3D printing company has about two decades of experience in 3DP projects and R&D. This case study provides perspective into an international, large scale manufacturer of 3D printed products having already made several advancements in the field and the factors that have affected their projects in the past and present.

Contour Crafting Corporation, USA was selected for the second case study. Contour Crafting is a robotics firm which builds robots that use the CC process to automate construction practices. This case study looks into the factors affecting a developing manufacturer of 3D printing robots and their projects.

Laticrete International, USA was selected for the third case study to understand the factors influencing projects by a young, 3D printed products contractor.

Once the respondents returned the filled survey, a telephone interview was scheduled. A list of all the factors with measurement items was sent to them in advance for reference during the interview. During the interview, the interviewee was asked to provide general information about their company, collaborations and research with 3D printing project in construction. The interviewees were then asked to provide their views and interpretation of each factor and measurement item for 3D printing technology adoption and how they have influenced their work so far. All questions were open-ended to seek detailed information from the interviewees and to avoid bias. The presence or absence of each factor in the project was questioned and checked if implemented meaningfully. Each interview lasted about 30 to 40 minutes.

# 5. Data analysis

## 5.1. Respondent Analysis

Of the total of 82 respondents to the questionnaire survey, 26 belonged to academic institutions, 15 respondents from engineering consultants, 18 3DP producers, 6 from government R&D and engineering services, 4 from construction project management companies, and 10 from other areas like Health & Safety in infrastructure, natural and cultural resources, quantity surveying and mining. 3 respondents' area of practice was not specified.

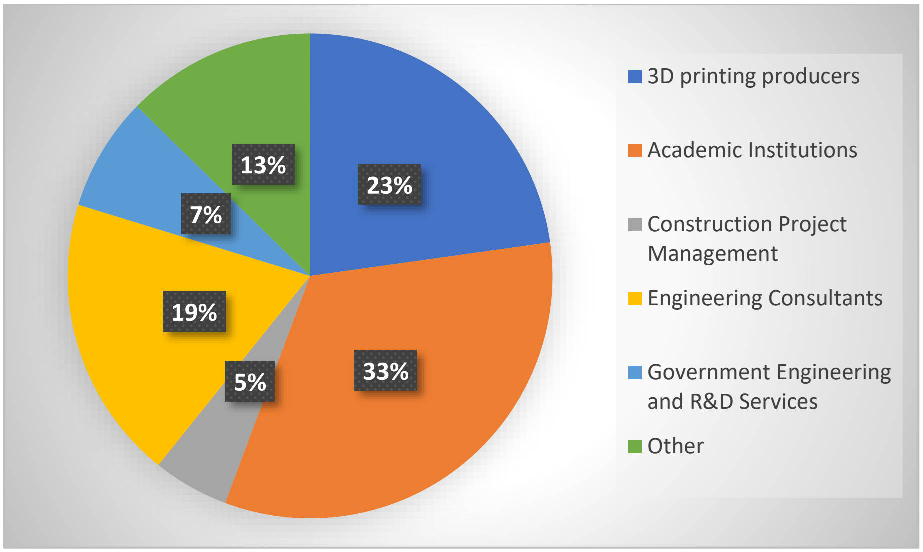


*Figure 12. Distribution of respondents by primary area of practice*

29 respondents have construction experience for 1-5 years (36.71%), 13 respondents have worked in construction for 6-10 years (16.46%) , 17 for 11-20 years (21.52%), and 20 have been working in the construction industry for more than 20 years (25.32%).

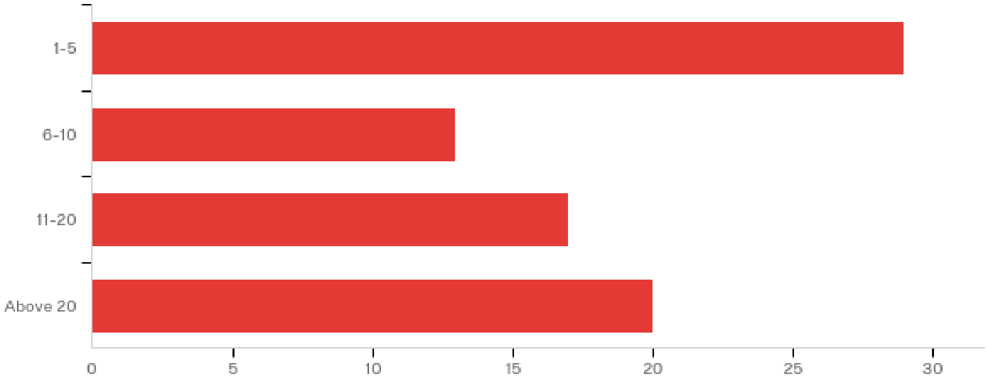


*Figure 13. Respondent's years of experience in construction industry*

31 respondents hold a doctoral degree (38.75%), 30 a master’s degree (37.50%), 11% hold a bachelor’s degree (13.75%) and 2 a high school diploma (2.50%). 6 of respondents hold other degrees such as diploma, associate degree, technical college etc. (7.50%). Two respondents’ education level was not specified.

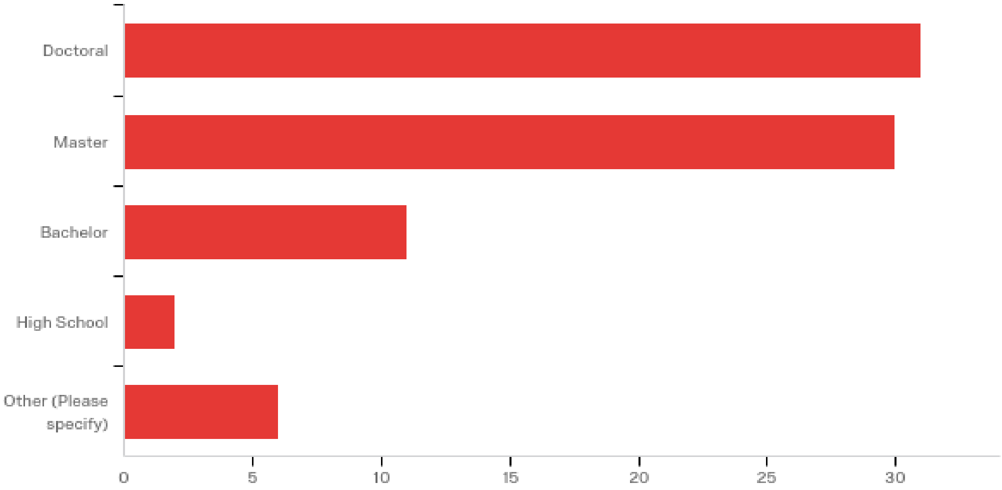


*Figure 14. Distribution of respondents by education level*

36.58% of the respondents were based in the USA, and the remaining 63.42% were international respondents from Spain, Sweden, UAE, Singapore, France, Oman, South Africa, Australia and Hungary among many others.

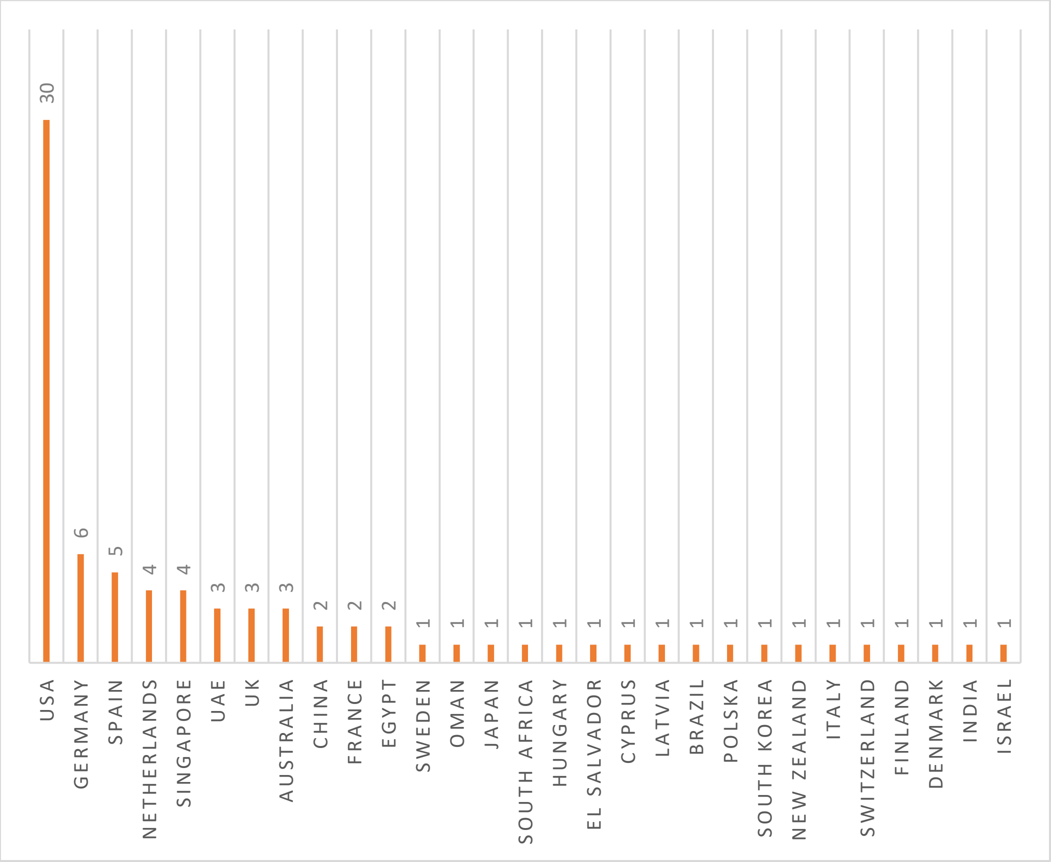


*Figure 15. Distribution of respondents by country*

## 5.2. Response Analysis by Content Validity Ratio (CVR)

Lawshe’s method (Lawshe,1975) suggests that significance analysis of the proposed measurement items can also be performed by calculating the content validity ratio (CVR) for each item. CVR is used to understand the importance of the variable based on recorded responses using the formula:

$$\text{CVR} = \frac{n - N/2}{N/2}$$

Where,

CVR = Content Validity Ratio

n = number of respondents who rated the item ‘3’, ‘4’ or ‘5’

N = Total number of respondents

For this analysis, respondents who rated the measurement item ‘3’, ‘4’ or ‘5’ on the 5-point scale in the questionnaire are considered to have marked the variable as relatively essential.

CVR value ranges from 0 to 1, value closer to 1 suggest the variable as more essential and value closer to 0 suggests the variable to be less essential (Wilson, Pan, & Schumsky, 2012).

The CVR values and mean importance value for each factor’s variables is recorded in the following tables.

### i. Relative Advantage

The factor is studied using the ranking allocated to its nine proposed measurement items.

| **Measurement Item** | **Number of Responses Ranking** | | | | | **CVR** | **Mean** |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | | |
| Improve material usage | 0 | 5 | 22 | 32 | 23 | 0.878 | 3.890 |
| Freedom of design at no extra cost | 1 | 9 | 14 | 25 | 33 | 0.756 | 3.976 |
| Optimize components/ structures and integrate more functionality into them | 2 | 6 | 20 | 35 | 19 | 0.805 | 3.768 |
| Construct in harsh and aggressive environments | 5 | 15 | 25 | 22 | 15 | 0.512 | 3.329 |
| Reduce manpower requirement | 4 | 3 | 23 | 30 | 22 | 0.829 | 3.768 |
| Reduce cost of construction component/structure | 0 | 8 | 22 | 25 | 27 | 0.805 | 3.866 |
| Reduce construction time | 1 | 1 | 17 | 26 | 37 | 0.951 | 4.183 |
| Reduce safety hazards | 0 | 10 | 19 | 22 | 31 | 0.756 | 3.902 |
| Reduce product quality problems | 3 | 8 | 29 | 29 | 13 | 0.732 | 3.500 |

*Table 1. Response analysis of Relative advantage factor*

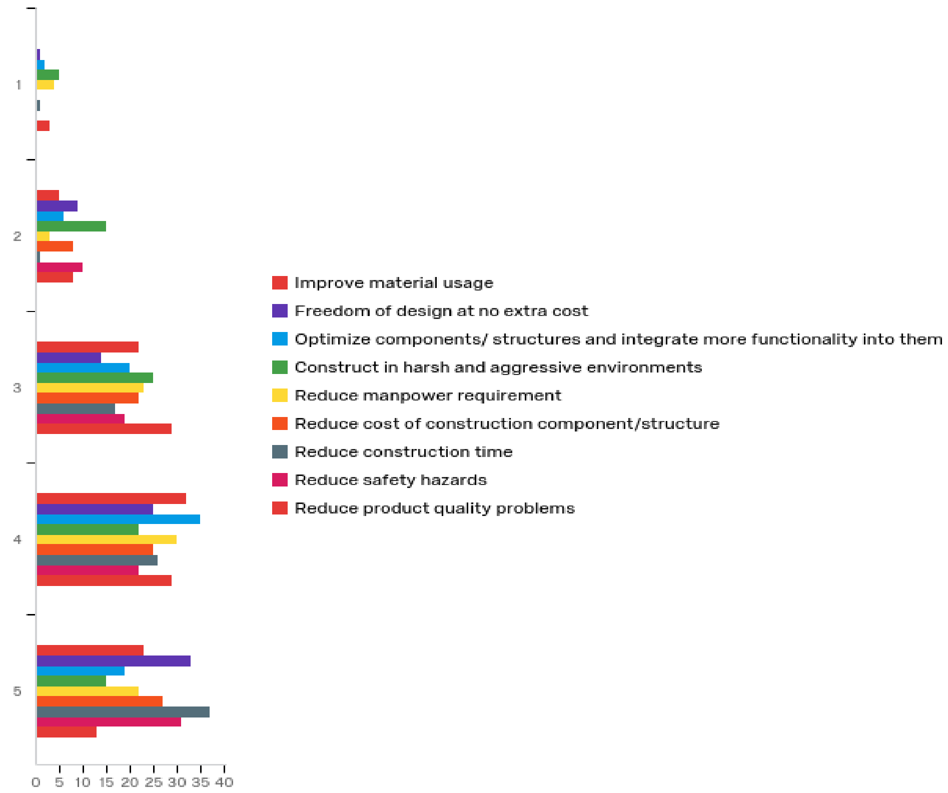


*Figure 16. Distribution of measure of Relative Advantage*

### ii. Complexity

The factor is studied using the ranking allocated to its four proposed measurement items.

| Measurement Item | Number of Responses Ranking | | | | | CVR | Mean |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | | |
| Computer-generated design process is easy | 4 | 7 | 27 | 28 | 16 | 0.732 | 3.549 |
| Managing digital construction process is easy | 2 | 10 | 23 | 32 | 15 | 0.707 | 3.585 |
| Operating 3D printer is easy | 4 | 7 | 19 | 33 | 19 | 0.732 | 3.683 |
| Maintaining 3D printer is easy | 6 | 13 | 23 | 28 | 12 | 0.537 | 3.329 |

*Table 2. Response analysis for Ease of Use factor*

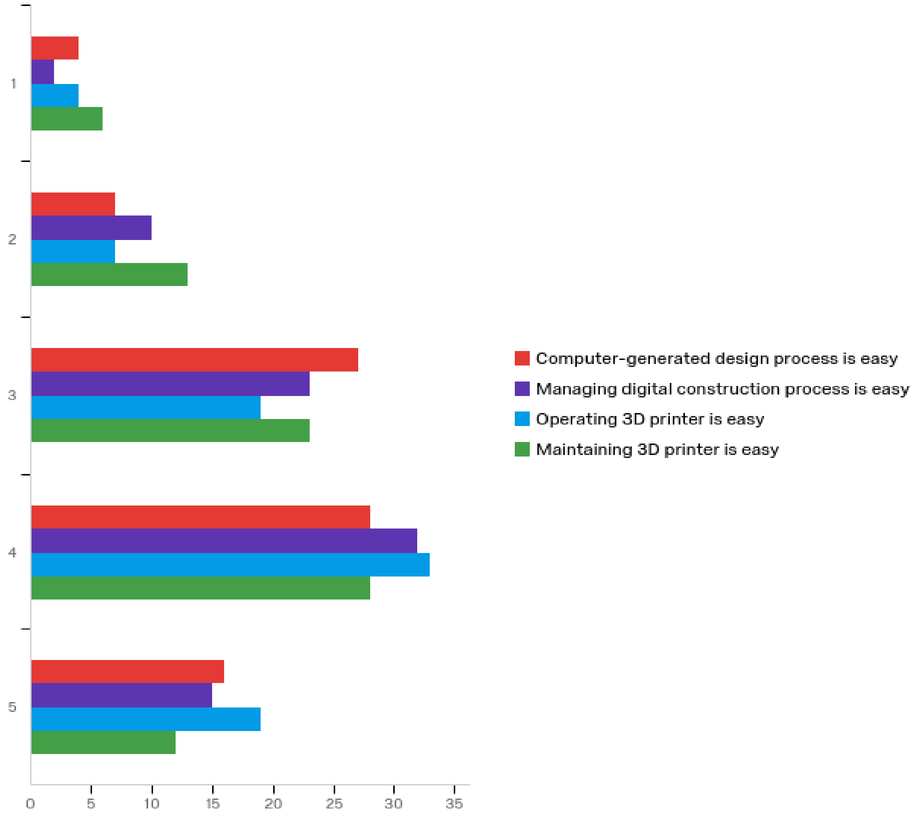


*Figure 17. Distribution of measure of Ease of Use*

### iii. Trialability

The factor is studied using the ranking allocated to its three proposed measurement items.

| Measurement Item | Number of Responses Ranking | | | | | CVR | Mean |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | | |
| 3D printing material properties are predictable | 4 | 7 | 14 | 35 | 22 | 0.732 | 3.780 |
| Behavior of 3D printing product from a long-term perspective (e.g. length of the product life cycle) | 3 | 13 | 17 | 32 | 17 | 0.610 | 3.573 |
| Precision of the printed objects is within acceptable tolerances | 0 | 4 | 22 | 31 | 25 | 0.902 | 3.939 |

*Table 3. Response analysis for Trialability factor*

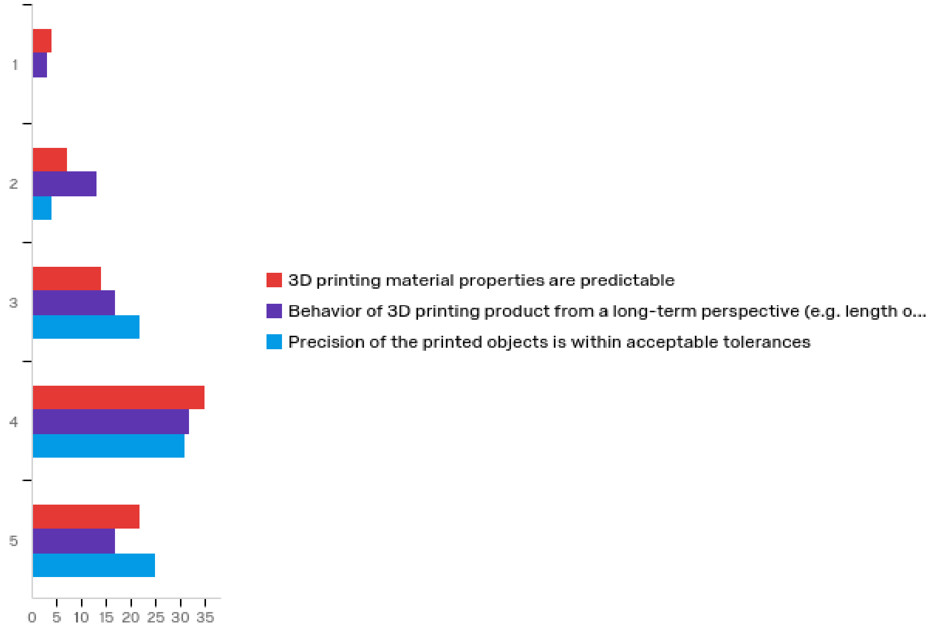


*Figure 18. Distribution of measure of Trialability*

### iv. Compatibility

The factor is studied using the ranking allocated to its four proposed measurement items.

| Measurement Item | Number of Responses Ranking | | | | | CVR | Mean |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | | |
| Flexibility to obtain various sizes of objects for different construction needs | 2 | 6 | 16 | 31 | 27 | 0.805 | 3.915 |
| Compatibility of construction site environment with 3D printing technology | 5 | 11 | 23 | 32 | 11 | 0.610 | 3.402 |
| Suitability of printing conventional design elements | 7 | 12 | 25 | 30 | 8 | 0.537 | 3.244 |
| Matching available 3D printing materials with the characteristics of legacy construction processes | 3 | 15 | 20 | 34 | 10 | 0.561 | 3.402 |

*Table 4. Response analysis for Compatibility Factor*

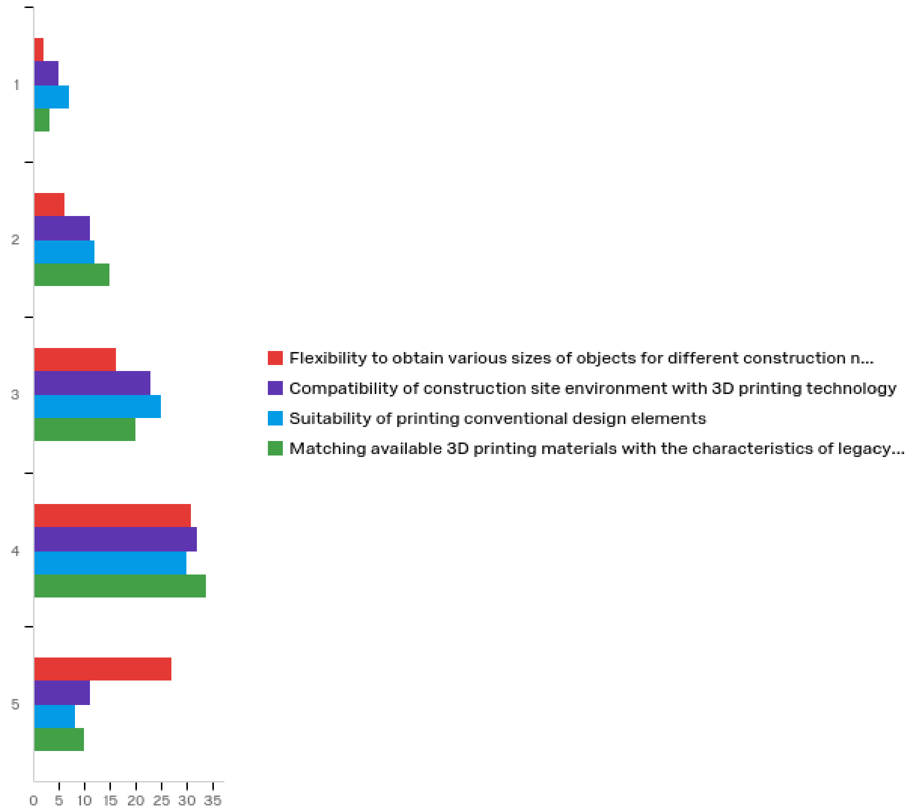


*Figure 19. Distribution of measure of Compatibility*

### v. Absorptive Capacity

The factor is studied using the ranking allocated to its seven proposed measurement items.

| **Measurement Item** | **Number of Responses Ranking** | | | | | **CVR** | **Mean** |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | | |
| Significant share of company capital expenditure devoted to R&D | 2 | 11 | 29 | 34 | 6 | 0.683 | 3.378 |
| Extensive cooperation with other companies or research institutions in R&D | 2 | 10 | 21 | 34 | 15 | 0.707 | 3.610 |
| Major share of employees has education at tertiary level | 5 | 13 | 34 | 24 | 6 | 0.561 | 3.159 |
| Knowledge, expertise, talent, creativity and skills of the company' workforce | 2 | 2 | 24 | 37 | 17 | 0.902 | 3.793 |
| Integrating a cross-functional team in a process to plan building product and process design, and construction activity | 2 | 3 | 20 | 36 | 21 | 0.878 | 3.866 |
| Company team attitudes toward 3D printing in general | 1 | 9 | 21 | 35 | 16 | 0.756 | 3.683 |
| Adequacy of company's resources to produce, test or implement 3D printing technology | 1 | 10 | 15 | 38 | 18 | 0.732 | 3.756 |

*Table 5. Response analysis for Absorptive Capacity factor*

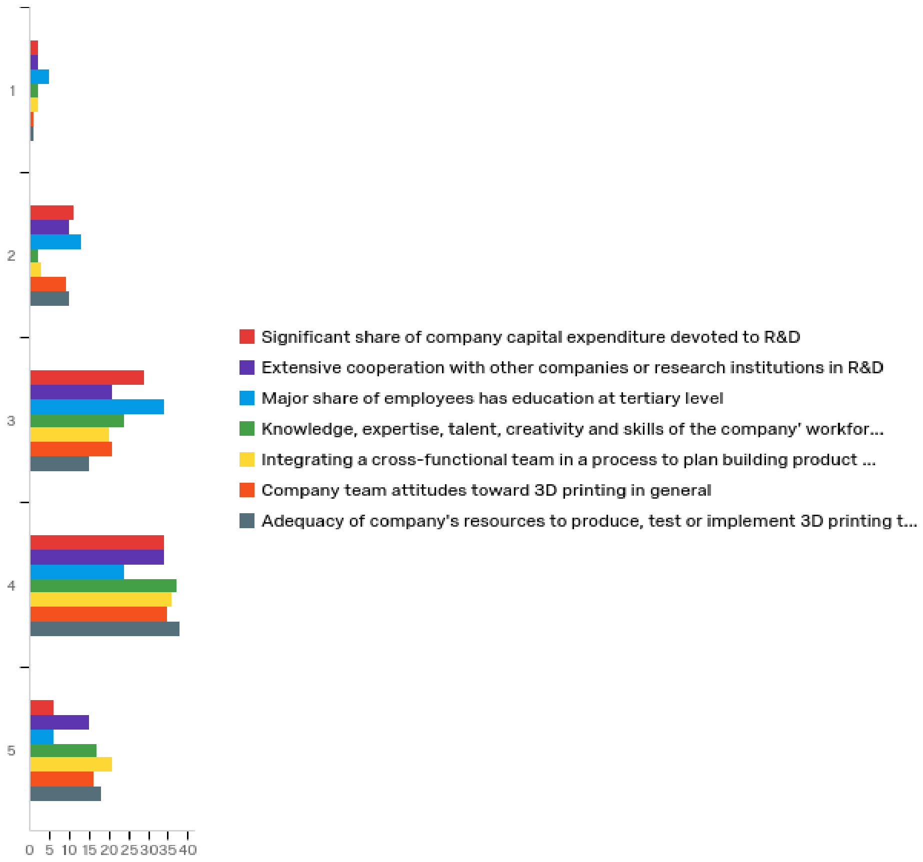


*Figure 20. Distribution of measure of Absorptive Capacity*

### vi. External Pressure

The factor is studied using the ranking allocated to its four proposed measurement items.

| **Measurement Item** | **Number of Responses Ranking** | | | | | **CVR** | **Mean** |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | | |
| Competitive pressure | 3 | 11 | 19 | 30 | 19 | 0.659 | 3.622 |
| Lack of technical standards, standards for quality control and product certification issues | 2 | 10 | 17 | 24 | 29 | 0.707 | 3.829 |
| Skeptical attitudes/ psychological barriers of consumers in relation to 3D printing technologies and product implementations | 0 | 12 | 17 | 29 | 24 | 0.707 | 3.793 |
| Lack of information on technical and economic benefits arising from innovation and restrictions imposed by regulations, contractors and consultants isolated from one another | 0 | 4 | 22 | 40 | 16 | 0.902 | 3.829 |

*Table 6. Response analysis for External Pressure factor*

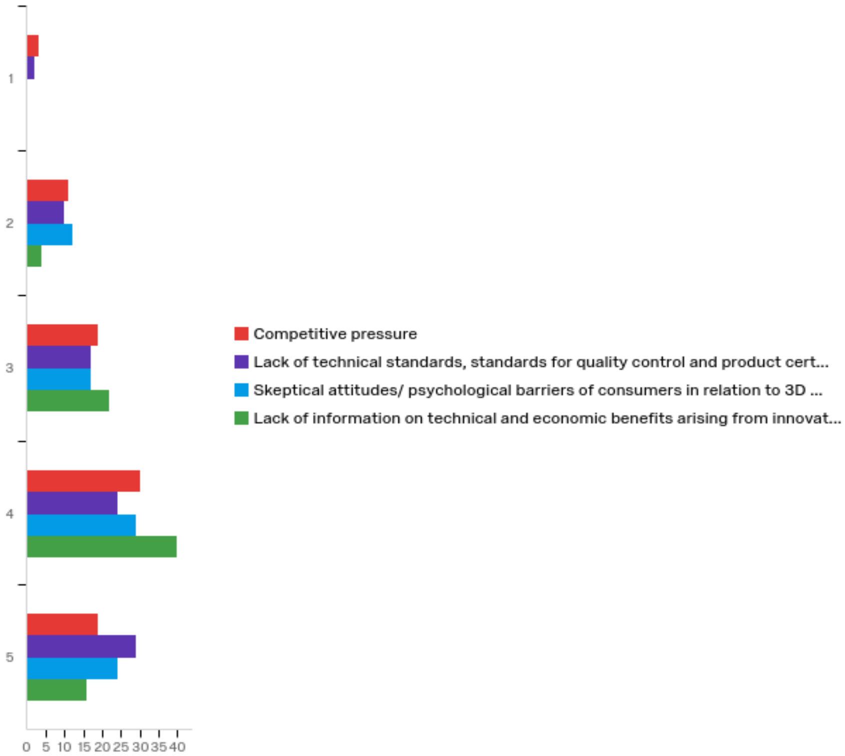


*Figure 21. Distribution of measure of External Pressure*

### vii. Uncertainty

The factor is studied using the ranking allocated to its three proposed measurement items.

| Measurement Item | Number of Responses Ranking | | | | | CVR | Mean |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | | |
| Perceived side effects associated with the innovation | 2 | 10 | 32 | 28 | 10 | 0.707 | 3.415 |
| Resistance to environmental influences and failure under exposure to high stress | 2 | 4 | 25 | 34 | 17 | 0.854 | 3.732 |
| Uncertainty in 3D printing technology profitability | 2 | 4 | 21 | 33 | 22 | 0.854 | 3.841 |

*Table 7. Response analysis for Uncertainty factor*

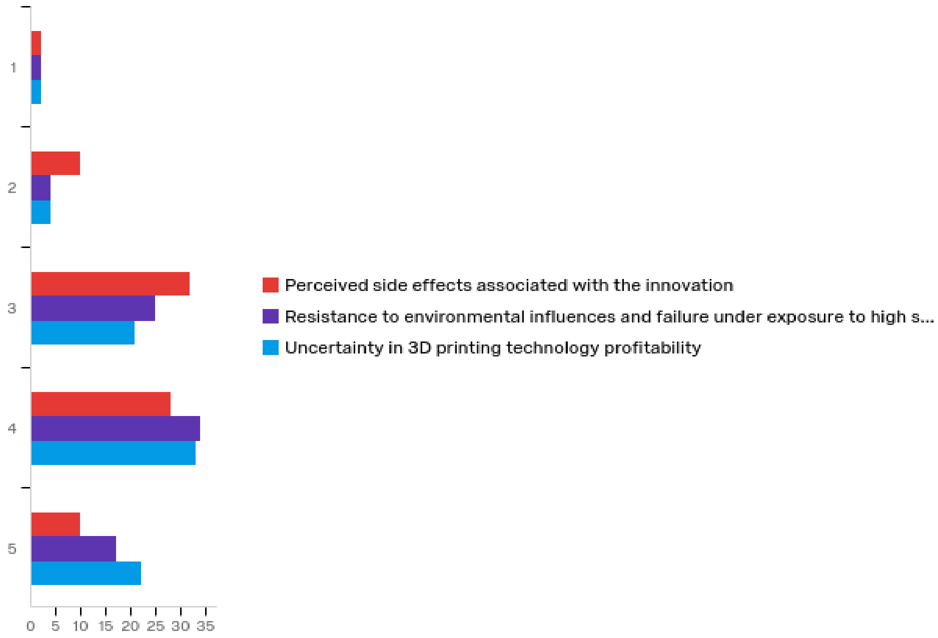


*Figure 22. Distribution of measure of Uncertainties*

### viii. Supply-side Benefits

The factor is studied using the ranking allocated to its five proposed measurement items.

| **Measurement Item** | **Number of Responses Ranking** | | | | | **CVR** | **Mean** |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | | |
| Reducing and/or simplifying construction tasks | 0 | 7 | 13 | 41 | 21 | 0.829 | 3.927 |
| Reducing the need for pre-assembly/ assembly activities | 3 | 9 | 24 | 26 | 20 | 0.707 | 3.622 |
| Reducing the need for transportation services | 3 | 16 | 15 | 29 | 19 | 0.537 | 3.549 |
| Reducing number of suppliers involved in construction process | 1 | 8 | 26 | 30 | 17 | 0.780 | 3.659 |
| Increasing collaboration among stakeholders (architects, engineers, constructors, suppliers, etc.) | 1 | 10 | 18 | 35 | 18 | 0.732 | 3.720 |

*Table 8: Response analysis for Supply-side Benefits factor*

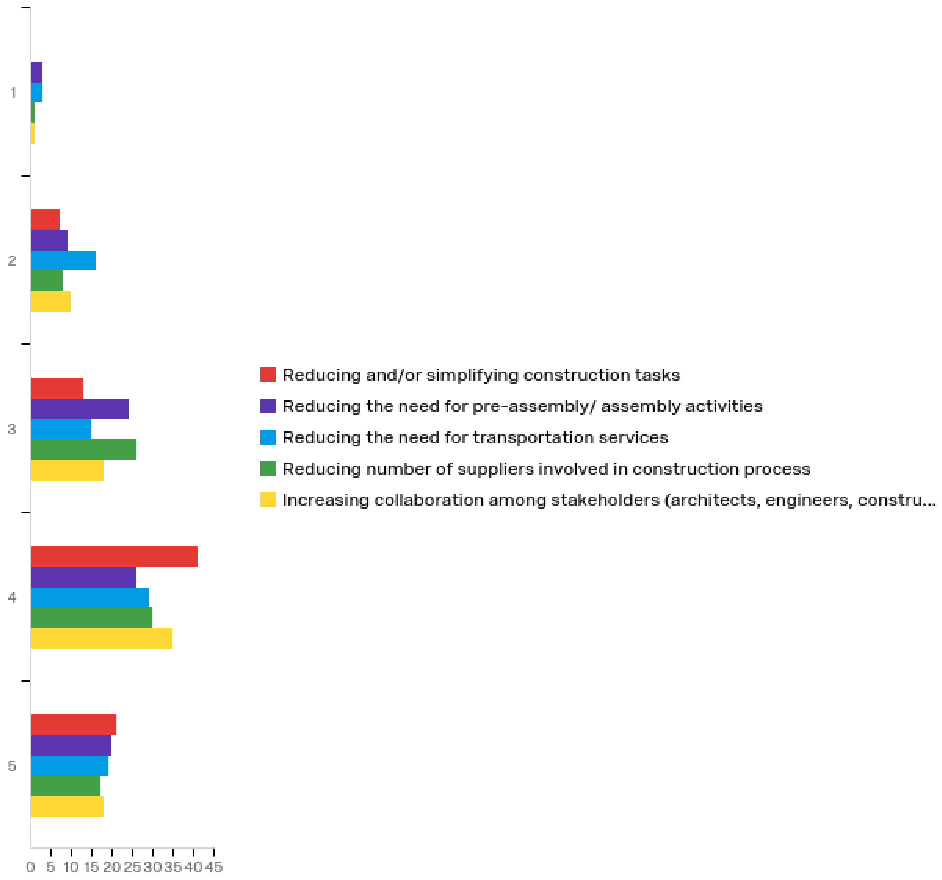


*Figure 23. Distribution of measure of Supply-side benefits*

### ix. Demand-side Benefits

The factor is studied using the ranking allocated to its three proposed measurement items.

| **Measurement Item** | **Number of Responses Ranking** | | | | | **CVR** | **Mean** |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | | |
| Customized production of printed components | 1 | 5 | 18 | 39 | 19 | 0.854 | 3.854 |
| Faster reaction to changing customer needs | 2 | 4 | 18 | 34 | 24 | 0.854 | 3.902 |
| Production in collaboration with the customer and supplier (e.g. customers integrated in product development) | 4 | 4 | 21 | 31 | 22 | 0.805 | 3.768 |

*Table 9. Response analysis for Demand-side Benefits factor*

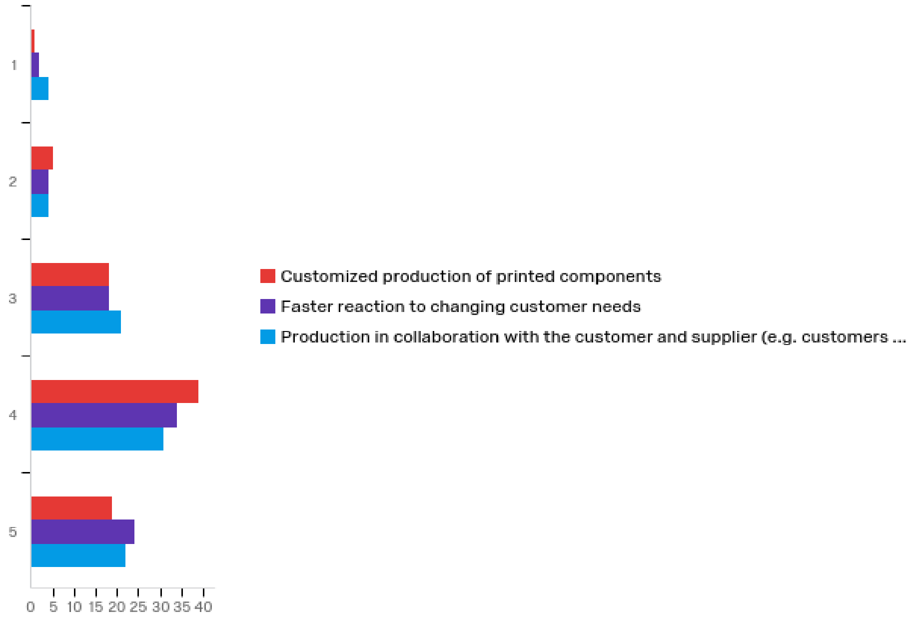


*Figure 24. Distribution of measure of Demand-side Benefits*

As can be derived from the scale of importance in the survey, all responses marked 3 or above on the scale of importance are deemed significant by the respondents. The mean rating of importance of all measurement variables suggest that all items have an average rating of more than 3, hence can all be considered significant in studying the success/failure of technology adoption in construction.

The CVR values of these measurement items provide a statistical understanding of the significance of the proposed success factors. When all responses are considered, it can be observed that all variables have a CVR value above 0.50 and hence can all be considered significant in studying the success/failure of technology adoption in construction.

## 5.3. Derivations

The **top five** important measurement items according to all respondents are:

| **Measurement Item** | **Factor** |
|---|---|
| Reduce construction time | Relative Advantage |
| Precision of the printed objects is within acceptable tolerances | Trialability |
| Knowledge, expertise, talent, creativity and skills of the company' workforce | Absorptive Capacity |
| Lack of information on technical and economic benefits arising from innovation and restrictions imposed by regulations, contractors and consultants isolated from one another | External Pressure |
| Improve material usage | Relative Advantage |

*Table 10. Top 5 important measurement items*

"Reduce construction time" is the top variable with highest CVR value. Evidently, construction 3D printing was initially introduced as a medium for Rapid Prototyping and later moved on to a process of Rapid Construction. Therefore, it can be concluded that reducing construction time using automation and machinery is the primary purpose of 3D printing.

It is also primary that automation of any process using machine ensures the product's accuracy and precision when compared to production by hand. This feature can be conveniently displayed by printing 'Rapid Prototypes' of any scale. Using standardized designs as input to the 3D printing machine ensures that the "Precision of the printed objects is within acceptable tolerances".

It is not surprising that the "Knowledge, expertise, talent, creativity and skills of the company's workforce" is highly ranked by the respondents. Construction 3D printing aims to reduce the reliance on physical manpower and generate more opportunities for brain power in the industry by making the process semi or fully autonomous. Understanding the design and technology and its implementation shifts the importance of construction site workers to employees with knowledge and expertise in the technology.

The "Lack of information on technical and economic benefits arising from innovation and restrictions imposed by regulations, contractors and consultants isolated from one another" is highly rated by the respondents suggesting the major challenge posing in front of the 3DP technology adoption. Since 3DP is not a standardized construction practice yet, there is no code or regulation either. This makes it difficult to explore, adopt and trust even within the stakeholders inside the business.

The final top variable is “Improved material usage”. In addition to being a rapid construction process, additive manufacturing reduces the overall usage and waste of printing material as compared to the conventional subtractive manufacturing in construction. This in turn, provides more relative advantage like sustainability and reducing the overall construction cost.

The **bottom five** important measurement items according to the respondents are:

| Measurement Item | Factor |
|---|---|
| Construct in harsh and aggressive environments | Relative Advantage |
| Reducing the need for transportation services | Supply-side Benefits |
| Maintaining 3D printer is easy | Complexity |
| Suitability of printing conventional design elements | Compatibility |
| Major share of employees has education at tertiary level | Absorptive Capacity |

*Table 11. Bottom 5 important measurement items*

The least important measurement item according to all respondents is “Construct in harsh and aggressive environments”. This can be explained by the fact that, most 3D printed components for construction are printed off-site in a controlled environment and then transported and assembled on site. Several R&D teams have only recently begun exploring the means to print on site using special configurations for the printer and printing material. The lack of exposure to this change and limitations in innovative compatible products explains the lower importance associated with this variable.

“Reducing the need for transportation services” is also ranked low and is also related to the fact that majority construction 3D printing is performed off-site. Instead of transporting the construction material to site for conventional building, 3D printed components need to be transported to the site. This process hardly reduces the construction cost. It is possible to reduce the cost of transportation by printing on site, but it is highly likely that the product quality might get compromised or the printer is too large or expensive to assemble or use on site.

“Maintaining 3D printer is easy” is expected to be an important factor but is surprisingly rated relatively low on the importance scale. This could possibly be a bias since 77% of all respondents do not belong to 3D Printing Production Companies and might have underestimated the significance of maintaining the 3D printer given its size, configuration and compatibility with the printing materials and printing environment.

The “Suitability of printing conventional design elements” is also rated lower than other variables. 3D printing is used in the construction market to make complex and unconventional construction of elements and structures easier using automation. The scope of construction 3DP goes beyond replacing the means of constructing conventional design elements. Most companies still use 3D printing for architectural and decorative building components. Hesitation also exists in adopting a new practice when the conventional method is already highly reliable and standardized.

“Major share of employees has education at tertiary level” also has a relatively low importance. Organizations participating in construction 3D printing have either been in business for years or are start-up companies diving in the innovation market. The employees' approach towards innovation, experience with the construction process, machinery and new materials and creativity are practically more or as important as education in the field.

## 5.4. USA responses with USA responses

| **Non-USA responses** | | | **USA responses** | | |
|---|---|---|---|---|---|
| **Factor** | **CVR** | **Mean** | **Factor** | **CVR** | **Mean** |
| **RA1** | 0.923 | 3.846 | **RA1** | 0.742 | 3.839 |
| **RA2** | 0.769 | 4.058 | **RA2** | 0.677 | 3.710 |
| **RA3** | 0.808 | 3.692 | **RA3** | 0.742 | 3.774 |
| **RA4** | 0.577 | 3.365 | **RA4** | 0.355 | 3.161 |
| **RA5** | 0.846 | 3.712 | **RA5** | 0.742 | 3.742 |
| **RA6** | 0.808 | 3.808 | **RA6** | 0.742 | 3.806 |
| **RA7** | 0.923 | 4.135 | **RA7** | 0.935 | 4.097 |
| **RA8** | 0.769 | 3.827 | **RA8** | 0.677 | 3.871 |
| **RA9** | 0.692 | 3.481 | **RA9** | 0.742 | 3.387 |
| **CX1** | 0.769 | 3.635 | **CX1** | 0.613 | 3.290 |
| **CX2** | 0.769 | 3.654 | **CX2** | 0.548 | 3.355 |
| **CX3** | 0.808 | 3.808 | **CX3** | 0.548 | 3.355 |
| **CX4** | 0.577 | 3.346 | **CX4** | 0.419 | 3.194 |
| **TA1** | 0.769 | 3.846 | **TA1** | 0.613 | 3.548 |
| **TA2** | 0.577 | 3.481 | **TA2** | 0.613 | 3.613 |
| **TA3** | 0.923 | 3.962 | **TA3** | 0.806 | 3.774 |
| **CP1** | 0.885 | 3.981 | **CP1** | 0.613 | 3.677 |
| **CP2** | 0.577 | 3.423 | **CP2** | 0.613 | 3.258 |
| **CP3** | 0.462 | 3.154 | **CP3** | 0.613 | 3.290 |
| **CP4** | 0.615 | 3.404 | **CP4** | 0.419 | 3.290 |
| **AC1** | 0.654 | 3.385 | **AC1** | 0.677 | 3.258 |
| **AC2** | 0.692 | 3.673 | **AC2** | 0.677 | 3.387 |
| **AC3** | 0.654 | 3.212 | **AC3** | 0.355 | 2.968 |
| **AC4** | 0.923 | 3.827 | **AC4** | 0.806 | 3.613 |
| **AC5** | 1.000 | 4.000 | **AC5** | 0.613 | 3.452 |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| **AC6** | 0.731 | 3.500 | **AC6** | 0.742 | 3.806 |
| **AC7** | 0.731 | 3.712 | **AC7** | 0.677 | 3.645 |
| **EP1** | 0.731 | 3.692 | **EP1** | 0.484 | 3.387 |
| **EP2** | 0.654 | 3.846 | **EP2** | 0.742 | 3.677 |
| **EP3** | 0.731 | 3.808 | **EP3** | 0.613 | 3.645 |
| **EP4** | 0.885 | 3.788 | **EP4** | 0.871 | 3.774 |
| **UC1** | 0.692 | 3.308 | **UC1** | 0.677 | 3.484 |
| **UC2** | 0.962 | 3.788 | **UC2** | 0.677 | 3.613 |
| **UC3** | 0.885 | 3.846 | **UC3** | 0.677 | 3.613 |
| **SS1** | 0.846 | 4.000 | **SS1** | 0.742 | 3.677 |
| **SS2** | 0.692 | 3.519 | **SS2** | 0.677 | 3.677 |
| **SS3** | 0.538 | 3.423 | **SS3** | 0.484 | 3.645 |
| **SS4** | 0.885 | 3.712 | **SS4** | 0.548 | 3.452 |
| **SS5** | 0.846 | 3.904 | **SS5** | 0.484 | 3.290 |
| **DS1** | 0.885 | 3.942 | **DS1** | 0.742 | 3.581 |
| **DS2** | 0.923 | 4.077 | **DS2** | 0.677 | 3.516 |
| **DS3** | 0.923 | 4.038 | **DS3** | 0.548 | 3.226 |

*Table 12. Respondent analysis for all measurement items classified by non-USA and USA respondents*

The **top eight** important measurement items for both categories are:

| **Non-USA respondents** | | **USA respondents** | |
|---|---|---|---|
| **Measurement Item** | **Factor** | **Measurement Item** | **Factor** |
| Integrating a cross-functional team in a process to plan building product and process design, and construction activity | Absorptive Capacity | Reduce construction time | Relative Advantage |
| Resistance to environmental influences and failure under exposure to high stress | Uncertainty | Lack of information on technical and economic benefits arising from innovation and restrictions imposed by regulations, contractors and consultants isolated from one another | External Pressure |
| Improve material usage | Relative Advantage | Precision of the printed objects is within acceptable tolerances | Trialability |
| Reduce construction time | Relative Advantage | Knowledge, expertise, talent, creativity and skills of the company' workforce | Absorptive Capacity |
| Precision of the printed objects is within acceptable tolerances | Trialability | Improve material usage | Relative Advantage |
| Knowledge, expertise, talent, creativity and skills of the company' workforce | Absorptive Capacity | Company team attitudes toward 3D printing in general | Absorptive Capacity |
| Flexibility to obtain various sizes of objects for different construction needs | Compatibility | Optimize components/ structures and integrate more functionality into them | Relative Advantage |
| Customized production of printed components | Demand-side Benefits | Reduce manpower requirement | Relative Advantage |

*Table 13. Top 8 measurement items for non-USA and USA respondents*

**Similarities:**

“Improve material usage”, “Reduce construction time”, “Precision of the printed objects is within acceptable tolerances” and “Knowledge, expertise, talent, creativity and skills of the company’s workforce” are the common top variables for non-USA and USA respondents. These are in congruence with the top variables established in the previous section.

**Differences:**

In addition to the common variables mentioned before, “Resistance to environmental influences and failure under exposure to high stress”, “Flexibility to obtain various sizes of objects for different construction needs” and “Customized production of printed components” were also rated as highly important by non-USA respondents.

“Lack of information on technical and economic benefits arising from innovation and restrictions imposed by regulations, contractors and consultants isolated from one another”, “Company team attitudes toward 3D printing in general”, “Optimize components/ structures and integrate more functionality into them” and “Reduce manpower requirement” have high CVR values considering responses from USA.

The **bottom eight** important measurement items for both categories are:

| **Non-USA respondents** | | **USA respondents** | |
|---|---|---|---|
| **Measurement Item** | **Factor** | **Measurement Item** | **Factor** |
| Suitability of printing conventional design elements | Compatibility | Construct in harsh and aggressive environments | Relative Advantage |
| Reducing the need for transportation services | Supply-side Benefits | Major share of employees has education at tertiary level | Absorptive Capacity |
| Compatibility of construction site environment with 3D printing technology | Compatibility | Maintaining 3D printer is easy | Complexity |
| Behavior of 3D printing product from a long-term perspective (e.g. length of the product life cycle) | Trialability | Matching available 3D printing materials with the characteristics of legacy construction processes | Compatibility |
| Maintaining 3D printer is easy | Complexity | Reducing the need for transportation services | Supply-side Benefits |
| Construct in harsh and aggressive environments | Relative Advantage | Increasing collaboration among stakeholders (architects, engineers, constructors, suppliers, etc.) | Supply-side Benefits |
| Matching available 3D printing materials with the characteristics of legacy construction processes | Compatibility | Competitive pressure | External Pressure |
| Major share of employees has education at tertiary level | Absorptive Capacity | Production in collaboration with the customer and supplier (e.g. customers integrated in product development) | Demand-side Benefits |

*Table 14. Bottom 8 measurement items for non-USA and USA respondents*

**Similarities:**

Reducing the need for transportation services", "Maintaining 3D printer is easy", "Construct in harsh and aggressive environments", "Matching available 3D printing materials with the characteristics of legacy construction processes" and "Major share of employees has education at tertiary level" are the rated relatively lower than both groups.

**Differences:**

"Suitability of printing conventional design elements", "Compatibility of construction site environment with 3D printing technology" and "Behavior of 3D printing product from a long-term perspective (e.g. length of the product life cycle" have lower CVR values for non-USA respondent group.

"Increasing collaboration among stakeholders (architects, engineers, constructors, suppliers, etc.)", "Competitive pressure" and "Production in collaboration with the customer and supplier (e.g. customers integrated in product development)" are allocated lower importance by USA respondents.

# 6. Case study

## 6.1. Yingchuang Building Technique (Shanghai) Co. Ltd, Or Winsun, China

### a. Introduction

Yingchuang Building Technique (Shanghai) Co. Ltd, or Winsun in China is one of the first companies in the world to realize the potentials of 3D printing in construction. Winsun has been working on 3D printing structures, new building material production, inventions, design architecture and R&D. Winsun is known for owning over 150 national patents and contributing to more than 500 real estate projects. Winsun holds the achievement of developing universal 3D ink and spray nozzle. The company also developed the largest continuous 3D printer (150m L, 10m W, 6.6m H). Winsun has production factories based in Shanghai, Suzhou and Xiangyang (Winsun's Website, n.d.).

### b. Printing process

The client's 3D Computer Aided Design (CAD) model is converted to 2D models and the material is added layer-by-layer through the spray nozzle. Each layer is 0.6cm to 3cm thick. The process allows printing of hollow structures to accommodate wiring and piping. The structure is often printed off-site and the finished parts are transported to the construction site for installation. Traditional foundations, steel or cement reinforcements and fittings and fixtures are assembled in accordance with the regional building regulations and customer requirements. The process saves about 80% of the construction cost, 60% of the labor cost and 60% of waste material (Winsun's Website, n.d.).

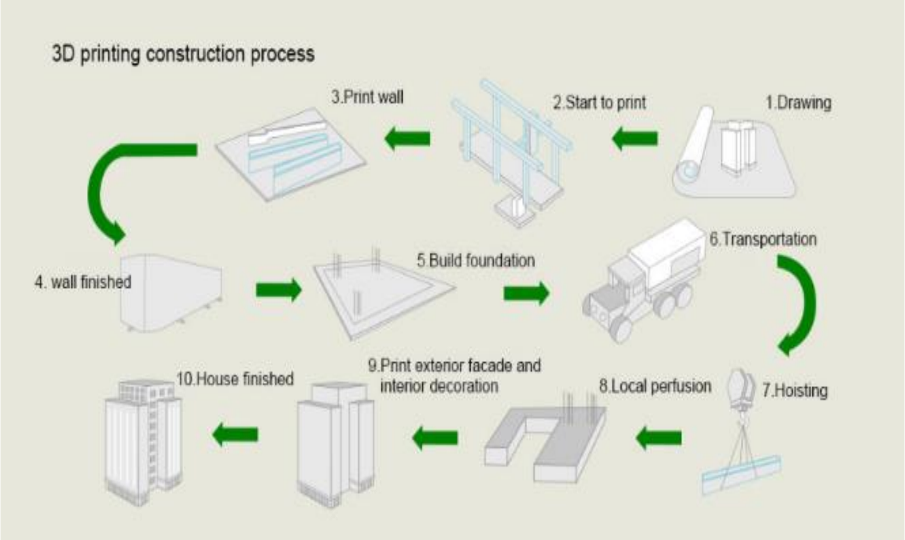


*Figure 25. Winsun's 3D printing process (Winsun's Website, n.d.).*

### c. Background History

Winsun was born an advanced building material supplier in 2002. It specialized in complex interior décor and exterior structures (*Winsun*, n.d.).

**Special materials:** Winsun's earliest inventions included new building materials such as GRG (special glass fiber reinforced gypsum board) in 2002, SRC (special glass fiber reinforced cement) and FRP (special glass fiber composite material) in 2006 and 3D printing Crazy Magic Stone (CMS) in 2007 (Winsun's Website, n.d.).

**3D printing equipment:** Winsun invented the first 3D printing spray nozzle in 2005. It also invented specialized 3D printing ink made by recycling construction waste. In 2008, the company developed the first continuous 3D printer with integrated input data collection, analysis and printing-output control system (Winsun, n.d.).

**Building printing:** Over the years 2008-2019, Winsun has printed products for construction and decoration of large-scale public buildings and used its expertise and experience in materials and architecture to step into sustainable and innovative construction for the benefit of the environment and society (Winsun's Website, n.d.).

### d. Projects

Winsun printed and assembled the world's first tallest 3D printed building in January, 2015. Located in Suzhou Industrial Park, Shanghai in China, the building has 6 floors (5 floors above ground level and 1 floor below ground level). Each floor took one day to print and two days to assemble. The building construction was completed in 15 days. Reinforced masonry wall standards were used and longitudinal and transverse rebar are inserted during printing for strength. Safety and quality inspection was conducted by Tongji University and the 3D printed building was reported to conform with the existing national building standards (Winsun's Website, n.d.).

*Figure 26: Yingchuang 3D printed 6-storey project (Winsun's Website, n.d.).*

The two-story 1100 square-meter residence costing $161,000 is the world's largest 3D printed mansion. It was completed in 2015 and is also on display in Suzhou Industrial Park, Shanghai. Sections of the building were printed by Winsun's 3D printer from CAD drawings. The printing material is made of cement, glass fiber, steel, hardening agents and recycled construction waste material and the building component was erected with internal bar structures. Each floor took one day to print and two days to assemble. Only three workmen were needed. Winsun claims that the construction is completed with significant reduction in building material volume, production time and labor cost. The mansion acts as a prototype for a set of ten orders by Taiwan based real estate company Tomson Group Limited ("China's WinSun Unveils Two New 3D Printed Buildings" 2015, January 28).

*Figure 27. Yingchuang 3D printed mansion (Winsun's Website, n.d.).*

*Figure 28: Winsun's Suzhou Industrial Park display, Shanghai (Winsun's Website, n.d.).*

Winsun also holds the achievement of building the world's largest 3D printed complex of seven buildings to be used as the company's Global 3D Printing Research and Development Center. Printing utilizes only one drawing, one computer and one printer for 50,000 square meter construction, and only one crane and several construction workers for on site assembly of building blocks. 70% of this project uses a specialized ink made by recycling construction and industrial (steel plant, power plant, coal industry) solid waste, providing environmental protection whilst building a more strong, durable and ecological complex (Winsun's Website, n.d.).

*Figure 29. Yingchuang 3D printed building complex (Winsun's Website, n.d.).*

Winsun printed 10 single room houses in the year 2015 in under 24 hours, for about $4,800 each using special ink made with high-grade cement and glass fiber base ("China's WinSun Unveils Two New 3D Printed Buildings" 2015, January 28).

*Figure 30. 3D printed houses constructed in one day (“China's WinSun Unveils Two New 3D Printed Buildings” 2015, January 28).*

Winsun also constructed the world’s first 3D printed toilet in 2016 for the scenic spot of Suzhou Yangshan in Jiangsu province and was awarded the Best Public Toilet award by the China Urban Environment Health Association. In addition to this project, the company has also worked on printing poverty alleviation toilets in Jinchang, Gansu province and tourist toilets in Hainan museum, Haikou (Winsun’s Website, n.d.).

*Figure 31. Winsun's 3D printed toilet in Suzhou Yangshan in Jiangsu (Winsun's Website, n.d.).*

*Figure 32. Winsun's poverty alleviation toilets in Jinchang, Gansu province (Winsun's Website, n.d.).*

*Figure 33. Winsun's tourist toilets in Hainan museum, Haikou (Winsun's Website, n.d.).*

In 2018, Winsun also 3D printed what is commonly known as the World's Ugliest Bus Stop. But according to Winsun, the bus stop serves its primary purpose whilst contributing to environmental protection and energy conversation since the special ink made from solid construction and industrial waste was used as the primary printing material (Winsun's Website, n.d.).

*Figure 34: Winsun's first 3D printed bus stop (Winsun's Website, n.d.).*

### e. Influencing Factors

Winsun has established itself in the construction 3D printing industry with over almost 2 decades of experience, research and innovation. The role of success factors influencing the absorption of new technology within the industry changed as the company grew. **Relative advantage** was the most important factor to be considered in Winsun's research and development phase. The company's primary aim in its initial years was to provide a better solution to construction needs by inventing new materials and equipment to reduce overall construction time and cost, improve material usage and reduce construction waste. Once these new products were introduced in the business, Winsun moved forward to publicize the innovation in the market. Winsun's idea of 3D printing several large structures and displaying them to the public as live prototypes to demonstrate the technology and its feasibility brings in the success of the **Triability** factor by the company. Winsun succeeded in demonstrating that 3D printing may not be limited to small scale structures and prototypes, and the material and structural properties are predictable and within acceptable tolerances. In order to work on the hesitation by clients and contractors towards participating in 3D printing, Winsun makes collaborations with several universities to educate the architects about the possibilities of 3DP.Winsun soon grew in business and landed several contracts from China, Dubai and Egypt governments for several units of their active building designs. Thus, after years of practice and experience in the innovation industry **Demand-side benefits** were eventually achieved. Winsun's future plan to setup a cloud-based platform to connect clients and designers to the company introduces the importance of **Supply-side benefits** factor by making an attempt to increase communication and collaboration among the stakeholders. All building prototypes by Winsun are **Compatible** with the building environment, and equipment with the material. The company tries to ensure all **Uncertainty** related to its products is eliminated.

The company has been in construction 3D printing business and **Absorptive Capacity** was a crucial factor in the initial developing phase, and was successfully implemented. The company continues to expend on R&D and resource allocation for innovation. Not enough information could be obtained on the **Complexity** of the design and operation for 3D printing, since its market started focusing on assembling large scale structures using conventional component design models. Hence, the factor has not been pro-actively investigated by the company. **External Pressure** is also a factor that does not affect the company at present because of its recognition in the market.

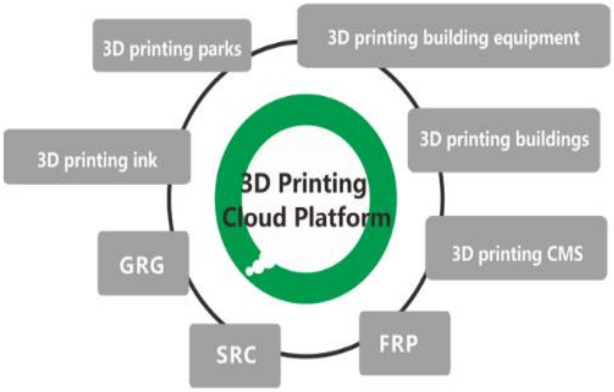


*Figure 35. Winsun's future plan (Winsun's Website, n.d.).*

## 6.2. Contour Crafting Corporation, California, USA

### a. Introduction

Contour Crafting is a startup company by Professor Behrokh Khoshnevis of the University of Southern Carolina. The company works on building fully automated machines to aid in construction 3D printing. The company aims to prepare the printing material and construct whole structures on site, saving all transportation costs and making construction fully autonomous. Contour Crafting isn’t on the market yet, it is more of an engineering and robotics research firm. Company CEO Koshnevis has over 100 related active patents in the domain at present. The professor hopes to introduce an entry-level machine to the market in the near future with new investments from construction companies.

### b. Background History

Professor Khoshnevis filed his first construction 3D printing patent in 1996 and built the first concrete 3D printed wall in 2004 under USC research. He developed an FDM 3D printer mounted on a robotic arm that extrudes layers of concrete to create the 3D model. The machine developed has a reach of 24 feet to 40 feet, and runs along the length of the building ground. The machine weighs less than 800 lbs and is easy to bring to site. His discovery marks the beginning of construction 3D printing (Muoio, D., 2016, July 30).

### c. Printing Process

The method the company used is also called contour crafting. In order to print the whole complete structure instead of parts and pieces of it, rails are installed around the building ground to direct the robotic arm, which moves back and forth extruding quick setting concrete from the nozzle. The machine can print single detached buildings, and can be modified to multi-nozzle assembly for larger buildings. Construction cost by this process is projected to be about one fifth of the conventional construction cost Muoio, D. (2016, July 30).

*Figure 36. Design prototype for building printing (Contour Crafting Co.'s Website. (n.d.)).*

## d. Projects

The professor began by proposing to use his invention to provide accelerated construction of homes for emergency reconstruction for disaster relief. But the scope of this printing was expanded to providing low-income housing to the poor and homeless. According to the World Health Organization, about 865 million people live in slums. Contour Crafting proposes that a 2500 square foot house can be 3D printed with automated installations (segments of reinforcements, plumbing, electrical network) along with automated finishing work, tiling and painting in 20 hours. High performance concrete mixed with composite fibers is used as printing material, which provides 10,000 psi strength as compared to 3,000 psi strength of normal concrete. The walls printed are hollow, light and provide heat conduction. Construction cost per square foot reduces to $50 as compared to $150 for conventional construction. Process eliminates the need if all physical labor, and creates new opportunities for brain power in construction industry. Construction is also done without waste, noise, dust and pollution (Contour Crafting Co.'s Website. (n.d.)).

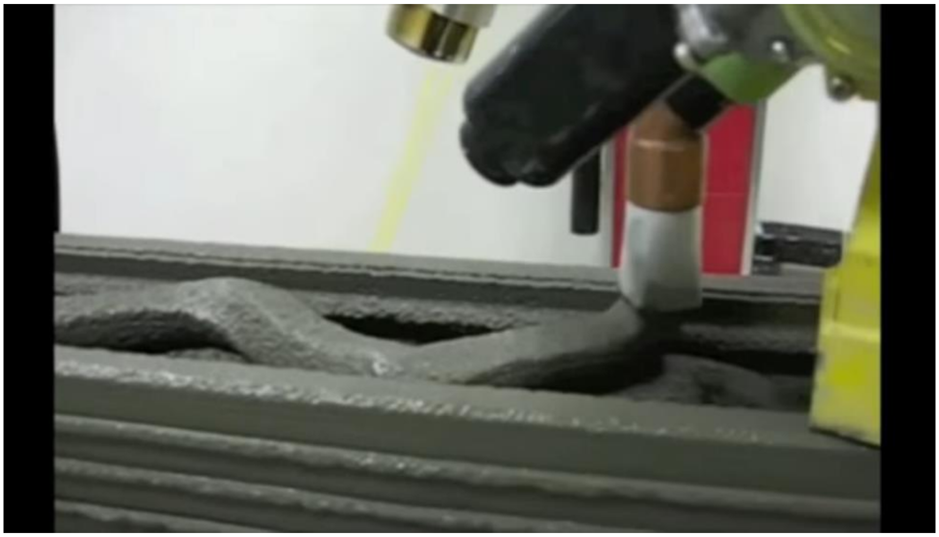


*Figure 37. 3D printed hollow walls (Contour Crafting Co.'s Website. (n.d.)).*

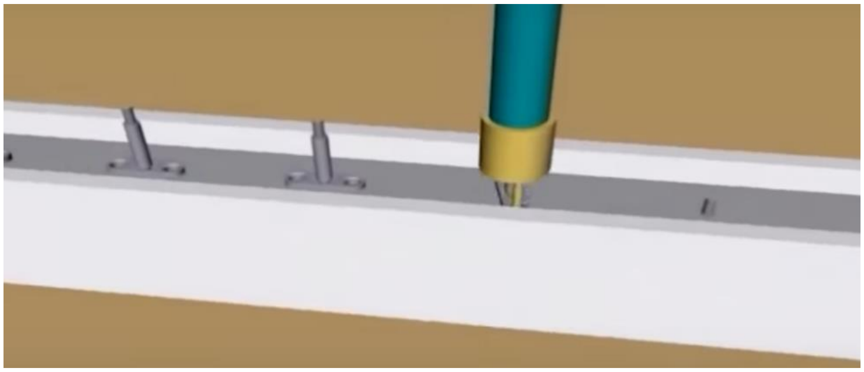


*Figure 38: Automated installation of rebars (Contour Crafting Co.'s Website. (n.d.)).*

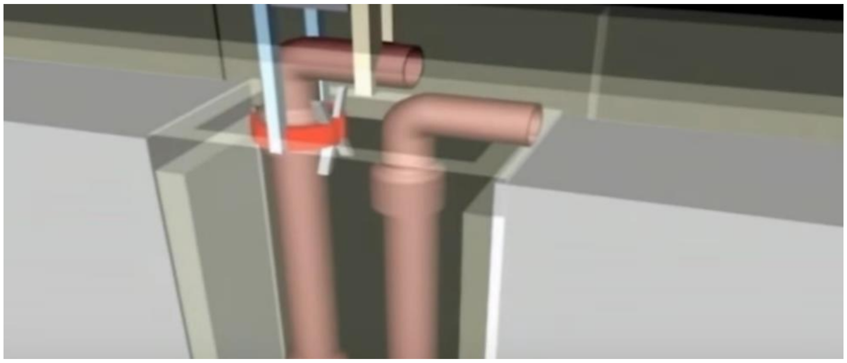


*Figure 39: Automated plumbing installation (Contour Crafting Co.'s Website. (n.d.)).*

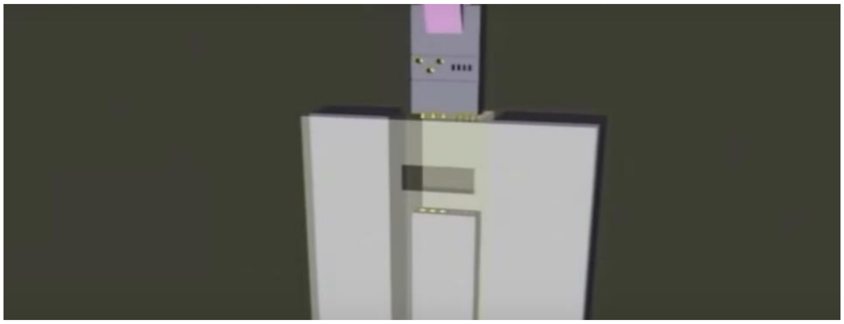


*Figure 40: Automated installation of electrical unit (Contour Crafting Co.'s Website. (n.d.)).*

Contour crafting proposes a new method of autonomous construction of tall concrete towers for wind turbines, bridge pylons, water towers, silos, chimneys etc. The method involves a set of vertically climbing robots to carry the nozzle assembly upwards and an elevating material deposition system in the center. This innovation aims to eliminate need for transporting the large steel tower sections from the factory to the wind farm. Towers taller than 100 meters can be constructed as the expense to build higher reaching cranes is eliminated. A small-scale prototype of the robot has been developed and tested for feasibility by the company. They soon aim to develop full scale towers.

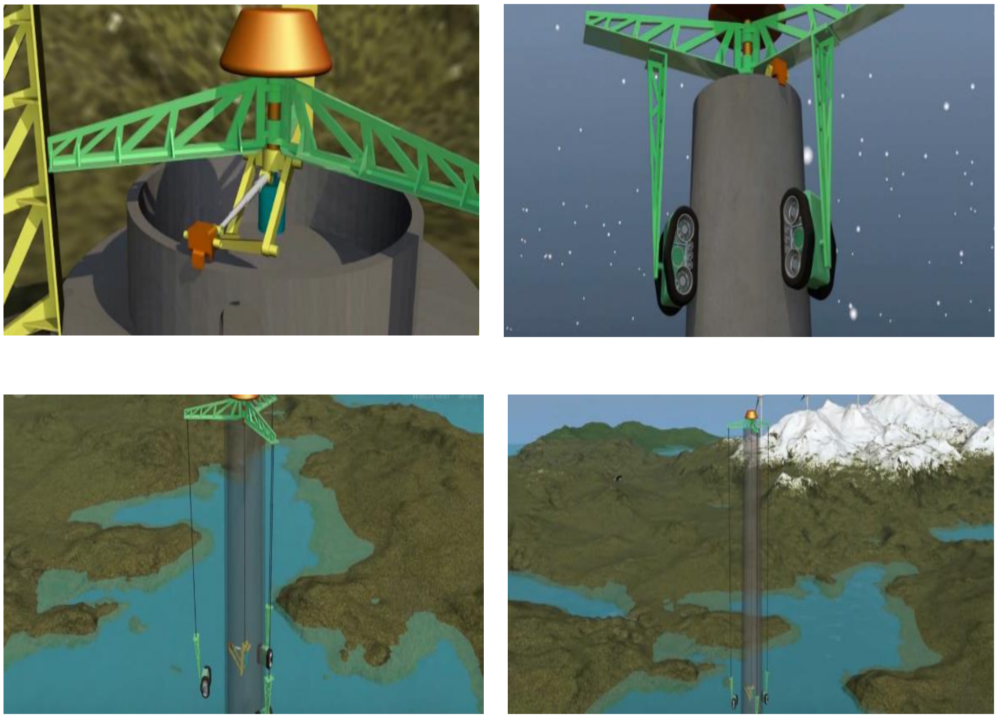


*Figure 41: Proposed assembly for tower construction (Contour Crafting Co.'s Website. (n.d.)).*

Contour Crafting recently received a grant for NASA to develop situ material into 3D printing material to construct structures on the moon and Mars by the process called Selective Separation Sintering (SSS) as a part of the Martian civilization project. SSS is a technique developed by a USC engineer that can effectively work in zero gravity condition. Planetary material is used for construction since it costs about $50,000 to transport a pound of building material to Mars. Koshnevis proposes the use of martian soil containing Sulphur be melted at 240 degrees F to make it act like cement and extrude it via a nozzle to print the desired structure on Mars. The process will be used to build small habitats on the planet, including landing pads, roads, hangers for landers, support walls, radiation protection walls, lunar fuel vessels etc. The company has printed a prototype using martian soil simulant with no water and Sulphur binder (Contour Crafting Co.'s Website. (n.d.)).

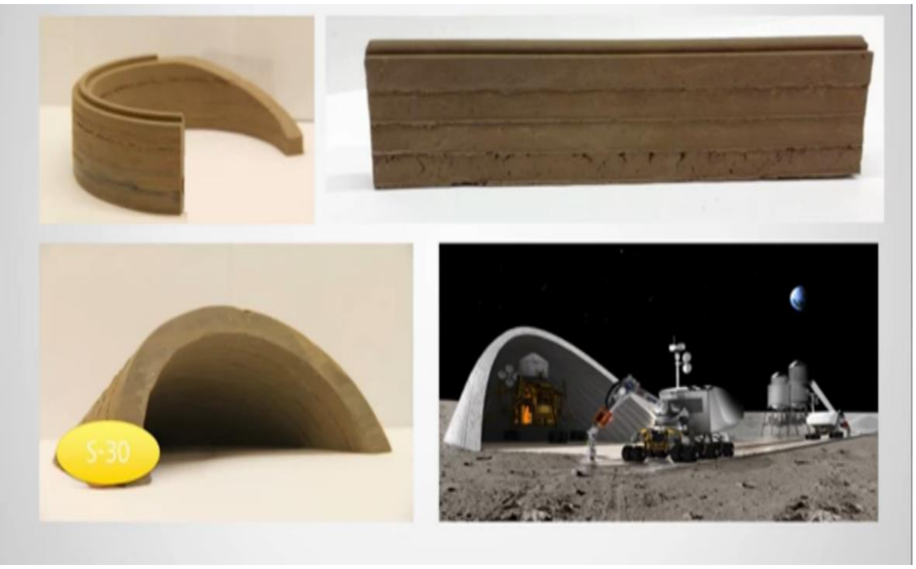


*Figure 42: Building with Martian material (Contour Crafting Co.'s Website. (n.d.)).*

### e. Influencing Factors

By simplifying construction tasks by automation and eliminating the need for pre-assembly/assembly activities, supplier requirements and transportation services, Contour Crafting achieves excellent **Supply-side benefits**. Providing innovative solutions for ensuring the printing technology's **Compatibility** with the construction site has been the focus of the company. The implementation of contour crafting technology has been difficult in the United States due to prevailing labor and zoning policies. Hence the hesitation and resistance to 3DP technology adoption addresses the importance of **External Pressure** and **Uncertainties**.

Contour Crafting emphasizes the importance of **Relative Advantage** by aiming for complete autonomy in its innovations by reducing manpower requirement and safety issues in construction. The company focuses on innovative robotic applications and thus has **Absorptive Capacity** through a workforce of engineers and expert technicians who ensure that **Complexity** is not a limitation. Contour Crafting has not provided for the market yet, thus **Demand-side Benefit** factor is not applicable to their case.

## 6.3. Laticrete International, Connecticut, USA

### a. Introduction

Founded in 1956, Laticrete International is a leader of construction installations providing tile and stone installation and maintenance, floor heating and decorative finishes. Headquartered in Bethany (New Haven), Connecticut, USA, Laticrete started working on 3D printing projects in 2017. Laticrete works with printing partners worldwide, printing building column components, wall sections, and decorative shapes. Most of Laticrete’s current and future work is for Dubai, UAE based projects. The company has several printing projects upcoming in Dubai. The company also has a team dedicated to construction 3D printing research and development.

### b. Projects

2018 project in Dubai, UAE in collaboration with KKrane, LLC, an industrial automation company founded in 2016 in Forest, Virginia that develops and produces concrete 3D printers. Laticrete provided 3D printed, non-standard shaped columns and wall sections for the project currently completed and undergoing weather testing. The total budget allocated for 3D printing is approximately $20,000 which includes procuring and dispatching the printer to Dubai, construction material costs, manpower and engineering services.

*Figure 43. Laticrete’s column printing*

Laticrete is currently printing a pavilion for Ball State University in Indiana, USA. This project will be out for display at Ball State's architectural event Columbus Exhibit. 150 cement-based components are being printed off-site, transported to site and assembled into a 50 feet x 30 feet pavilion over a span of one month. The project has a complex design and 3D printing makes its construction easier when compared to conventional means.

*Figure 44. Proposed design for pavilion for Ball State University*

Laticrete is also working with the Center for Rural Information and Action in India to 3D print multiple toilets in Khadibhandar, Bihar in India. This project is a 6-stacked modular component design, each unit is proposed to be 1.5m x 1.5m floor area and will be made of cement. The units will be printed off-site in Laticrete's office in Hyderabad and then transported and assembled in Bihar.

*Figure 45: Laticrete's model of 3D printed toilet*

### c. Influencing Factors

Laticrete being young in the 3D printing business aims to focus on encouraging the acceptance of the technology within the organization and among their contractors. The **Absorptive Capacity** of the company and its employees is a crucial success factor. Several other companies, including 3D printer and component suppliers, and raw material vendors contributed and collaborated in the project's R&D. Most employees working on the project have tertiary-level education. Laticrete believes that integrating a cross-functional team is primary. The project's material usage was not improved, in fact more material waste was registered while attempting to attain the desired pumping pressure to pour material, which is common in small-scale projects. Hence the importance of **Relative Advantage** comes into consideration for the future.

**Compatibility** of printed products and managing **Supply-side** and **Demand-side Benefits** are factors which the company is working towards to promote their practices to the market. **Complexity**, **Uncertainty** and **Trialability** are not factors that influence Laticrete’s practices since they are a small-scale contractor.

## 7. Results obtained and discussions

After qualitative and quantitative analysis of the data, the importance of each measurement item associated with each factor could be measured and compared.

a. All proposed factors are deemed important to consider in determining the successful adoption on 3D printing in construction. All measurement items are significant because mean response is more than 3 and CVR values of all measurement variables are more than 0.50 for all respondents.

b. Deeper study of CVR values for non-USA and USA respondent categories provide a few variables with CVR less than 0.50.

| Respondent Category | Measurement Item | CVR | Factor |
|---|---|---|---|
| USA | Construct in harsh and aggressive environments | 0.355 | Relative Advantage |
| USA | Major share of employees has education at tertiary level | 0.355 | Absorptive Capacity |
| USA | Maintaining 3D printer is easy | 0.416 | Complexity |
| USA | Matching available 3D printing materials with the characteristics of legacy construction processes | 0.416 | Compatibility |
| Non-USA | Suitability of printing conventional design elements | 0.462 | Compatibility |
| USA | Reducing the need for transportation services | 0.484 | Supply-side Benefits |
| USA | Increasing collaboration among stakeholders (architects, engineers, constructors,<br>suppliers, etc.) | 0.484 | Supply-side Benefits |
| USA | Competitive pressure | 0.484 | External Pressure |

*Table 15. Low CVR variables from non-USA and USA respondent categories*

Irrespective of the low importance indicated for the variables by CVR, the measurement items must still be considered significant because the low importance rated might be a result of bias arising due to:

  i. Respondent not considering the future possibilities and scope of 3D printing in construction while rating the variables and their importance.
  ii. Respondent not considering the importance of the measurement item outside of their professional field and restricting their opinion to their 3D printing area of practice.
  iii. Lack of a standard code of practice forming differences in practices and expectations of professionals from different countries, backgrounds and experiences.

c. The similarity in top and bottom important variables conveys that 3D printing technology is primarily expected to provide technical advantages over conventional means of construction, irrespective of the country or industry that adopts or develops it.

d. The differences in top and bottom important variables for the two groups suggest a different phase of technology adoption outside USA compared to within USA. Non-USA respondents seem to focus on future developments and applications of 3D printing technology in construction by emphasizing the importance of increasing product quality, flexibility and creativity in design. USA respondents seem to focus on troubleshooting the legal, organizational and market barriers in adopting the technology. This suggests more autonomy and development outside the USA and hesitation and restrictions within the USA.

## 8. Conclusion and future work

Construction industry has taken several efforts to adopt 3D printing technology. But despite being a great promise, its current usefulness is still limited. Apart from economic reasons, there are several social, market and business aspects of the technology which affect the extent and rate of 3DP adoption. The need to address these aspects and identify the factors affecting the success/failure of construction 3DP projects as the first step to pursue implementation of the technology prompted this research.

Nine success factors and forty-two corresponding measurement items have been identified and analyzed through literature review, case studies, surveys, interviews and correspondence with worldwide construction 3D printing experts and professionals. All factors are finally determined important to consider for the success of a construction 3DP project at its current phase. Relative significance of the factors and measurement items have been determined based on 82 questionnaire survey responses.

The research attempts at qualitatively and quantitatively understand the importance of the proposed factors and measurement items. Yet, the study has some limitations.

- The study is based on a small number of responses.
- Worldwide responses are considered but a major portion of respondents are USA-based. Scattered responses are obtained from other countries, with different economic backgrounds and construction practices.
- Responses from all stakeholders with uncommon areas of practice are accounted.
- Research assumes that the responses are unbiased. The possible biases are addressed.

Findings of the research may be used by practitioners to strategize for improvement of future 3D printing research and implementation in construction. Proposed factors can be updated by extending the literature to more studies and theories in the area of innovation and construction. Altogether, the findings can help achieve an understanding of 3DP and increase the likelihood of successful adoption in various sectors within construction.

# Appendices

## A. Questionnaire survey

Part I. Rating the importance of success/failure factors for 3D printing in construction

| **Factors** | **Measurement items** | **Scale of importance** | | | | |
|---|---|---|---|---|---|---|
| | | **1 (very low imp)** | **2 (low imp )** | **3 (fair imp)** | **4 (very imp)** | **5 (extr-emely imp)** |
| **Relative advantage** | Reduce construction time | | | | | |
| | Freedom of design at no extra cost | | | | | |
| | Improve material usage | | | | | |
| | Reduce safety issues | | | | | |
| | Reducing cost of construction component/structure | | | | | |
| | Optimize components/ structures and integrate more functionality into them | | | | | |
| | Reduce manpower requirement | | | | | |
| | Reduce product quality problems | | | | | |
| | Construct in harsh and aggressive environments | | | | | |
| **Complexity** | Operating 3D printer is easy | | | | | |
| | Managing digital construction process is easy | | | | | |
| | Computer-generated design process is easy | | | | | |
| | Maintaining 3D printer is easy | | | | | |
| **Trialability** | Precision of the printed objects is within acceptable tolerances | | | | | |
| | 3D printing material properties are predictable | | | | | |
| | Behavior of 3D printing product from a long-term perspective | | | | | |
| **Compatibility** | Flexibility to print various sizes of objects for different construction needs | | | | | |
| | Matching available 3D printing materials with the characteristics of legacy construction processes | | | | | |
| | Compatibility of construction site environment with 3D printing technology | | | | | |
| | Suitability of printing conventional design elements | | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Absorptive capacity** | Integrating a cross-functional team in a process to plan building product and process design, and construction activity | | | | | |
| | Knowledge, expertise, talents, creativity and skills of a company' workers | | | | | |
| | Adequacy of company's resources to produce, test or implement 3D printing technology | | | | | |
| | Company team attitudes toward 3D printing in general | | | | | |
| | Extensive cooperation with other companies or research institutions in R&D | | | | | |
| | Significant share of company capital expenditure devoted to R&D | | | | | |
| | Major share of employees has education at tertiary level | | | | | |
| **External pressure** | Lack of information on technical and economic benefits arising from the innovation and restrictions imposed by regulations, contractors and consultants isolated from one another | | | | | |
| | Skeptical attitudes/psychological barriers of consumers in relation to 3D printing technologies and product implementations | | | | | |
| | Lack of technical standards, standards for quality control and product certification issues | | | | | |
| | Competitive pressure | | | | | |
| **Uncertainty** | Uncertainty in 3D printing technology profitability | | | | | |
| | Resistance to environmental influences and failure under exposure to high stress | | | | | |
| | Perceived side effects associated with the innovation. | | | | | |
| **Supply-side benefits** | Reducing and/or simplifying construction tasks | | | | | |
| | Increasing collaboration among stakeholders (architects, engineers, constructors, suppliers, etc.) | | | | | |
| | Reducing the need for pre-assembly/ assembly activities | | | | | |
| | Reducing number of suppliers involved in construction process | | | | | |
| | Reducing the need for transportation services | | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Demand-side benefits** | Faster reaction to changing customer needs | | | | | |
| | Customized production of printed components | | | | | |
| | Production in collaboration with the customer and supplier (e.g. customers integrated in product development) | | | | | |

## Part II. Respondent Information

Q. 1. Respondent data

Name

Organization

Organization website

Title/Position

Email

Country

Q.2. Respondent's years of experience in construction industry

- 1-5
- 6-10
- 11-20
- Above 20

Q.3. Respondent's education level

- Doctoral
- Master
- Bachelor
- High school
- Other (Please specify) ___________________

Q.4. Respondent's primary area of professional practice

○ 3D printing organizations and manufacturing
○ Academic and professional institutions
○ Developers and clients
○ Construction project management
○ Engineering consulting
○ Quantity surveying
○ Manufacturers and suppliers
○ Estate and facilities management
○ Government organizations
○ Other (Please specify) ____________________

## B. Respondent Information

| Name | Organization | Organization Website | Title/Position | Email |
|---|---|---|---|---|
| **Ali Kazemian** | Contour Crafting Corporation | | | |
| **Adithya VS** | Tvasta Manufacturing Solutions Private Ltd. | tvastagroup.in | C.E.O | adithyavs@tvastagroup.in |
| **wei** | hkust | null | stu | wzhangay@ust.hk |
| **Ole Ellinghausen** | COBOD International A/S | www.cobod.com | Head of Production | ole@cobod.com |
| | CyBe Construction | CyBe.eu | | |
| **Ehab Samir Awad** | Orascom Construction | Orascom.com | Senior Project Controls Manager | ehab.awad@orascom.com |
| **Alvino Levario** | Gilton construction | | Carpenter | alvinolevario691@icloud.com |
| **Andre Fuqua** | Entech Engineering PC | www.entech.nyc | Project Engineer | andrefuqua@columbia.edu |
| **Dorottya Tamasi** | Lafarge Cement Hungary Ltd. | www.lafarge.hu | Quality manager | dorottya.tamasi@lafargeholcim.com |
| **Maider Azpeitia** | TECNALIA | www.tecnalia.com | Reseacher | maider.azpeitia@tecnalia.com |
| **Liz Brathwaite** | Skanska | www.skanska.co.uk | Health & Safety Manager | liz.brathwaite@skanska.co.uk |
| **Timothy Wangler** | ETH Zurich Institute for Building Materials | | Senior Researcher | wangler@ifb.baug.ethz.ch |
| **Ming Qu** | Purdue University | Www.purdue.edu | Associate prof | Mqu@purdue.edu |
| **Johan Potgieter** | Massey University | http://massey.ac.nz | Professor | j.potgieter@massey.ac.nz |
| **Frank W. Gayle** | NIST - Advanced Manufacturing National Program Office | manufacturing.gov | Deputy Director, Office of Advanced | fgayle@nist.gov |

| | | | | |
|---|---|---|---|---|
| | | | Manufacturing | |
| **Joshua Scott Steelman** | University of Nebraska - Lincoln | | Assistant Professor | joshua.steelman@unl.edu |
| **Mikel** | TECNALIA | | Market Manager | mikel.barrado@tecnalia.com |
| **Mo Ehsani** | QuakeWrap, Inc. | www.QuakeWrap.com | President & CEO | Mo@QuakeWrap.com |
| **Eric Compton** | Genesis Dimensions | www.GenesisDimensions.com | Principal Engineer | Eric@G3D.IO |
| **Patti Harburg-Petrich** | BuroHappold | | Principal | patti.harburg-petrich@burohappold.com |
| **Brian Post** | Oak Ridge National Laboratory | www.ornl.gov/manufacturing | R&D Staff Member | Postbri@gmail.com |
| **Yong Gan** | Cal Poly Pomona | www.cpp.edu | Professor | yxgan@cpp.edu |
| **John Read** | Arup | Www.arup.com | Associate Director | john.read@arup.com |
| **Negar Kalantar** | California College of the Arts | California College of the Arts | Assistant Professor | kalantar@cca.edu |
| **Toni Tolonen** | SGS | sgs.com | Team Leader | toni.tolonen@sgs.com |
| **D Honour** | Aurecon | www.aurecon.com | Professional technologist | dave.honour@aurecongroup.com |
| **Jose A CHICA** | TECNALIA | www.tecnalia.com | Digital Construction Director | joseantonio.chica@tecnalia.com |
| **Patricia Clayton** | University of Texas at Austin | | Assistant Professor | clayton@utexas.edu |
| **Amaia Aramburu** | TECNALIA | www.tecnalia.com | Leader of 3d Platfrom in Construction | |

| | | | | |
|---|---|---|---|---|
| **M. BRUURS** | Witteveen+Bos | witteveenbos.com | Consultant digital construction | marijn.bruurs@witteveenbos.com |
| **WESTEEL** | TTO OUEST VALORISATION | www.ouest-valorisation.com | Marketing Director | bruno.westeel@ouest-valorisation.fr |
| **Richard Murphy** | Aurecon | https://www.aurecongroup.com/ | Technical director | richard.murphy@aurecongroup.com |
| **Luis Clemente** | ACCIONA Construccion SA | acciona.com | 3D Printing Executive director | lclemente@acciona.com |
| **Declan Barrett** | Aurecon | www.aurecongroup.com | Digital Practice Leader | declan.barrett@aurecongroup.com |
| **Ho Chaw Sing** | NTUitive | www.namic.sg | MD | chawsing@ntuitive.sg |
| **Ignacio Fernandez** | Arup | www.arup.com | Associate Director | ignacio.fernandez@arup.com |
| **Biranchi Panda** | Nanyang Technological University, Singapore | Nanyang Technological University, Singapore | | BIRANCHI001@e.ntu.edu.sg |
| **Kjell Skjeggerud** | HeidelbergCement Norway | | Head of Development | |
| | | Www.rvo.nl | | |
| **Tony Bisio** | | | | TONY.BISIO@ARUP.COM |
| **MASSIMO BORSA** | ITALCEMENTI - HEIDELBERG CEMENT GROUP | www.heidelbergcement.com | Head of Innovation Laboratories - Global Product Innovation Department | m.borsa@italcementi.it |
| **Leonard Dodd** | ErectorBot | ErectorBot.com | CEO | admin@erectorbot.com |

| | | | | |
|---|---|---|---|---|
| **Eric Herrmann** | Institute of structural Design | https://www.tu-braunschweig.de/ite | Research assistant | e.herrmann@tu-bs.de |
| **jihoon Chung** | Yonsei University | | Graduate Researcher Assitant | j_chung@yonsei.ac.kr |
| **Kroon** | | | IP consultant | yp.kroon@rvo.nl |
| **Gita Sakale** | Heidelbergcement, HC Betons Latvia | https://www.hcbetons.lv/lv | Quality manager | gita.sakale@heidelbergcement.com |
| **Viacheslav Markin** | TU Dresden | | | v.markin@outlook.de |
| **Francisco Shwortshik** | Holcim Central América | www.holcim.com.sv | Commercial Director Central America | francisco.shwortshik@lafargeholcim.com |
| **Frank Will** | TU Dresden / Stiftungsprofessur für Baumaschinen | tu-dresden.de/ing/maschinenwesen/imd/bm | Professor | frank.will@tu-dresden.de |
| **Florian Storch** | Technische Universität Dresden | https://tu-dresden.de/ing/maschinenwesen/imd/bm | research assistant | florian.storch@tu-dresden.de |
| **Klaudius Henke** | TUM Chair of Timber Structures and Building Construction | http://www.hb.bgu.tum.de/startseite/ | Research Associate | henke@tum.de |
| **Julian Leland Bell** | MIT Media Lab, Mediated Matter Group | https://mediatedmattergroup.com/ | Research Assistant (Former) | jleland@mit.edu |
| **Matthew Carli** | Laticrete | Www.laticrete.com | Director innovation | Mdcarli@laticrete.com |
| **Rick Blanton** | Terrapin Works | terrapinworks.umd.edu | DTO | rlbjr@umd.edu |
| **Andrew Oliver** | Terrapin Works | terrapinworks.umd.edu | Senior Lab Manager | terrapinworks@umd.edu |
| **George Tryfonos** | University Of Cyprus | http://www.ucy.ac.cy | Special Scientist | at07tg2@ucy.ac.cy |

| | | | | |
|---|---|---|---|---|
| **Vukorep** | BTU | | Prof. | |
| **Martin Krause** | Technical University Dresden | https://tu-dresden.de/bu/bauingenieurwesen/ibb | Scientific Assistant | martin.krause3@tu-dresden.de |
| **Peng FENG** | Tsinghua University | http://www.tsinghua.edu.cn/publish/thu2018/index.html | Professor | fengpeng@tsinghua.edu.cn |
| **Mahmoud Awad** | LafargeHolcim | | Quality Manager | mahmooud.awad@gmail.com |
| **Blair Souter** | Armatron Systems | www.armatron.com | COO | blair@armatron.com |
| **Dr. Guillermo A Riveros** | USACE | | Research Civil engineer | guillermo.a.riveros@usace.army.mil |
| **Heron Werner Junior** | Clinica de Diagnóstico por Imagem - CDPI | www.feto3d.com | MD/PhD | heronwerner@hotmail.com |
| **Izabela Hager** | Cracow University of Technology | Cracow University of Technology | Dr | ihager@pk.edu.pl |
| **Perrot Arnaud** | Université de Bretagne Sud | Université de Bretagne Sud | associate professor, PhD | arnaud.perrot@univ-ubs.fr |
| **Tom Newman** | Holcim (US) Inc. | | Geologist | tom.newman@lafargeholcim.com |
| **Kathy Mitchell** | US Army Corps of Engineers | | Environmental Agreements PM | kathy.s.mitchell@usace.army.mil |
| **Lixiong Cai** | Huazhong University of Science and Technology | | Postdoctoral | cailixiongjob@163.com |
| **Kho Verian** | Laticrete International, Inc. | Laticrete International, Inc. | Scientist | kverian@laticrete.com |
| **Sebastian Bendall** | Tall Oaks Construction PTY LTD | | Director | seb_c_b@hotmail.com |
| **Batoul** | UAE University | https://www.uaeu.ac.ae/en/ | Research Assistant | b_hittini@uaeu.ac.ae |
| **Denis van der Graaff** | 3D Potter | https://3dpotter.com/ | IT Manager | techsupport@3dpotter.com |

|  |  |  |  |  |
|---|---|---|---|---|
| **Tyson James** | AECOM | aecom.com | Civil Engineer II | Tyson.James@aecom.com |

## C. Respondents years of experience in construction

| Answer | % | Count |
|---|---|---|
| **1-5** | 37.50% | 30 |
| **6-10** | 16.25% | 13 |
| **11-20** | 21.25% | 17 |
| **Above 20** | 25.00% | 20 |
| **Total** | 100% | 80 |

## D. Respondents education level

| Answer | % | Count |
|---|---|---|
| **Doctoral** | 38.75% | 31 |
| **Master** | 37.50% | 30 |
| **Bachelor** | 13.75% | 11 |
| **High School** | 2.50% | 2 |
| **Other (Please specify)** | 7.50% | 6 |
| **Total** | 100% | 80 |

## E. Respondents type of organization

| Answer | % | Count |
|---|---|---|
| **3D printing producers** | 22.78% | 18 |
| **Academic Institutions** | 32.91% | 26 |
| **Construction Project Management** | 5.06% | 4 |
| **Engineering Consultants** | 18.99% | 15 |
| **Government Engineering and R&D Services** | 7.59% | 6 |
| **Other** | 12.66% | 10 |
| **Total** | 100.00% | 79 |

## F. Response Statistics

### i. Relative Advantage

| Measurement Item | 1 | | 2 | | 3 | | 4 | | 5 | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Improve material usage** | 0.00% | 0 | 6.10% | 5 | 26.83% | 22 | 39.02% | 32 | 28.05% | 23 | 82 |
| **Freedom of design at no extra cost** | 1.22% | 1 | 10.98% | 9 | 17.07% | 14 | 30.49% | 25 | 40.24% | 33 | 82 |
| **Optimize components/ structures and integrate more functionality into them** | 2.44% | 2 | 7.32% | 6 | 24.39% | 20 | 42.68% | 35 | 23.17% | 19 | 82 |
| **Construct in harsh and aggressive environments** | 6.10% | 5 | 18.29% | 15 | 30.49% | 25 | 26.83% | 22 | 18.29% | 15 | 82 |
| **Reduce manpower requirement** | 4.88% | 4 | 3.66% | 3 | 28.05% | 23 | 36.59% | 30 | 26.83% | 22 | 82 |
| **Reduce cost of construction component/structure** | 0.00% | 0 | 9.76% | 8 | 26.83% | 22 | 30.49% | 25 | 32.93% | 27 | 82 |
| **Reduce construction time** | 1.22% | 1 | 1.22% | 1 | 20.73% | 17 | 31.71% | 26 | 45.12% | 37 | 82 |
| **Reduce safety hazards** | 0.00% | 0 | 12.20% | 10 | 23.17% | 19 | 26.83% | 22 | 37.80% | 31 | 82 |
| **Reduce product quality problems** | 3.66% | 3 | 9.76% | 8 | 35.37% | 29 | 35.37% | 29 | 15.85% | 13 | 82 |

### ii. Ease of Use

| Measurement Item | 1 | | 2 | | 3 | | 4 | | 5 | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Computer-generated design process is easy** | 4.88% | 4 | 8.54% | 7 | 32.93% | 27 | 34.15% | 28 | 19.51% | 16 | 82 |
| **Managing digital construction process is easy** | 2.44% | 2 | 12.20% | 10 | 28.05% | 23 | 39.02% | 32 | 18.29% | 15 | 82 |
| **Operating 3D printer is easy** | 4.88% | 4 | 8.54% | 7 | 23.17% | 19 | 40.24% | 33 | 23.17% | 19 | 82 |
| **Maintaining 3D printer is easy** | 7.32% | 6 | 15.85% | 13 | 28.05% | 23 | 34.15% | 28 | 14.63% | 12 | 82 |

### iii. Trialability

| **Measurement Item** | **1** | | **2** | | **3** | | **4** | | **5** | | **Total** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **3D printing material properties are predictable** | 4.88% | 4 | 8.54% | 7 | 17.07% | 14 | 42.68% | 35 | 26.83% | 22 | 82 |
| **Behavior of 3D printing product from a long-term perspective (e.g. length of the product life cycle)** | 3.66% | 3 | 15.85% | 13 | 20.73% | 17 | 39.02% | 32 | 20.73% | 17 | 82 |
| **Precision of the printed objects is within acceptable tolerances** | 0.00% | 0 | 4.88% | 4 | 26.83% | 22 | 37.80% | 31 | 30.49% | 25 | 82 |

### iv. Compatibility

| **Measurement Item** | **1** | | **2** | | **3** | | **4** | | **5** | | **Total** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Flexibility to obtain various sizes of objects for different construction needs** | 2.44% | 2 | 7.32% | 6 | 19.51% | 16 | 37.80% | 31 | 32.93% | 27 | 82 |
| **Compatibility of construction site environment with 3D printing technology** | 6.10% | 5 | 13.41% | 11 | 28.05% | 23 | 39.02% | 32 | 13.41% | 11 | 82 |
| **Suitability of printing conventional design elements** | 8.54% | 7 | 14.63% | 12 | 30.49% | 25 | 36.59% | 30 | 9.76% | 8 | 82 |
| **Matching available 3D printing materials with the characteristics of legacy construction processes** | 3.66% | 3 | 18.29% | 15 | 24.39% | 20 | 41.46% | 34 | 12.20% | 10 | 82 |

v. Absorptive Capacity

| Measurement Item | 1 | | 2 | | 3 | | 4 | | 5 | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Significant share of company capital expenditure devoted to R&D** | 2.44% | 2 | 13.41% | 11 | 35.37% | 29 | 41.46% | 34 | 7.32% | 6 | 82 |
| **Extensive cooperation with other companies or research institutions in R&D** | 2.44% | 2 | 12.20% | 10 | 25.61% | 21 | 41.46% | 34 | 18.29% | 15 | 82 |
| **Major share of employees has education at tertiary level** | 6.10% | 5 | 15.85% | 13 | 41.46% | 34 | 29.27% | 24 | 7.32% | 6 | 82 |
| **Knowledge, expertise, talent, creativity and skills of the company' workforce** | 2.44% | 2 | 2.44% | 2 | 29.27% | 24 | 45.12% | 37 | 20.73% | 17 | 82 |
| **Integrating a cross-functional team in a process to plan building product and process design, and construction activity** | 2.44% | 2 | 3.66% | 3 | 24.39% | 20 | 43.90% | 36 | 25.61% | 21 | 82 |
| **Company team attitudes toward 3D printing in general** | 1.22% | 1 | 10.98% | 9 | 25.61% | 21 | 42.68% | 35 | 19.51% | 16 | 82 |
| **Adequacy of company's resources to produce, test or implement 3D printing technology** | 1.22% | 1 | 12.20% | 10 | 18.29% | 15 | 46.34% | 38 | 21.95% | 18 | 82 |

vi. External Pressure

| **Measurement Item** | **1** | | **2** | | **3** | | **4** | | **5** | | **Total** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Competitive pressure** | 3.66% | 3 | 13.41% | 11 | 23.17% | 19 | 36.59% | 30 | 23.17% | 19 | 82 |
| **Lack of technical standards, standards for quality control and product certification issues** | 2.44% | 2 | 12.20% | 10 | 20.73% | 17 | 29.27% | 24 | 35.37% | 29 | 82 |
| **Skeptical attitudes/ psychological barriers of consumers in relation to 3D printing technologies and product implementations** | 0.00% | 0 | 14.63% | 12 | 20.73% | 17 | 35.37% | 29 | 29.27% | 24 | 82 |
| **Lack of information on technical and economic benefits arising from innovation and restrictions imposed by regulations, contractors and consultants isolated from one another** | 0.00% | 0 | 4.88% | 4 | 26.83% | 22 | 48.78% | 40 | 19.51% | 16 | 82 |

### vii. Uncertainty

| Measurement Item | 1 | | 2 | | 3 | | 4 | | 5 | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Perceived side effects associated with the innovation** | 2.44% | 2 | 12.20% | 10 | 39.02% | 32 | 34.15% | 28 | 12.20% | 10 | 82 |
| **Resistance to environmental influences and failure under exposure to high stress** | 2.44% | 2 | 4.88% | 4 | 30.49% | 25 | 41.46% | 34 | 20.73% | 17 | 82 |
| **Uncertainty in 3D printing technology profitability** | 2.44% | 2 | 4.88% | 4 | 25.61% | 21 | 40.24% | 33 | 26.83% | 22 | 82 |

### viii. Supply-side Benefits

| Measurement Item | 1 | | 2 | | 3 | | 4 | | 5 | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Reducing and/or simplifying construction tasks** | 0.00% | 0 | 8.54% | 7 | 15.85% | 13 | 50.00% | 41 | 25.61% | 21 | 82 |
| **Reducing the need for pre-assembly/ assembly activities** | 3.66% | 3 | 10.98% | 9 | 29.27% | 24 | 31.71% | 26 | 24.39% | 20 | 82 |
| **Reducing the need for transportation services** | 3.66% | 3 | 19.51% | 16 | 18.29% | 15 | 35.37% | 29 | 23.17% | 19 | 82 |
| **Reducing number of suppliers involved in construction process** | 1.22% | 1 | 9.76% | 8 | 31.71% | 26 | 36.59% | 30 | 20.73% | 17 | 82 |
| **Increasing collaboration among stakeholders (architects, engineers, constructors, suppliers, etc.)** | 1.22% | 1 | 12.20% | 10 | 21.95% | 18 | 42.68% | 35 | 21.95% | 18 | 82 |

### ix. Demand-side Benefits

| **Measurement Item** | **1** | | **2** | | **3** | | **4** | | **5** | | **Total** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Customized production of printed components** | 1.22% | 1 | 6.10% | 5 | 21.95% | 18 | 47.56% | 39 | 23.17% | 19 | 82 |
| **Faster reaction to changing customer needs** | 2.44% | 2 | 4.88% | 4 | 21.95% | 18 | 41.46% | 34 | 29.27% | 24 | 82 |
| **Production in collaboration with the customer and supplier (e.g. customers integrated in product development)** | 4.88% | 4 | 4.88% | 4 | 25.61% | 21 | 37.80% | 31 | 26.83% | 22 | 82 |

## G. Frequency of USA and non-USA responses

i. Non-USA (52 responses)

| **Factor/Respondent** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| RA1 | 0 | 2 | 16 | 22 | 12 |
| RA2 | 0 | 6 | 8 | 15 | 23 |
| RA3 | 1 | 4 | 15 | 22 | 10 |
| RA4 | 3 | 8 | 18 | 13 | 10 |
| RA5 | 2 | 2 | 15 | 23 | 10 |
| RA6 | 0 | 5 | 15 | 17 | 15 |
| RA7 | 1 | 1 | 9 | 20 | 21 |
| RA8 | 0 | 6 | 14 | 15 | 17 |
| RA9 | 1 | 7 | 18 | 18 | 8 |
| CX1 | 0 | 6 | 18 | 17 | 11 |
| CX2 | 0 | 6 | 14 | 24 | 8 |
| CX3 | 1 | 4 | 13 | 20 | 14 |
| CX4 | 2 | 9 | 15 | 21 | 5 |
| TA1 | 2 | 4 | 8 | 24 | 14 |
| TA2 | 2 | 9 | 10 | 24 | 7 |
| TA3 | 0 | 2 | 14 | 20 | 16 |
| CP1 | 2 | 1 | 12 | 18 | 19 |
| CP2 | 3 | 8 | 12 | 22 | 7 |
| CP3 | 5 | 9 | 15 | 19 | 4 |
| CP4 | 3 | 7 | 14 | 22 | 6 |
| AC1 | 2 | 7 | 17 | 21 | 5 |
| AC2 | 1 | 7 | 11 | 22 | 11 |
| AC3 | 3 | 6 | 25 | 13 | 5 |
| AC4 | 1 | 1 | 15 | 24 | 11 |
| AC5 | 0 | 0 | 15 | 22 | 15 |
| AC6 | 0 | 7 | 18 | 21 | 6 |
| AC7 | 0 | 7 | 11 | 24 | 10 |
| EP1 | 1 | 6 | 13 | 20 | 12 |
| EP2 | 0 | 9 | 9 | 15 | 19 |
| EP3 | 0 | 7 | 11 | 19 | 15 |
| EP4 | 0 | 3 | 13 | 28 | 8 |
| UC1 | 2 | 6 | 23 | 16 | 5 |
| UC2 | 1 | 0 | 17 | 25 | 9 |
| UC3 | 1 | 2 | 13 | 24 | 12 |
| SS1 | 0 | 4 | 6 | 28 | 14 |
| SS2 | 1 | 7 | 17 | 18 | 9 |
| SS3 | 2 | 10 | 12 | 20 | 8 |

| | | | | | |
|---|---|---|---|---|---|
| SS4 | 0 | 3 | 20 | 18 | 11 |
| SS5 | 0 | 4 | 11 | 23 | 14 |
| DS1 | 0 | 3 | 12 | 22 | 15 |
| DS2 | 0 | 2 | 10 | 22 | 18 |
| DS3 | 1 | 1 | 10 | 23 | 17 |

ii. USA (30 responses)

| **Factor/Respondent** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| RA1 | 0 | 3 | 6 | 10 | 11 |
| RA2 | 1 | 3 | 6 | 10 | 10 |
| RA3 | 1 | 2 | 5 | 13 | 9 |
| RA4 | 2 | 7 | 7 | 9 | 5 |
| RA5 | 2 | 1 | 8 | 7 | 12 |
| RA6 | 0 | 3 | 7 | 9 | 11 |
| RA7 | 0 | 0 | 8 | 7 | 15 |
| RA8 | 0 | 4 | 5 | 8 | 13 |
| RA9 | 2 | 1 | 11 | 12 | 4 |
| CX1 | 4 | 1 | 9 | 11 | 5 |
| CX2 | 2 | 4 | 9 | 8 | 7 |
| CX3 | 3 | 3 | 6 | 13 | 5 |
| CX4 | 4 | 4 | 8 | 7 | 7 |
| TA1 | 2 | 3 | 6 | 11 | 8 |
| TA2 | 1 | 4 | 7 | 8 | 10 |
| TA3 | 0 | 2 | 8 | 11 | 9 |
| CP1 | 0 | 5 | 4 | 13 | 8 |
| CP2 | 2 | 3 | 11 | 10 | 4 |
| CP3 | 2 | 3 | 10 | 11 | 4 |
| CP4 | 0 | 8 | 6 | 12 | 4 |
| AC1 | 0 | 4 | 12 | 13 | 1 |
| AC2 | 1 | 3 | 10 | 12 | 4 |
| AC3 | 2 | 7 | 9 | 11 | 1 |
| AC4 | 1 | 1 | 9 | 13 | 6 |
| AC5 | 2 | 3 | 6 | 14 | 5 |
| AC6 | 1 | 2 | 4 | 14 | 9 |
| AC7 | 1 | 3 | 5 | 14 | 7 |
| EP1 | 2 | 5 | 6 | 10 | 7 |

| | | | | | |
|---|---|---|---|---|---|
| EP2 | 2 | 1 | 8 | 9 | 10 |
| EP3 | 0 | 5 | 6 | 10 | 9 |
| EP4 | 0 | 1 | 9 | 12 | 8 |
| UC1 | 0 | 4 | 9 | 12 | 5 |
| UC2 | 1 | 3 | 8 | 9 | 9 |
| UC3 | 1 | 3 | 8 | 9 | 9 |
| SS1 | 0 | 3 | 7 | 13 | 7 |
| SS2 | 2 | 2 | 7 | 8 | 11 |
| SS3 | 1 | 6 | 3 | 9 | 11 |
| SS4 | 1 | 5 | 6 | 12 | 6 |
| SS5 | 1 | 6 | 7 | 12 | 4 |
| DS1 | 1 | 2 | 6 | 17 | 4 |
| DS2 | 2 | 2 | 8 | 11 | 7 |
| DS3 | 3 | 3 | 11 | 7 | 6 |

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