THE IMPACT OF DIGITAL TECHNOLOGY ON CREATING VIRTUAL ENVIRONMENT IN THE AEC INDUSTRY

by

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Declaration of Authorship

I declare that this thesis is my own work and, to the best of my knowledge and belief, it does not contain material published or written by a third party, except where permission has been obtained and/or appropriately cited through full and accurate referencing.

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Dedication

I dedicate this thesis to beloved parents and the whole small family, my friends, my advisor, my colleagues at both university and work. Your continuous support has equipped me with what I need to push through.

Abstract

The construction industry has been incorporating technology over the last two decades, albeit gradually, as 'technology-push' continues to overcome traditional passivity typical in the sector. Advanced technological tools are crucial to generate a simulated virtual environment that allows for better collaboration, communication and data processing which ultimately leads to less errors and more successful outcomes. The objective of this thesis research is to investigate how digital technology is making headway in the construction industry because of COVID-19. Particularly, the study aims to investigate the extent of use of technology in three periods – pre-COVID, during-COVID and post-COVID. The second objective of this thesis is to examine which digital technology tools impact the virtual environment within an Architecture, Engineering, Construction (AEC) firm the most. For this research, digital technology tools are divided into three groups: data acquisition, processing, and communication. The methodology involved conducting two questionnaire surveys among the construction professionals in the UAE. The first survey's results show the increasing level of usage of digital technology in the AEC industry from pre-COVID, to during COVID and post-COVID periods. Among the three categories, communication technology indicated a higher extent of use as compared to the other two. It was also noticed that there was a slight drop in the use of communication technology from during COVID to post-COVID time, apparently as some of the functions and operations are expected to return to normalcy after the pandemic. In relation to the contribution of digital technologies to the virtual environment, the second survey's results were analyzed using AHP and found that the most significant digital technology level with the highest impact on enhancing the virtual environment is BIM level 3. While the digital technology level that was the least significant was data collection level 1 (manual/paper-based). Furthermore, the results also revealed that 23% of the companies studied in this research displayed a low virtual environment level (10-40%). While 50% of the companies included in this research displayed a medium virtual environment level (40-70%) and 27% of the companies displayed a high virtual environment level in their construction projects (70-100%).

Search Terms: Digital Technology, construction industry, UAE, COVID-19, Virtual Environment

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Chapter 1. Introduction

1.1 Introduction

In this chapter, an overview of the Architecture, Engineering and Construction (AEC) industry, digital technology tools, virtual environments will be provided. Further, this overview will provide a background on how the AEC industry was impacted by the COVID-19 pandemic. This is followed by presenting the problem statement of this research and the thesis' objectives. Lastly, this section is concluded by discussing the structure of the thesis.

1.2 Overview on the AEC industry

Global construction is a $12 trillion (USD) industry, accounting for close to 13.5% of global GDP [1]. Yet, in terms of sector productivity, construction lags manufacturing and the total world economy. "Globally, construction sector labor-productivity growth averaged 1 percent a year over the past two decades, compared with 2.8 percent for the total world economy and 3.6 percent for manufacturing" [2]. There are strong indications from professionals and researchers in the construction industry that advanced Digital Technology (DT) can play a pivotal role, either directly or as a catalyst, in improving construction productivity. However, it is also a fact that construction is traditionally slow in adopting technology. Despite being sluggish as compared to the service and the manufacturing industries, construction has been incorporating digital technology gradually over the last two decades - as 'technology-push' continues to overcome customary and traditional passivity. BIM, or building information modeling, is a prime example of a digital technology that took a long time to gain acceptance in the mainstream construction industry. It is now widely accepted and is proving itself almost essential in the industry. It is more apparent now than ever before in the wake of the COVID-19 crisis. A recent IFS study based on a survey reported that companies concerned with economic disruption were 20% more likely to plan increased spending on digital transformation [3]. It appears that the construction industry is ready to embrace a technological revolution to address these issues and that the global pandemic is perhaps the catalyst the industry needed. Numerous studies listed contemporary digital technologies suitable for use and application in construction. For instance, PwC [4] lists eight essential technologies that are making large impacts on the business of construction. They are artificial intelligence, virtual reality, augmented reality, blockchain, drones, Internet of Things (IoT), robotics, and 3-D printing.

The early months of 2020 witnessed the rise of the COVID-19 pandemic, which had its adverse effects on almost all regions and industry sectors in the globe. However, many claim that the Architecture, Engineering and Construction (AEC) industry was one of the sectors that was hit the hardest by the pandemic. According to a recent Los Angeles investigation, construction crews reported the highest number of positive cases when compared to workers in other sectors such as transport and manufacturing [5]. It is with no doubt that the COVID-19 pandemic affected the United Arab Emirates' (UAE) AEC industry in many ways. Dadlani [6] explained how precautionary measures were enforced in construction companies to ensure prioritization of health and safety of workers. These measures included frequent disinfection programs, social distancing measures, construction workers' body temperatures check and isolation rooms in the event of workers showing any symptoms of the coronavirus. Additionally, during the first six months of 2020, contract awards in the GCC region fell by 20%, this coincided with an increase in payment delays and disputes [7]. In addition, supply chains and subcontractors in the UAE were pressurized by such marketing challenges, causing some of them to go out of business [8].

Digital technology, although not new and existed for some time, was not utilized extensively prior to the 'lockdown' situation caused by the pandemic. The AEC industry has been incorporating digital technology gradually over the last two decades, but remains sluggish as compared to other sectors, such as the service and the manufacturing industries for instance. Ironically, the COVID-19 pandemic has developed an urgency towards adopting new technologies that will play a key role in reshaping the future of the AEC industry, allowing collaboration, data-driven decision making and greater control. The utilization of such technologies shall also facilitate the move towards a sustainable future for contractors and developers [9]. Wallet [10] noted that this pandemic has provided a silver-lining as construction professionals grew more confident in dealing with these technologies which not only helped keep the industry moving during those drastic times but also provided cost and time saving tools that construction professionals can benefit from in the long run.

Despite their attractive potential capabilities, many advanced digital technologies were viewed as tools that could lead to poor results and inefficiencies in the AEC industry prior to the new realization during pandemic [11]. For instance, Hinks and Allen [12] discovered that videoconferencing was not in sync with existing processes. Even in the period post 2010, digital technologies remained in an 'under-utilization' state. In a study conducted in 2014, only 2 out of 14 interviewed AEC firms mentioned that video conferencing software is being utilized to communicate information [13]. To sum up, the capacity and value of digital technologies in the business context was poorly recognized by the AEC firms prior to the COVID-19 pandemic.

The disruptive nature of COVID-19 has pressured many AEC companies to immediately remodel their business strategies via the usage of digital technologies [14]. In many cases, AEC firms lacked the essential digital infrastructure to make the move simple. As a result, obtaining necessary software packages and other resources posed significant challenges, leading to severe inefficiencies [15]. For instance, in the early stages of the pandemic, it was reported that several coordination problems arose due to online communication. Considering a design consultant, such coordination issues caused a delay in the design process during work from home. Additionally, difficulties in meeting with clients were evident as some of the online meetings turned out to be ineffective and unnecessarily prolonged [16]. In many cases, organizations were required to make additional technological investments to improve their ability to work under the changed circumstances. Several businesses, for example, have invested in Virtual Private Networks (VPNs) to acquire remote access to resources and software packages. Only a few companies reported that they already had cloud solutions in place to access licensed software and company databases, making the shift smooth [15].

Besides COVID-19, the impacts of digital technology tools on virtual environments should also be investigated. At first glance, the term "virtual environment" may sound similar to virtual reality technology. However, a virtual environment could describe a wider setting, rather than a specific technology. While there is no consensus within the literature about what exactly a virtual environment is, the term has been usually associated with technology and advancement. For instance, a study in 2003 looked at virtual environment from a "dimension" (2D, 3D, 4D, etc.) perspective, measuring virtual environments in terms of the level of human interaction with a building model, on a computer screen [17]. Similarly, another study compared the capabilities of different "VE displays" in visualizing 3D visuals of a building, one of which was the Head Mounted Display (HMD) [18]. As remote working started becoming a new norm in 2020 and 2021, other studies have looked virtual environments as communicating through online environments (e.g.: video calls, social media) to achieve successful project management [19], not just to visualize building models. In a nutshell, it is logical to look at the term "virtual environment" as the output of utilizing digital technology tools, where digital technology tools are the input in this case. In other words, “virtual environment” can describe a firm’s level of technological setting allowing for smooth and efficient project delivery through the utilization of digital technology.

Virtual environments through the use of digital technologies have contributed to numerous improvements and enhancements in the AEC industry. Due to the fragmented nature of the AEC industry, continuity between the design and construction phases of a construction project has always been an issue which digital technology has successfully minimized. Specifically, Building Information Modelling (BIM) has resolved several collaboration and clash issues, something that bridged a major gap between design and construction [20]. In addition, BIM has enabled integration of the design and construction phases with the operation phase and facility management through an improved project understanding amongst all project stakeholder [21]. Other issues that had their impact minimized by technologies are poor record storage and collaboration in a construction project. Cloud computing technology has allowed for remote massive storage capacities (hundreds of GBs) to minimize storing documents on site with no space and time restrictions on retrieving such data [22]. Through online clouds, big data such as models, cannot only be stored, but also viewed and shared collaboratively between project stakeholders [23].

1.3 Problem Statement

As populations grow and markets expand, business continue to look for innovative ways to survive and grow, and the construction industry is no different. In fact, the complexity and fragmentation of the construction industry makes it tough for AEC firms to stand out in all business aspects, especially in terms of productivity, time and cost efficiency, disputes resolution, and safety [24]. “Going digital” has been the trend which a lot of businesses have been trying to implement over the past few decades. AEC firms have been slowly integrating digital technology in their day-to-day operations to enhance quality, efficiency, and productivity during a construction project [25]. As such, industry 4.0 has shed light on various digital technologies such as robots, BIM, Artificial intelligence, augmented and virtual realities, cloud computing and many more, to improve automation within the sector [26]. Besides, over the past two years, demand for digital technology has peaked due to the rise of the COVID-19 pandemic, making it a necessity rather than a luxury [27].

Hence, the problem statement of this research can be divided into two core elements. The first core element is about the pandemic. It is evident that most construction organizations' (owners, consultants, and contractors) investment in digital technology prior to the pandemic were inadequate to deal with the demands imposed by the crisis. It is likely that several technologies already available and deployed were not utilized at the expected and optimum level. The pandemic abruptly made them more useful than before. As an example, the use of technology necessary for virtual meetings can be cited. This technology has become essential during the lockdown phase, although most likely remained underutilized before the crisis. Perhaps it was not considered necessary or did not have the necessary bandwidth for smooth operations. Therefore, it is important to assess the level of use and investments in digital technology before, during and after the pandemic.

The second core element of the problem statement is that most construction organizations' (owners, consultants, and contractors) utilization of digital technology and hence, degree of virtual environment, vary with the magnitude of the firm, time, geography, and need. As it continues to evolve in all industries, technology is becoming pivotal for businesses to thrive and ensure survival in their respective industries through achieving high degrees of virtual environments. Technology offers several benefits to companies such as ease of operation, better commercial management, reduced costs, and shorter durations to deliver products and services. Therefore, it is important to have means for assessing the level of digital technology necessary to meet the increased demand in Virtual Environments. This assessment will provide guidance for further investment as demand increases in the AEC industry.

1.4 Thesis Objectives

The main aim of this research is to investigate the levels of usage and effectiveness of digital technologies in the Architecture, Engineering, and Construction (AEC) industry. To achieve this aim, the following objectives need to be fulfilled:

- To investigate the use and investment in digital technology for construction projects amid, and in the aftermath of, the COVID-19 pandemic in the context of the UAE construction industry.
- To assess the relative weights of the levels of digital technologies within three categories of technologies (data collection, data processing and data

communication technologies) in enhancing the virtual environment in construction projects.

- To compare the effectiveness of all the three digital technology categories against each other (e.g.: collection vs communication) in terms of achieving a higher degree of virtual environment.
- To determine the current levels of utilization of digital technology and whether higher utilization of digital technology would contribute to higher levels of overall project success.

1.5 Research Contribution

The main contributions of this research are listed below:

- There is currently no clear visibility on the levels of utilization of different digital technology categories due to the rise of the COVID-19 pandemic. Furthermore, the AEC industry is eager to understand how the utilization levels would change after the pandemic has ended. This research will address this gap and provide predictions for AEC firms, this would help firms take more informed decisions about acquiring digital technologies.

- Current literature investigates the benefits of specific technologies and how such technologies have evolved over time. This research however will expand on this subject through categorizing technologies into 3 groups and will look at the impact of individual technologies on the virtual environment of an AEC firm.

1.6 Thesis Organization

This thesis is broken down into 5 main chapters as follows:

Chapter 1- Introduction

This chapter provides an overview of the digital technologies and the virtual environment definitions in the context of construction projects. The chapter also highlights the research significance, aims and objectives and the problem statement.

Chapter 2- Literature Review

This chapter represents the state of art practice in the field of digital technologies and virtual environment in construction projects, as well as the benefits and uses of the different categories of digital technologies.

Chapter 3- Digital Technology and COVID-19

This chapter discusses the methodology used and results of the first survey, which was designed to measure the levels of usage and investment of DT across the three COVID periods.

Chapter 4- Digital Technology and Virtual Environment

This chapter presents the methodology used and results of the second survey, which investigated the magnitude of the impact of each individual digital technology tool on the virtual environment of an AEC firm.

Chapter 5- Summary and Conclusions

Lastly, chapter six concludes the thesis and provides ideas on the potential future works that can add value to this broad topic.

Chapter 2. Literature Review

This chapter explores the benefits and uses of three digital technology categories, namely, data acquisition technologies, data processing technologies, and data communication technologies. Chapter 2 will achieve this objective through presenting an extensive literature review of these three categories.

2.1 Digital Technology Applications in the AEC Industry

The benefits of using Digital Technology (DT) in the AEC industry are multifarious and significant. The adoption of technological innovation gives construction companies the opportunity to rebrand themselves as the providers of smart engineering solutions. In fact, adopting such technological innovations is a strategic decision to improve the image of the construction company and its reputation in the market. Not only this, but digitalizing the construction industry makes it more appealing to young graduates as it challenges the traditional notion of construction jobs being dangerous, difficult, and dirty [28], in addition to being labelled as backward. Furthermore, the efficient use of emerging digital technology helps improve communication, collaboration, better project comprehension, improved information retrieval and increased productivity rates as well as time and cost savings. These benefits contribute to offering a distinct advantage to the market as well as creating a healthier organizational culture where project team members feel more connected to each other through advanced means of communication that raises a sense of belonging and commitment to the construction project [29].

The adoption of technological innovations helps reduce the risks associated with construction projects by directing the construction industry away from the high-risk and towards the low-risk sector zone [30]. In addition, the nature of today's construction industry demands project teams that are geographically dispersed in different time zones across diverse organizational cultures and boundaries. It is only through using such advanced technological innovations, that a collaborative project delivery system can be established where teams can work closely with various disciplines in an effective way [31]. Besides, adopting technological innovations can also help improve the monitoring and inspection of construction sites. For instance, Zhou et al. [32] introduced an AR technique to overlook the inspection process of segment displacement during tunneling construction. The technique enabled overlaying a quality control baseline model on to the real segment and reported the discrepancies.

Despite the benefits offered by digital technology, their adoption in the construction sector is still very low. In fact, Manyika [33] stated that the level of digitalization index for construction industry ranked the lowest among 22 other industries. Delgado et al. [34] divided the challenges of creation of virtual environment in the construction industry, in terms of limitations, into three categories: social, technical, and economic limitations. The social limitations included (but were not limited to) lack of trained workforce, repugnance to change, and data privacy issues. Whereas technical limitations included large space as well as prohibitive processing requirements, lack of user friendliness and accuracy issues. Economic limitations included expensive hardware, expensive training needs, lack of client interest, lack of funds for research and development. It can be concluded that the last one, namely the economic issues, are mainly responsible for lack of necessary investment for promoting digital technology in construction. In this research, digital technology applications are broken down into three facets: data acquisition, data processing, and data communication.

2.1.1 Data acquisition

These are technology and tools in which their utilization in the construction industry would assist in a faster and more efficient data gathering. Regardless of whether the information is gathered onsite or off-site, the data is essential for a successful project delivery. Data acquisition tools include RFID (Radio Frequency Identification), drones, and 3-D laser scanning. Drones, for instance, are aircrafts designed to fly without a pilot or passengers, controlled remotely using radio waves [35]. These innovations have high mobility and visual data acquisition capabilities. As a matter of fact, drones can play a significant role in conducting quantitative analysis of productivity and safety related metrics through the reconstruction of three-dimensional (3D) point clouds from video images produced by the drones [36]. Furthermore, a site staff equipped with a drone can do the same job as multiple personnel without a drone. Thus, using drones can be a powerful tool to comply with the COVID-19 imposed social distancing measures, as the number of people on site would be a few. While some firms may be facing major financial constraints to invest in drone technology, it is critical to note that this technology helped construction firms reduce wastage in time by 18.4% and the time to survey a site by 98% - translating into money savings in the long term [8]. Lastly, this smart system gives construction professionals access to real time data which allows organizations to keep track of their inventory plan and better plan their construction site in general making room for any adjustments needed as soon as possible [37].

Another data acquisition tool that could be well integrated and utilized in the construction industry, as mentioned earlier, is RFID. Radio Frequency Identification (RFID) technology allows for automated tracking of equipment and materials in storage or during delivery and makes information readily available for the personnel who handle material tracking and delivery processes [38]. Furthermore, laser scanning technologies are powerful data acquisition tools that have the capability of capturing complex geometries, angles and distances [39]. While laser scanning technologies require expert operators to run, these technologies provide a great value as the output of these technologies can be used as the basis to develop as-built BIM models of a building [39]. Table 1 shows some of the potential applications of RFID, drones, and laser scanning technologies in the construction industry.

Table 1 - Examples of applications of data acquisition technologies.

Data acquisition technology	**Application(s)**
Radio Frequency Identification Device (RFID)	• Three-dimensional (3D) location of buried utilities [40] • Equipment tracking to prevent collision accidents with heavy equipment [41]
Drones	• Live site surveillance • Quality & Safety checks and monitoring
Laser Scanning	• Dimensional accuracy & structural performance assessment [42] • Characterization of steel reinforcement corrosion [43]

2.1.2 Data processing

The second stage that ultimately comes after data collection is data processing. A virtual innovation that facilitates such a task is Building Information Modelling (BIM). BIM is defined by the US National Institute of Building Sciences as a "digital representation of physical and functional characteristics of a facility creating a shared knowledge resource for information about it forming a reliable basis for decisions during its life cycle, from earliest conception to demolition" [44]. Kaner et al. [45] revealed that BIM enables the design and detail processing of complex 3D geometric shapes to a high level of accuracy with error-free drawings. Additionally, through features of clash detection and early error identification, the probability of disputes and claims are greatly minimized due to the utilization of BIM [46]. Besides this, other features of BIM include automated quantity take off that enable users to avoid the traditional error prone method of measuring elements of a project and assigning related costs to each. This feature also allows stakeholders to know costs early in the design phase so more informed decisions can be made [47],[48].

Lastly, there exist tools/software that processes schedule-related and cost-related data such as Primavera P6 and Esti-mate, respectively. Primavera P6 for instance, is a very commonly used scheduling and resource-planning tool in the AEC industry. "P6" has the capacity to allow users to develop complex and large-scale programs, forecast scenarios using what-if analysis, and track resources and costs through the project life cycle [49]. Comparably, "Esti-mate" is an estimation tool that could be utilized by quantity surveyors, project managers, contract managers and vendors to process and coordinate Bills of Quantities (BoQs), subcontractor and material inquiries and tender adjudications, allowing for accurate and timely project cost tracking [50]. Table 2 illustrates some applications of data processing tools.

Table 2 - Examples of applications of data processing technologies.

Data processing technology	**Application(s)**
BIM	• Allows staff to edit, manage and document design [51] • Documenting the design and project reviews [51]
Primavera P6	• CPM calculations • Resource allocation, delay analysis etc.
Esti-mate	• Quantity takeoffs

2.1.3 Data communication

As far as communication is concerned, some tools provide features such as discussion boards, work sharing, project websites, videoconferencing with data sharing as well as real time data manipulation and exchange through virtual teaming [52].

Furthermore, a virtual platform that has a huge potential to transform coordination in the construction industry is cloud computing. According to Mell and Grance [53], clouding computing is a model for "enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources that can be rapidly provisioned and released with minimal management effort or service provider interaction." In a recent study by Du et al. [54], they proposed a cloud based multiuser virtual reality headset system which is an innovation that collects BIM meta data and translates it into a multiuser virtual communication environment. The technology allows remote project stakeholders to interact and connect simultaneously, thus improving collaboration. Cloud computing software (e.g.: Dropbox) can also provide the necessary features to complement intelligent contracts, or 'icontracts'. An icontract is an advanced smart contract that utilizes computer codes to automate the execution of contractual clauses between project parties [55]. For instance, an icontract connected to a BIM model, would enable the release of payments to a design consultant upon completion of a pre-specified BIM milestone in the contract. Through dropbox and other cloud computing technologies, data sources such as models and emails, which may be linked to icontracts, can be stored, accessed, and updated by various project stakeholders [55]. In a similar manner, blockchain-based intelligent contracts are envisaged to upgrade the supply chain financing industry through "smart factoring" [56].

Furthermore, Google Meet and Zoom calls along with the utilization of "Dropbox" and E-mail communication is a few of several communication technologies that are adopted in the AEC industry. Due to the ongoing pandemic, video conferencing platforms have now become embedded into the day-to-day AEC work life in the UAE [57]. Despite their current recognized benefits, video conferencing mediums have the potential to be further optimized to ensure high productivity, which would be especially beneficial for countries that adopt a four or a four-and-a-half-day work week, such as Iceland and the UAE [58]. Table 3 identifies the applications of these technologies.

Table 3 - Examples of applications of data communication technologies.

Data communication technology	**Application(s)**
Google Meet/Zoom	• Virtual employees with candidates • Conducting from-home coordination meetings

Dropbox (cloud computing)	• Sharing of contract documents/other relevant files among project stakeholders [55].
Email	• Contractor-Consultant communication (e.g.: Request for Information-RFI) • Direct file sending/receiving

To explore the levels of use of communication technologies in the Nigerian construction industry, a questionnaire [59] revealed that different positions within an AEC firm utilize electronic communications at different levels of sophistication, based on the position's need. The questionnaire revealed that email systems were the most frequently used tools to achieve effective information management [59]. Oliver [60] stated that current communication platforms provide the necessary features to allow for higher levels of interactivity, intimacy, and immediacy for AEC stakeholders to experience better social and technical communications. Thus, digital communication technologies may ease cost pressures and technical complexities [61]. For instance, there is a high potential for video conferencing ICTs to solve corporate difficulties in an international market through overcoming lack of expertise and lowering travel expenses [11]. It is worth noting that Computer-Mediated Communication (CMC) processes have existed for years. However, such communication technologies may not be well-integrated into existing industries to improve their efficacy [62], meaning they are underutilized.

Chapter 3. Digital Technology and COVID-19

Chapter 3 will look into the research methodology used to investigate the use and investment in digital technology for construction projects amid, and in the aftermath of, the COVID-19 pandemic in the context of the UAE construction industry. This chapter will also discuss the results of the research thoroughly. Several sections of this chapter were extracted from the academic paper titled "Impacts of COVID-19 on the Use of Digital Technology in Construction Projects in the UAE" [27], which was published by the author of this thesis during the course of the research. It is worth noting that the survey(s) presented in this thesis document was approved by the Institutional Review Board (IRB) of the American University of Sharjah.

3.1 Materials and Methods

The study used a quantitative approach to differentiate between the level of usage and investment in three digital technology categories (data acquisition, processing, and communication) across three classes (phases) - pre-COVID, during COVID, and post-COVID. In order to select the frequently used digital technology for the purpose of this research study, a thorough literature survey of published materials was conducted. This included journals articles, periodicals and books that discuss the leading digital technologies currently in use in the construction industry. In the next stage, a questionnaire survey was developed and distributed to construction professionals in the UAE using online means. The first section of the survey consisted of general information about the respondents' companies or organizations. These included years of experience, respondents' role, and whether the organizations or companies are local or international. The remaining sections of the survey were designed to elicit the perceptions of the respondents on the frequency of usage and level of investment of the three digital technology categories across the three classes: Pre-COVID, During-COVID and Post-COVID. The questions related to the level of usage of all three digital technology categories pre-COVID and during COVID followed a Likert scale of 1-5 where five represented "almost always" and one represented "never". The level of investment of all three digital technology categories pre-COVID and during COVID followed a Likert scale of 1-5 where five represented "very high" and one represented "very little". All questions related to the class post-COVID, as being a future state, followed a Likert scale of 1-5 where 5 represented "Strongly agree-will increase greatly" and 1 represented "Strongly Disagree-will return to pre-Pandemic level."

The data was then analyzed using multivariate analysis of variance (MANOVA) as the data comprised of multiple dependent variables namely the level of, investment, and frequency of usage of the three digital technology categories and a single independent qualitative variable designated as classes: Pre-COVID, during COVID and Post-COVID. MANOVA is used to determine if there is a difference between the level of and investment and frequency of usage of the three digital technologies across these classes. In particular, the researchers were interested in determining whether during COVID phase a peak in the level of usage and investment in digital technology is evident as expected to meet the demands imposed by the pandemic. The statistical analysis mainly examined whether or not the average of the dependent variables differs between the three categories of the class variable. MANOVA is an extension of the analysis of variance (ANOVA) in order to incorporate more than one dependent variable by combining the multiple dependent variables into a single optimum value to maximize the difference between the classes. Furthermore, MANOVA is also more appropriate than ANOVA because it provides additional insights into the effects of the independent variables on the dependent variable [63], [64].

MANOVA is a very effective statistical tool that has been previously used in the construction context in literature. For instance, Zhao et al. [65] have used MANOVA analysis to test whether or not different factors such as construction type, technology level, climate and conditioned floor area significantly affect energy use and whether or not the effect changes over time. The authors tested the 'between-subject' effect to analyze the factor's effect across all building units and used the 'within-subject' effects to test the factor's effect over time. The authors modeled the 'between-subject' effect by fitting the sum of the repeated measures to the model effect while the 'within-subject' effect was modeled using a function that fits differences in the repeated measures.

There are three main assumptions when conducting MANOVA analysis. First, the data should be multivariate normally distributed. While the second assumption is concerned with the equality of the covariance matrices for all treatments in the study. The third and last assumption states that all observations must be independent of each other as this will affect the significance level reported in results later on [66]. Furthermore, Wilk's Lambda test statistic (Λ) is used in MANOVA to test whether there are differences between the means of the three classes on the frequency of usage and on the level of the investment of the three digital technologies or in other words to test the **two-null** hypothesis H_0 shown below.

H_0 for frequency of usage of the three digital technologies= $\begin{bmatrix} \mu_{11} \\ \mu_{12} \\ \mu_{13} \end{bmatrix} = \begin{bmatrix} \mu_{21} \\ \mu_{22} \\ \mu_{23} \end{bmatrix} = \begin{bmatrix} \mu_{31} \\ \mu_{32} \\ \mu_{33} \end{bmatrix}$ … (1)

H_0 for level of investment of the three digital technologies= $\begin{bmatrix} \mu_{11} \\ \mu_{12} \\ \mu_{13} \end{bmatrix} = \begin{bmatrix} \mu_{21} \\ \mu_{22} \\ \mu_{23} \end{bmatrix} = \begin{bmatrix} \mu_{31} \\ \mu_{32} \\ \mu_{33} \end{bmatrix}$ … (2)

where μ_{ip}, i= (1,2,3) is the number of the 3 classes population (Pre-COVID, during COVID, post-COVID) while 'p' is the number of dependent variables which in this study is 3 since there are 3 digital technology categories (acquisition, processing, and communication) for the variable frequency of usage and the variable level of investment. Furthermore, to test if there is no difference between the three population mean vectors, Λ will be used according to the Equation 3 [66] as it is the test statistic preferred for MANOVA where H0 will be rejected if Λ is small. Lambda is a value that ranges between zero and one, a null hypothesis would be rejected if Lambda is close to zero, but it should be considered in conjunction with a small P-value as well where the P-value here represents the probability that measures the consistency between the data and the hypothesis being tested [62]. The alpha level that the P-value will be compared against in this study is 0.1 indicating a level of confidence of 90%. Wilk's Lambda test statistic is defined as:

$$\Lambda = \frac{|S_{error}|}{|S_{effect} + S_{error}|} \qquad (3)$$

where:

S_{error} is the variation of the residual within the matrix of sum of squares cross product

S_{effect} is the variation of the treatment between the matrixes of sum of squares cross product

3.2 Results and Discussions

A total of 39 responses were received from the online survey. The respondents' profile showed that 15% of them worked in international offices while 85% worked in local offices. Moreover, 13% of the respondents had more than 20 years of experience. Thus, most of the respondents were local contractors in the building industry with less than 5 years in business. In addition, it was observed that 56.4% of the respondents were involved in projects with an average project size of AED 50 million (considered large) or more, while 43.6% respondents' average project size was less than AED 50 million (considered small). In this research, these two groups' (large and small) responses were further analyzed for gaining important insights.

Descriptive analysis was conducted to compute the mean of the three populations in each variable (Table 4). The results show that the mean of frequency of using the three digital technologies (y1, y3, y5) in class 0 (pre-COVID) population is 3.29. While the mean of the level of investment (y2, y4, y6) in class 0 was 3.30. Similar calculations were done for class 1 (during COVID) population and the mean of frequency of usage and level of investment are 4.03 and 3.75 respectively. Whereas the mean of frequency of usage in class 2 population (post-COVID) is 4.26 and the mean of the level of investment is 4.23. This indicates that there is in fact an increasing trend from pre-COVID to post-COVID in terms of mean frequency of usage and level of investment in digital technology for data gathering, processing and communication. The results are summarized in Table 4.

Table 4 - Means of the responses of the three classes.

Variable	Questions on usage and investment	Class 0 Mean (Pre-COVID)	Class 1 Mean (During- COVID)	Class 2 Mean (Post-COVID)
y1	Frequency of using digital technology for data and information gathering	3.10	3.64	4.28
y2	Level of company's investment in digital technology for data and information gathering	3.13	3.59	4.23
y3	Frequency of using digital technology for data and information processing	3.56	3.95	4.23
y4	Level of company's investment in digital technology for communication of data and information	3.33	3.69	4.23
y5	Frequency of using digital technology for communication of data and information	3.21	4.49	4.28
y6	Level of company's investment in digital technology for communication of data and information	3.44	3.97	4.26
	Average of frequency of usage (y1, y3, y5)	3.29	4.03	4.26
	Average of level of investment (y2, y4, y6)	3.30	3.75	4.23

In addition, the questionnaire contained three questions related to project success. The questionnaire statements and the weighted average of responses, indicating a high degree of agreement, are listed below:

- Use of digital technology for data and information gathering contributes towards project success – 4.36 (out of 5).
- Use of digital technology for data and information processing towards project success – 4.59 (out of 5).
- Use of digital technology for communications of data and information towards project success – 4.28 (out of 5).

Thus, it is substantiated by the above findings that digital technologies do indeed contribute to overall success of construction projects. Furthermore, the results presented in Table 4 also indicate that the frequency of using digital technology for communication was at its peak (variable y5 with a value of 4.49) during COVID as the demands imposed by the pandemic was higher than it was before the pandemic, indicated by a value of 3.21, and is somewhat decreased from the peak to 4.28 in the post-COVID phase as in-person communication is expected to return back somewhat, but probably not, at the pre-COVID level. This is because it is expected that the professionals in the industry will retain some of the communication technologies and conveniences as they will be increasingly more familiar and comfortable with the technology. The results also indicate, predictably, that investment in communication technologies (variable y6) had increased during the pandemic, 3.97 from 3.44 (pre-COVID) and is higher after the pandemic at 4.26.

In an effort to compare the responses based on the project size, two groups were created, as noted earlier. Small projects with sizes less than 50 million AED and large projects with sizes 50 million AED or more. These two groups are almost equally represented in the survey.

In general, it should be noted that, while in class 0 (pre-COVID) both the average frequency of usage and level of investment were both greater in larger organizations than the smaller ones. The difference shrinks in both when compared to class 1(during-COVID) and class 2 (post-COVID), as the data in the last two rows of Table 4 indicate. This is a significant observation as it substantiated two facts – (1) overall there has been an increase in both the usage and investment in digital technologies in construction during pandemic and the trend will continue after the pandemic, and (2) the extent of both usage and investment is significantly greater in smaller organizations than the larger ones during and post-COVID stages.

The results show that in class 2 (post-COVID), as illustrated in Table 4, the average of the frequency of usage and the level of investment were equal in the large projects but in small projects the average of the frequency of usage was higher than the average of the level of investment. Furthermore, both the averages were greater in small projects than in large projects in class 2 and that could be due to the fact that large projects were ahead of small projects in terms of digital technology usage before the pandemic, and therefore will not need to invest as much as the small projects to keep up with the demands created by the pandemic. Another observation that can be drawn is the fact that in class 1, the averages of the frequency of digital technology usage were almost the same in both small and large projects - in data gathering (variable y1, 3.69-small to 3.61-large) and communication (variable y5, 4.63-small to 4.40-large) technologies, but not so different in processing technologies (variable y3, 3.69-small versus 4.13-large). Again, it is not surprising as data/information processing technologies are more capital-intensive (high initial investment cost) compared to the other two – acquisition and communication technologies and organizations dealing with smaller projects would not have investment capital available to them during pandemic. This observation naturally leads to a closer look at what happens to expected investment responses after the pandemic. Results in Table 5 shows that it is expected that organization with smaller projects would increase their investments significantly – in data acquisition (y2) from pre-COVID response of 3.00 to 4.38; in data processing (y4) from 3.00 to 4.18; and lastly in data communication (y6) from 3.25 from 4.25. The average of all three variables shows an increase in responses from 3.08 to 4.27. For organizations with larger projects the extent of this difference in investment level between pre-COVID and post-COVID is much lower – from 3.45 to 4.23, although higher as predicted. These results are shown in Table 5.

Table 5 - Means of the three class populations across small vs. large projects.

Variable	Questions on usage and investment	Class 0 Mean (Pre-COVID)		Class 1 Mean (During- COVID)		Class 2 Mean (Post-COVID)	
		small	large	small	large	small	large
y1	Frequency of using digital technology for data and information gathering	2.75	3.35	3.69	3.61	4.44	4.17
y2	Level of company's investment in digital technology for data and information gathering	3.00	3.22	3.50	3.65	4.38	4.18
y3	Frequency of using digital technology for data and information processing	3.06	3.91	3.69	4.13	4.25	4.22
y4	Level of company's investment in digital technology for communication of data and information	3.00	3.57	3.56	3.78	4.18	4.26
y5	Frequency of using digital technology for communication of data and information	2.69	3.57	4.63	4.40	4.25	4.30
y6	Level of company's investment in digital technology for communication of data and information	3.25	3.57	3.81	4.10	4.25	4.26
	Average of frequency of usage (y1, y3, y5)	2.83	3.61	4.00	4.05	4.31	4.23
	Average of level of investment (y2, y4, y6)	3.08	3.45	3.62	3.84	4.27	4.23

To gain further insight, the responses from the survey were then analyzed using SAS statistical software as per the methodology explained in the earlier section. The MANOVA test was conducted using F approximation to test the hypothesis of no significant difference between the means of the three classes populations (pre-, during-, and post-COVID) on the frequency of usage and level of investment of the three digital technologies as shown in Table 6 and Table 7 respectively. Table 6 shows that the P value is less than alpha (0.1) for the null hypothesis of 'no overall class difference' and therefore it can be rejected, and it can be concluded with 90% confidence that there is in fact a significant difference between the means of the three class populations on the frequency of usage of the three digital technologies. Therefore, the analysis was taken a step further to conduct pairwise comparisons between the means of class 0 (pre-

COVID) and class 1 (During COVID), class 0 (pre-COVID) and class 2 (post-COVID) as well as class 1 (During COVID) and 2 (post-COVID). The results have shown that in all three MANOVA tests, the P-values were less than alpha (0.1) which leads to the rejection of the null hypothesis and the conclusion with 90% confidence that there is a significant difference between the means of class 0 and class 1, and between the means of class 0 and 2, as well as between the means of class 1 and 2 on the frequency of usage of the three digital technology categories. Similar conclusions were drawn when MANOVA was conducted to compare between the means of the three class populations on the level of investment of the three digital technology categories and the results are shown in Table 7.

Table 6 - MANOVA Test: Wilk's Lambda for frequency of usage

Comparison	Overall Class Effect	Difference between classes 0 and 1	Difference between classes 0 and 2	Difference between classes 1 and 2
Wilk's Lambda	0.639	0.728	0.778	0.894
P-Value	0.0001	0.0001	0.0001	0.0055

Table 7 - MANOVA Test: Wilk's Lambda for level of investment

Comparison	Overall Class Effect	Difference between classes 0 and 1	Difference between classes 0 and 2	Difference between classes 1 and 2
Wilk's Lambda	0.807	0.935	0.827	0.932
P-Value	0.0005	0.0551	0.0001	0.0486

The first row in the tables above shows the value of Wilk's Lambda (refer to equation 3) in each MANOVA test. It measures how well each category of the independent variable (class) contributes to the model. The scale ranges from 0 to 1 as mentioned earlier where 0 means total discrimination and 1 means no difference. Since all the Lambda values are less than 1 and are associated with a small P-value (significant at the 0.1 level), it can be concluded with 90% confidence that there is in fact a difference between the means of the three classes on both the frequency of usage and level of investment of the three digital technology categories. The P value represents the probability that measures the consistency between the data and the hypothesis being tested. The null hypothesis that there is no overall class effect and no difference between the classes in pairwise comparisons is evaluated regarding this P value. For a given alpha level, if the P-value is less than alpha then, this null hypothesis is rejected. The alpha level used in this study is 0.1 and the tables show that all P values are less than 0.1. It should be noted that some of the P values are slightly higher for 'no difference between classes 1 and 2' and 'no difference between classes 0 and 1' in the level of investment, they are still less than 0.1. Therefore, it is safe to reject all the null hypotheses and conclude with 90% confidence that there is in fact a significant difference between the means of the three classes on both the frequency of usage and level of investment of the three digital technology categories. Future studies can focus on testing a larger sample size in order to achieve a smaller P-value and a higher confidence level.

3.3 Conclusions

It is common knowledge that overall productivity increases in the construction sector, both regional and global, are minimal and significantly lower than the manufacturing and the service sectors. One reason frequently cited by the researchers and the practitioners alike is the slow adoption of technology, digital in particular, in construction. This study takes a deep look into this issue of adoption (usage and investment) of digital technology in construction in the context of the prevalent pandemic caused by COVID-19 since early 2020. COVID-19, ironically, presented an opportunity to investigate the status of use of digital technology adoption in the construction industry. Thus, this study is undertaken to determine the status in three levels, pre-COVID, during COVID, and post-COVID. The premise of the study is that digital technologies in three major categories—data acquisition, processing, and communication of data and information—are all impacted by the pandemic. There was a noticeable increase in the use of, and investment in, these digital technologies in the industry since early 2020 as a reaction to the restrictions put in place to reduce the spread of the COVID-19 virus. This crisis caused by the COVID-19 pandemic imposed a de facto mandate by instilling a sense of urgency among the construction professionals for digitalization of many processes and operations in construction and to perform them virtually. Digital technology, although not new and having existed for some time, was not utilized extensively prior to the "lockdown" situation caused by the pandemic. Oddly, COVID-19 provided the necessary impetus for digitalization in the construction industry. This crisis, as unexpected and undesirable as it is, offers a window of opportunity to improve and make the industry better positioned for the future. This research study, despite the limitations, identified several significant facts and provided important insights. The most significant among them are that COVID-19 revealed that the use of digital technology, although remaining underutilized, is gaining wider acceptance in the industry. It also showed that the benefits of digital technology, once realized, will continue to be used. As a consequence, investment in digital technology in the construction industry will continue to increase. This will have long-term transformational and beneficial impacts on productivity in the construction sector. The methodology developed and employed in this study can be utilized to investigate certain selected technologies for use and investment decisions. A decision-making model for use in the industry can be developed using the categories as outlined in this study.

The results of this chapter emphasize the significance of advanced digital technologies in today's construction world. In light of this, the next chapter will assess the impact of different digital technologies in enhancing the virtual environment of construction projects.

Chapter 4. Digital Technology and Virtual Environment

Chapter 4 will investigate the research methodology used to investigate the impacts of digital technologies within these three categories on the virtual environment of AEC firms.

4.1 Digital Technologies: Impact on Virtual Environment

Digital technologies in the Architecture, Engineering and Construction (AEC) industry are vast and are continually growing. Utilizing digital tools can happen at any stage of the project, from design initiation to post-construction handover. In this chapter, digital technologies that will contribute to a firm's virtual environment will be categorized into three groups, namely: data acquisition technologies, data processing technologies, and data communication technologies. Figure 1 better portrays this framework.

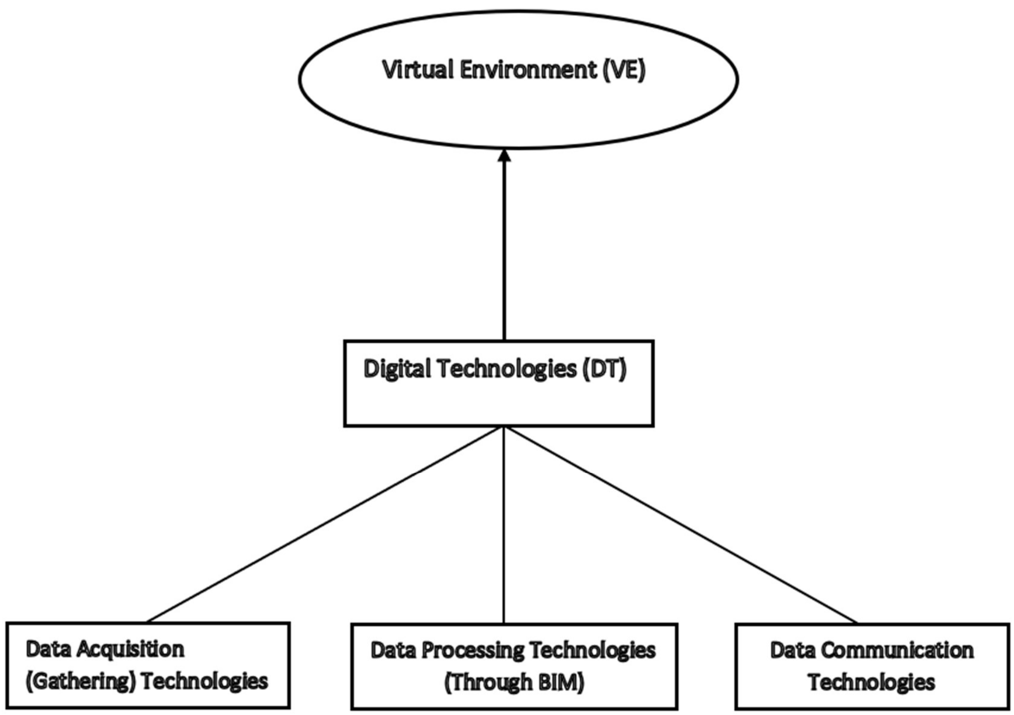

Figure 1 - Research Framework

4.1.1 Virtual environment by data acquisition tools

Data collection, or acquisition, is a critical process in any construction project. It is defined as the means by which information is identified, collected, stored, transmitted and presented [67]. Several methods have evolved over the years as to how such critical data can be efficiently and accurately gathered. As technology has been making headway in the AEC industry recently, it is important for firms to get better visibility of the levels of sophistication of data acquisition technologies. Considering a contracting firm on site as an example, the contractor relies on collecting accurate data to apply for progress payments, mitigate delays, and monitor construction quality. In addition Digital data acquisition and detection tools play an important part in automated progress monitoring operation [68].

The earliest forms of data acquisition relied on extensive manual interventions that were not only inaccurate but also very time consuming and labor intensive [69]. As time progressed, various data acquisition technologies have been developed to improve productivity and build an integrated environment that allows all project participants to instantly connect their operations [70]. These tools include but are not limited to RFID (Radio Frequency Identification), drones, and 3D laser scanning [27]. To describe a few, an RFID system consists of a transponder (tag), transceiver and antenna or coil - the tag is composed of a computer chip with an internal memory in which a limited amount of information can be stored, whereas the set of transceiver and antenna are called reader and it can read data on the tag holding information about the object attached to it by generating an electromagnetic field [71]. Another data acquisition tool is a 3D laser scanner. 3D laser scanners capture geospatial information of the scanned environment and deliver the cartesian or spherical coordinates of thousands of points in the scene called "point cloud". These point clouds that contain huge amount of information then need to be taken through a series of process including data editing, registration, and modeling [72].

In this study, data acquisition technologies will be categorized into three levels, A1, A2 and A3, in the order of increasing levels of sophistication. The categorization of these levels follows a study provided by Omar and Nehdi [73] who explained the progression in data acquisition technologies going from the conventional methods that depend heavily on manual interaction to the emergence of different automatic approaches such as multimedia and handheld computing and finally into a heavily automated data acquisition environment that consists of RFID and Laser Scanning. The levels of data acquisition technologies adopted in this research are defined below:

A1: Manual/Paper-based – staff manually collecting data from site.

A2: Semi-automated – CCTVs, Phone cameras, Site Tablets, Voice, multimedia.

A3: Highly automated – 3D Laser scanning, Photogrammetry, Drones, RFID, GIS/GPS

4.1.2 Virtual environment by data processing tools (through BIM)

In simple terms, data processing involves retrieving or transforming data into valuable information. Processing design and construction data enables AEC professionals to benefit from a valuable output that enables a successful project delivery [74] Amongst several data processing tools in the AEC industry, Building Information Modelling (BIM) has proven itself to be a pivotal data processing tool utilized during the design and construction phases of a project. BIM is defined as a "digital representation of physical and functional characteristics of a facility creating a shared knowledge resource for information about it forming a reliable basis for decisions during its life cycle, from earliest conception to demolition" [75]. In other words, BIM simulates the construction activities in a virtual environment, allowing support to design through clash detections, it also supports procurement, construction activities and allows for a better realization of the facility [76]. For instance, looking at partial cross-sections and the 3D model enables better visualization of a problem during construction and help clear doubts at the construction site [77].

BIM utilization varies across firms, nations, and project phases. In addition, utilizing BIM can occur in varying levels of sophistication, contributing to varying levels of virtual environments. A popular scale to measure the maturity of BIM has been developed by Bew and Richards [78] in the UK in 2008, classifying BIM on levels ranging from 0 to 3. Where 0 represented the use of unmanaged CAD, level 1 is managed CAD 2D format, level 2is managed in 3D environment. The last level, level 3 represents a fully open interoperable and integrated processes that are managed by a collaborative model. It is safe to say however, that the use of BIM in construction industry has not yet reached its full potential. In fact, In Nigeria, a developing country in Africa, a study has revealed that BIM is utilized at a level somewhere around 0 and 1, which could be improved to allow for better team coordination, labor efficiency, and lower claims and disputes [28]. Similarly, a study of the Iraqi construction industry found that 73% of BIM users in Iraq rely on simple 2D drawings to deliver construction projects, which is a BIM level 0 application [79]. Furthermore, a study in the UK has revealed that 53% of AEC organizations utilize BIM at level 0 or 1, and 21% rely on level 2 BIM to deliver construction projects [80].

In this study, data processing through BIM will be categorized into three levels, B1, B2 and B3, in the order of increasing levels of sophistication. These levels are defined below:

B1: BIM Level 0/1 – 2D drawing shared electronically/paper based, limited concept 3D models.

B2: BIM Level 2 – 2D and 3D information, increased spatial coordination, models shared electronically between members.

B3: BIM Level 3 – Collaborative, online model that includes sequencing (4D), cost information (5D), lifecycle information (6D) and more.

4.1.3 Virtual environment by data communication tools

Due to the complexity of the construction industry, effective communication is very important to ensure that all parties are aware of the latest information. Communication refers to the act of sending or receiving ideas, knowledge, and other resources among team members and organizations [81]. Given the vast amounts of information within a construction project, utilizing sophisticated communication technologies is evident to be a solution to enhance quality and productivity [82]. There are various types of communication, such as written, verbal, and non-verbal. Some common mediums of communication include but are not limited to letters, emails, memos, voicemails and video conferencing [27]. A recent study concluded that emails are the most commonly used tool for communicating information in the construction industry [83]. Phone calls are also considered to be a leading communication tool amongst construction professionals [19]. Another pivotal communication tool which construction firms are lately diverting towards is video conferencing. Over the past two years, video conferencing technology has witnessed a drastic improvement that enabled this technology become more efficient, used-friendly, effective, and optimized [84]. Despite their common use, emails and video conferencing technologies may not be the optimal solution to transfer files and construction documents, especially large ones. Instead, a large fraction of construction professionals opts to use "clouds" for this purpose. Cloud computing is a model for enabling convenient, on-demand network access to a shared pool of configurable computing resources such as networks, servers, storage, applications, and services that can be rapidly provisioned and released with minimal management effort or service provider interaction [53]. In addition, cloud computing has been found effective to resolve high-cost issues for SMEs, who have limited financial capabilities to acquire high-end computing services [85].

Due to the nature of the construction industry, it has been known that information is very important to ensure that all parties are aware of the latest developments. Upon screening of the literature, it can be concluded that the most common modes of data communication in construction are either written communication which includes, hard copy documents, letters and emails or they can also be visual communication with the use of videoconferencing and presentations [86], [87]. The third mode of communication that is heavily cited in literature is the use of advanced information and communication technologies (ICT) such as cloud computing and site surveillance technologies [88]. Therefore, this paper aims to provide an analysis of the various levels of communication technologies that are currently being utilized in the construction industry. In this study, data communication technologies will be categorized into three levels, C1, C2 and C3, in the order of increasing levels of sophistication. These levels are defined below:

C1: Phone calls and Emails.

C2: Phone calls, Emails and Video Conferencing.

C3: Phone calls, Emails, Video Conferencing and Cloud Computing (Live Data Servers)

4.2 Virtual Environment

At first glance, the term "virtual environment" may sound like virtual reality technology. However, a virtual environment describes a wider setting, rather than a specific technology. While there is no consensus within the literature regarding what exactly a virtual environment means, the term has been usually associated with technology and advancement, specifically, digital. For instance, a study in 2003 looked at virtual environment from a "dimension" (2D, 3D, 4D, etc.) perspective, measuring virtual environments in terms of the level of human interaction with a building model, on a computer screen [17]. Similarly, another study compared the capabilities of different "VE displays" in visualizing 3D visuals of a building, one of which was the Head Mounted Display (HMD) [18]. As remote working started becoming a new norm in 2020 and 2021, other studies have looked at virtual environments as communicating through online environments (e.g.: video calls, social media) to achieve successful project management [19], not just to visualize building models. In a nutshell, it is logical to look at the term "virtual environment" as the output of utilizing digital technology tools, where digital technology tools are the input in this case. In other words, "virtual environment" can describe a firm's level of technological setting allowing for smooth and efficient project delivery through the utilization of digital technology.

The measurement of virtual environments can be categorized into various scales, ranging from low to high fidelity. These scales determine the level of immersion and interaction within the virtual environment. The low scale refers to basic 2D displays and simple user interactions, whereas high-scale environments are characterized by a high level of interaction, immersion, and realism [89]. Virtual environments can also be measured based on their level of interactivity. This can range from passive observation, where users can only view the virtual environment, to active participation, where users can interact with and manipulate objects within the environment [90]. The level of interactivity is an important factor in determining the effectiveness of the virtual environment in achieving project goals. In addition, the fidelity of the virtual environment is another important measure that is used to determine its effectiveness. High-fidelity virtual environments are designed to replicate real-world conditions accurately, providing users with a high degree of immersion and realism [91]. On the other hand, low-fidelity virtual environments provide basic representations of the real world.

Overall, virtual environments can be measured based on their scales of fidelity, interactivity, and realism. These measurements can be used to evaluate the effectiveness of the virtual environment in achieving project goals and enhancing project delivery through the utilization of digital technology tools.

The scale of the virtual environment that will be used in this research is 0-100. Where 100 represents the highest level of virtual environment that translates to the use of the third level in all three digital technologies (i.e. A3, B3 and C3) and zero represent the absence of any digital technologies in the construction project.

4.3 Methodology

The research used a mixed approach of qualitative and quantitative to differentiate between the levels of digital technology in terms of their contribution to enhancing the virtual environment of construction projects. To begin with, in order to develop a spectrum of digital technology levels across each of the digital technology categories, a detailed literature review of published materials was conducted. This included, but was not limited to, journal articles, conference papers and books that investigated the sophistication of selected digital technologies currently being utilized by construction professionals. In the next stage, a questionnaire survey was developed and distributed to construction professionals in the United Arab Emirates (UAE) using online means. These construction professionals included employees working for contracting firms, consultancy firms, project management consultancy firms and as client representatives. The survey consisted of 21 questions, and the duration of the survey was approximately 5 minutes. Furthermore, the survey was designed in a systematic manner, where the definition of each digital technology level (A1, A2, etc.) was clearly stated to ensure that the questions and comparisons are well-understood by the respondents.

The first part of the survey consisted of general information such as years of experience and the type of projects they work on to be able to generate a respondent's profile. In the second part of the survey, respondents were asked to conduct AHP pairwise comparisons between the effectiveness of the identified digital technology levels in the three categories of data collection, data processing and data communication in enhancing the virtual environment of the construction projects. In other words, different digital technology levels (e.g.: A1, A2, A3) within the same digital technology category were compared in terms of effectiveness towards enhancing the virtual environment. Table 8 explains the AHP scale according to Saaty [92]. AHP was used in this research as it is a highly preferred approach in decision-making problems. It is an objective tool that helps organize factors within a hierarchy structure and provides solutions to unorganized problems which are all important features for any decision-making problem [93].

Table 8 - Definition of AHP Scales [92]

AHP Scale of Importance for Comparison of Pairs	**Numeric Rating**
Extremely More Important	9
Very Strongly More Important	7
Strongly More Important	5
Moderately More Important	3
Equally Important	1

In the third part of the survey respondents compared the effectiveness of the three categories of digital technologies: data acquisition, data processing and data communication in enhancing the virtual environment of construction projects (A vs B vs C). The respondent first determines which category is more significant and then determines the level of intensity of that significance according to the provided scale. Figure 2 illustrates a sample of the pairwise comparisons between the three categories of digital technologies.

	Extremely				Equal Importance				Extremely	
Data collection	9	7	5	3	1	3	5	7	9	Data Processing Through BIM
Data collection	9	7	5	3	1	3	5	7	9	Data Communication
Data Communication	9	7	5	3	1	3	5	7	9	Data Processing Through BIM

Figure 2 - Pairwise Comparison: Scale

Penultimately, respondents were asked to choose the level of digital technology in each of the three data phase categories (data collection, data processing and data communication) utilized by their respective firms during recent construction projects. The weights of these three digital technology levels were added and then normalized in order to compute the level of virtual environment achieved in each firm. Lastly, the researchers aimed to confirm the positive correlation between higher utilization of digital technology and overall project success.

Thirty responses were collected out of 91 distributed surveys using a snowball sampling technique, which represents a response rate of 33%. The results showed that 50% of the respondents worked in local companies while 50% worked in international companies. Additionally, 70% of the respondents worked on buildings while 30% worked on infrastructure projects. Table 9 further illustrates the respondents' profile.

Table 9 - Respondents' Profiles

Category	Respondents (Total 30)	
	Number	%

Years of experience	> 20 years	3	10
	11 - 20 years	4	13.3
	5 - 10 years	7	23.3
	< 5 years	16	53.3
Company	Local	15	50
	International	15	50
Project Type/Expertise	Buildings	21	70
	Infrastructure	9	30
Role	Owner	2	6.7
	Consultant	18	60
	Contractor	7	23.3
	Construction/Project Management Firm	3	10
Average Project Size	< 50 (Million AED)	4	13.3
	50 – 200 (Million AED)	13	43.3
	201 – 500 (Million AED)	2	6.7
	> 500 (Million AED)	11	36.7

4.4 Results and Discussion

4.4.1 Digital technology levels weights

The survey's comprehensive analysis is illustrated in table 10 which shows the local and global weight of the three data technologies categories and the different levels in each category. The local weight represents the weight of each level in its corresponding digital technology category. While the global weight of each digital technology level represents the weight of each level with respect to the overall digital technologies' levels list. Normalized AHP matrix of the three digital technologies categories is shown in Table 11. After the respondents have performed the pairwise comparison between each two digital technologies categories, the geometric mean of the responses was then calculated. These values were then transformed to generate a normalized matrix.

Finally, the average of each row in the normalized matrix was computed to yield the weight of each corresponding digital technology category. The results revealed that the digital technology category with the highest weight of 0.468 is data processing through BIM, followed by data communication with a weight of 0.308 and finally data collection had a weight of 0.224.

Table 10 - Local and Global Weights of Digital Technologies' Levels

Data Technologies Levels	**Local Weight**	**Global Weight**
Data Collection	-	0.224
A1: *Manual/Paper-based*	0.065	0.0145
A2: *Semi-Automated-CCTVs, Phone cameras, Site Tablets, Voice, multimedia.*	0.289	0.0647
A3: *Highly automated – 3D Laser scanning, Photogrammetry, Drones, RFID, GIS/GPS*	0.646	0.145
Data Processing through BIM	-	0.468
B1: *BIM Level 0/1 – 2D drawing shared electronically/paper based, limited concept 3D models*	0.064	0.030
B2: *BIM Level 2 – 2D and 3D information, increased spatial coordination, models shared electronically between members.*	0.343	0.161
B3: *BIM Level 3 – Collaborative, online model that includes sequencing (4D), cost information (5D), lifecycle information (6D) and more.*	0.593	0.278
Data Communication	-	0.308
C1: *Phone calls and Emails.*	0.064	0.0197
C2: *Phone calls, Emails and Video Conferencing*	0.375	0.116
C3: *Phone calls, Emails, Video Conferencing and Cloud Computing (Live Data Servers)*	0.561	0.173

Table 11 - Normalized AHP Matrix of the Three Digital Technologies Categories

	Data Collection	**Data Processing through BIM**	**Data Communication**	**Weight**
Data Collection	0.221879792	0.227529289	0.223047751	**0.224152**
Data Processing through BIM	0.491329745	0.455217175	0.457858146	**0.468135**
Data Communication	0.286790462	0.317253536	0.319094103	**0.307713**

The results revealed that the data technology category which has the highest impact on enhancing the virtual environment of construction projects is data processing through BIM. Specifically, BIM level 3 which represents a collaborative online model that includes sequencing (4D), cost information (5D), lifecycle information (6D) and more has the highest overall global weight of 0.278. These results are in line with previous studies that emphasized the significance of data-rich BIM that simulates a virtual construction project. BIM not only demonstrates the geometry and physical properties but the whole building lifecycle with spatial relationships, fabrication and procurement information. This ultimately leads to an enhanced virtualization of the construction project. Furthermore, the third level in communication (C3) which consists of phone calls, emails, video conferencing and cloud computing ranked second place in enhancing the virtual environment of construction projects with a global weight of 0.173. Indeed, the use of globalizing communication technology is a big catalyst for the virtualization of project teams. This advanced digital communication level simulates a real-like interaction between team members and gives project participants the flexibility to share knowledge and expertise from different time zones and locations to successfully execute the construction project [71], [73]. On the other hand, the digital technology level that has the least impact on enhancing the virtual environment in a construction project is A1, which is the manual/paper-based data collection. In fact, this is a very traditional approach of data collection that takes a lot of time and resources and is prone to so many deficiencies and incorrect assessment of job conditions that could ultimately lead to time and cost overruns in a construction project [94]. In light of this discussion, it is recommended that in order to enhance the virtual environment in a construction project, investment in BIM level 3 and communication level 3 should be emphasized.

4.4.2 Status of UAE construction companies

As far as the second objective of this chapter is concerned which deals with the status of the virtual environment level adopted in the construction companies in the UAE, Figure 3 reveals the companies' distribution graph. The results have shown that the lowest level of virtual environment is 10.7% where the company would be using A1, B1 and C1. While the highest virtual environment level that a company can reach is 100% if they adopt A3, B3 and C3. Seven out of the thirty companies studied in total displayed around (10-40) % virtual environment level. Whereas fifteen out of the thirty companies displayed (40-70) % virtual environment level. Finally, eight out of thirty companies displayed a virtual environment level that ranges from (70-100) %. These results indicate that the medium quartile is 58% virtual environment level, the lower quartile is 31% virtual environment level, and the upper quartile is 79% virtual environment level. In fact, the virtual environment level can be divided into three levels:

low, medium, and high. Where the low level represents (10-40) % which includes 23% of the companies studied in this research. The medium virtual environment level represents (40-70) % and includes 50% of the companies in this research. Lastly, the high virtual environment level represents (70-100) % and includes 27% of the companies studied in this research. It follows from the above discussion that the status of the virtual environment level in the companies in the UAE follows an approximately normal distribution.

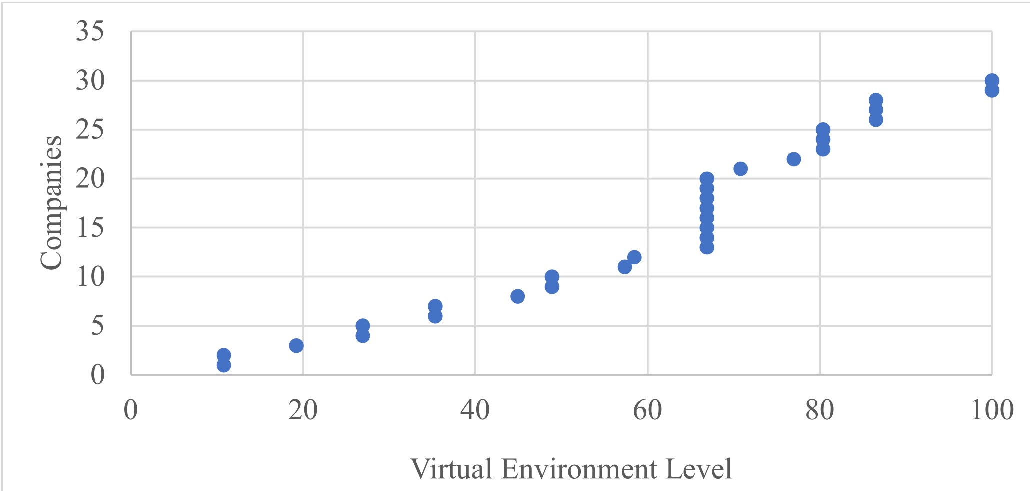

Figure 3 - Companies' Distribution Graph

It is also worth mentioning that sixty percent of the respondents strongly agree that utilizing more advanced digital technology and hence more virtualization contributes in the end to overall project success. Thirty-seven percent further agree with this theory, while only three percent strongly disagree with this theory. These results indicate that the potential presence of a positive correlation between the utilization of digital technology and overall project success is promising.

4.5 Summary and Conclusions

Digitalization of the construction industry is a topic that has been gaining a lot of attention over the past years. Advanced technological tools are essential to generate a simulated virtual environment that allows for better collaboration, communication and data processing which ultimately leads to less errors and more successful outcomes. Available literature however lacks recommendations and guidelines on which digital technologies should construction companies invest in to further enhance the virtual environment in their projects. Therefore, this paper bridges this gap by computing the relative weights of the levels of digital technologies within three categories technologies: data collection, data processing and data communication technologies in enhancing the virtual environment in construction projects. Furthermore, the paper also investigated the current levels of utilization of digital technology adopted in construction companies in the UAE. A survey was administered to construction professionals in the UAE to compare the effectiveness of digital technology levels against each other in enhancing the virtual environment of construction projects using AHP. The results revealed that the most significant digital technology level with the highest impact on enhancing the virtual environment is BIM level 3. While the digital technology level that was the least significant was data collection level 1 (manual/paper-based). Furthermore, the results also revealed that 23% of the companies studied in this research displayed a low virtual environment level (10-40%). While 50% of the companies included in this research displayed a medium virtual environment level (40-70%) and 27% of the companies displayed a high virtual environment level in their construction projects (70-100%). Additionally, sixty percent of the respondents strongly agree that utilization of advanced digital technology leads to overall project success. The results of this research will provide project managers with a justified rationale for choosing to invest in advanced technological level such as BIM level 3 and communication level 3 to enhance the virtualization of their construction projects. Further, and by making practical use of figure 3 above, decision makers within the AEC industry could gain an edge over their competitors in the market through acquiring digital technology levels that would place them in the higher range of virtual environment.

Chapter 5. Summary and Conclusions

This chapter highlights the summary, conclusions, limitations, and future recommendations in the field of digital technologies and virtual environment in construction projects.

5.1 Summary

Over the past 20 years, the construction industry has been slowly but steadily adopting technology, despite its historical reluctance to change. This adoption has been driven by the advancement of new technologies, which have allowed for the creation of virtual environments that improve collaboration, communication, and data processing. As a result, there are fewer mistakes and more successful outcomes in construction projects. Through categorizing digital technologies into three groups: data acquisition, processing, and communication, and through conducting two questionnaire surveys among the construction professionals in UAE, this research investigated the extent of use of technology in three periods – pre-COVID, during-COVID and post-COVID. The second survey in this research aimed is to examine which digital technology tools impact the virtual environment within an AEC firm the most. The second survey's results were analyzed using AHP.

5.2 Conclusions

The conclusions that are can be drawn from the first survey's results are listed below:

1. There is an increasing level of usage of digital technology in the AEC industry from pre-COVID, to during COVID and post-COVID periods.
2. Among the three categories, communication technology indicated a higher extent of use as compared to the other two.
3. A slight drop in the use of communication technology from during COVID to post-COVID time is envisaged, apparently as some of the functions and operations are expected to return to normalcy after the pandemic.

The conclusions that are can be drawn from the second survey's results are listed below:

1. The most significant digital technology level with the highest impact on enhancing the virtual environment is BIM level 3.
2. The digital technology level that was the least significant was data collection level 1 (manual/paper-based).

3. The results revealed that 23% of the companies studied in this research displayed a low virtual environment level (10-40%). While 50% of the companies included in this research displayed a medium virtual environment level (40-70%) and 27% of the companies displayed a high virtual environment level in their construction projects (70-100%).
4. Majority of the respondents strongly agree that utilization of advanced digital technology leads to overall project success.

5.3 Limitations and Future Recommendation

Some of the limitations encountered in this research include:

- The database was limited to construction professionals in the UAE, it was hard to acquire a wider and a more global dataset.
- The research only focused on the three digital technologies categories: data collection, processing, and communication.

Despite the first limitation listed above, it is worth noting the results of both surveys, and hence the research, can be effectively utilized in other geographies. While it is true that AEC firms within developing countries or countries with low GDP may not be financially or technically capable of acquiring high levels of sophistication on digital technologies (i.e.: A3, B3, C3), the overall conclusions and trends related to the levels of use and investment are envisaged to remain valid across the global AEC industry. In terms of impact on virtual environment, it would fair to assume that trends and conclusions related to the impact on virtual environment to be valid for other geographies, assuming AEC professional around the world are knowledgeable of the capabilities of the digital technologies presented in this research.

Some of the future recommendations in this field include:

- Expanding the categories of digital technologies to include other derivatives of the main categories included in this research
- Build on the results of this research to create an investment decision model that can help decision makers choose the most appropriate digital technology level that they should invest in to better enhance the virtual environment in the construction project.

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Appendix A

<u>Survey #1 – Digital Technology and COVID-19</u>

<u>Section 1 (General Information)</u>

In this section, you will be asked about your general information.

Your company?
□ Local (Main Office in UAE)
□ International (Main Office outside UAE)
Years of experience in UAE
□ <5
□ 5-10
□ 11-20
□ > 20
Project Type/expertise
□ Buildings
□ Infrastructure
□ Other
Current role
□ Owner
□ Consultant
□ Contractor
□ Construction/project management firm
Average size of projects
□ <50M AED
□ 50 to 200M AED
□ >200- 500M AED
□ >500M AED

<u>Section 2: Digital Technology</u>

In this section, you will be asked to rate the level of usage, investment decisions, and the success potential for three types of digital technologies: ***a.*** data and information gathering; ***b.*** data analysis and processing; and ***c.*** communication.

<u>Data and information gathering (e.g. RFID, Barcode or Drones)</u>

1. Do you believe that the use of digital technology (such as drones) for **data and information gathering** contributes towards project **success**?
   □ Strongly Agree
   □ Agree
   □ Neutral
   □ Disagree
   □ Strongly Disagree

2. **Prior** to the COVID-19 Pandemic, how frequently your company have **used** digital technology for **data and information gathering?**
   □ Almost Always
   □ Often

□ Sometimes
□ Rarely
□ Never

3. **During** the COVID-19 Pandemic (after March 2020), how frequently your company have **used** digital technology for **data and information gathering**?
    □ Almost Always
    □ Often
    □ Sometimes
    □ Rarely
    □ Never

4. Please indicate your choice related to the statement: **After** COVID-19 Pandemic is essentially over, the **usage** of digital technology *will increase* beyond the level reached during COVID-19 Pandemic for **data and information gathering**.
    □ Strongly Agree - Will increase greatly
    □ Agree - Will slightly increase
    □ Neutral - remain the same as already reached
    □ Disagree - Will slightly decrease
    □ Strongly Disagree - Will return to the pre-Pandemic level

5. **Prior** to the COVID-19 Pandemic, what is the level of your company's **investment** in digital technology for **data and information gathering**?
    □ Very high
    □ High
    □ Normal
    □ Adequate
    □ Very little

6. **During** the COVID-19 Pandemic (after March 2020), what is the level of your company's **investment** in digital technology for **data and information gathering**?
    □ Very high
    □ High
    □ Normal
    □ Adequate
    □ Very little

7. Please indicate your choice related to the statement: **After** COVID-19 Pandemic is essentially over, the **investment** in digital technology will increase beyond the level reached during COVID-19 Pandemic for **data and information gathering**.
    □ Strongly Agree - Will increase greatly
    □ Agree - Will slightly increase
    □ Neutral - remain the same as already reached
    □ Disagree - Will slightly decrease
    □ Strongly Disagree - Will return to the pre-Pandemic level

<u>Data and Information Processing Technology (e.g. Building Information Modeling or BIM (Revit), Scheduling program, such as Primavera, Procore, CMIC(?), Estimating software)</u>

1. Do you believe that the use of digital technology (such as BIM) for **data and information processing** contributes towards project **success**?
   □ Strongly Agree
   □ Agree
   □ Not sure
   □ Disagree
   □ Strongly Disagree

2. **Prior** to the COVID-19 Pandemic, how frequently your company have **used** digital technology for **data and information processing**?
   □ Almost Always
   □ Often
   □ Sometimes
   □ Rarely
   □ Never

3. **During** the COVID-19 Pandemic (after March 2020), how frequently your company have used digital technology for **data and information processing**?
   □ Almost Always
   □ Often
   □ Sometimes
   □ Rarely
   □ Never

4. Please indicate your choice related to the statement: **After** COVID-19 Pandemic is essentially over, the **usage** of digital technology will increase beyond the level reached during COVID-19 Pandemic for **data and information processing**.
   □ Strongly Agree - Will increase greatly
   □ Agree - Will slightly increase
   □ Neutral - remain the same as already reached
   □ Disagree - Will slightly decrease
   □ Strongly Disagree - Will return to the pre-Pandemic level

5. **Prior** to the COVID-19 Pandemic, what is the level of your company's **investment** in digital technology for **data and information processing**?
   □ Very high
   □ High
   □ Normal
   □ Adequate
   □ Very little

6. **During** the COVID-19 Pandemic (after March 2020), what is the level of your company's **investment** in digital technology for **data and information processing**?
   □ Very high
   □ High
   □ Normal
   □ Adequate
   □ Very little

7. Please indicate your choice related to the statement: **After** COVID-19 Pandemic is essentially over, the **investment** in digital technology will increase beyond the level reached during COVID-19 Pandemic for **data and information processing**.
   □ Strongly Agree - Will increase greatly
   □ Agree - Will slightly increase
   □ Neutral - remain the same as already reached
   □ Disagree - Will slightly decrease
   □ Strongly Disagree - Will return to the pre-Pandemic level

Information & Communication Technology (e.g. Video Conferencing, Dropbox, etc.)

1. Do you believe that the use of digital technology (such as video conferencing and file sharing) for **communications of data and information** (including virtual meetings) contributes towards project **success**?
   □ Strongly Agree
   □ Agree
   □ Not sure
   □ Disagree
   □ Strongly Disagree

2. **Prior** to the COVID-19 Pandemic, how frequently your company have **used** digital technology for **communication of data and information** (including virtual meetings)?
   □ Almost Always
   □ Often
   □ Sometimes
   □ Rarely
   □ Never

3. **During** the COVID-19 Pandemic (after March 2020), how frequently your company have used digital technology for **communication of data and information** (including virtual meetings)?
   □ Almost Always
   □ Often
   □ Sometimes
   □ Rarely
   □ Never

4. Please indicate your choice related to the statement: **After** COVID-19 Pandemic is essentially over, the **usage** of digital technology will increase beyond the level reached during COVID-19 Pandemic for **communication of data and information** (including virtual meetings).
   □ Strongly Agree - Will increase greatly
   □ Agree - Will slightly increase
   □ Neutral - remain the same as already reached
   □ Disagree - Will slightly decrease
   □ Strongly Disagree - Will return to the pre-Pandemic level

5. **Prior** to the COVID-19 Pandemic, what is the level of your company's **investment** in digital technology for **communication of data and information** (including virtual meetings)?
   □ Very high
   □ High
   □ Normal
   □ Adequate
   □ Very little

6. **During** the COVID-19 Pandemic (after March 2020), what is the level of your company's **investment** in digital technology for **communications of data and information** (including virtual meetings)?
   □ Very high
   □ High
   □ Normal
   □ Adequate
   □ Very little

7. Please indicate your choice related to the statement: **After** COVID-19 Pandemic is essentially over, the **investment** in digital technology will increase beyond the level reached during COVID-19 Pandemic for communication of **communications of data and information** (including virtual meetings).
   □ Strongly Agree - Will increase greatly
   □ Agree - Will slightly increase
   □ Neutral - remain the same as already reached
   □ Disagree - Will slightly decrease
   □ Strongly Disagree - Will return to the pre-Pandemic level

Survey #2 – Digital Technology and Virtual Environment

Section 1 (General Information)

In this section, you will be asked about your general information.

Your company?
□ Local (Main Office in UAE)
□ International (Main Office outside UAE)

Years of experience
□ <5
□ 5-10
□ 11-20
□ > 20

Project Type/expertise
□ Buildings
□ Infrastructure
□ Others, please specify ……………….

Current role
□ Owner
□ Contractor
□ Consultant
□ Project/Construction Management Firm

Average size of projects
□ <50M AED
□ 50 to 200M AED
□ 201- 500M AED
□ >500M AED

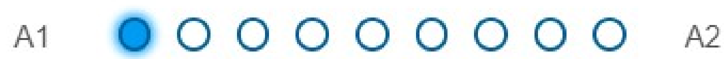
Section 2: AHP Pairwise Comparisons between the Digital Technology Levels

In this section you will be asked to conduct AHP Pairwise Comparisons between the effectiveness of the digital technology levels in the three categories of data collection, data processing (BIM) and data communication in enhancing the virtual environment of the construction projects. The following table explains the scale:

AHP Scale of Importance for Comparison of Pairs	Numeric Rating
Extremely More Important	9
Very Strongly More Important	7
Strongly More Important	5
Moderately More Important	3
Equally Important	1

For instance, if you believe A1 is extremely more important than A2 then choose 9 from the left side as shown in the figure below.

9 7 5 3 1 3 5 7 9



There are three digital technology levels in the Data **collection** Category

A1: **Manual/Paper-based** – staff manually collecting data from site.

A2: **Semi-automated** – CCTVs, Phone cameras, Site Tablets, Voice, multimedia.

A3: **Highly automated** – 3D Laser scanning, Photogrammetry, Drones, RFID, GIS/GPS

1. Which data collection technology level is more effective in enhancing the virtual environment of construction projects?

Extremely ← **Equal Importance** → **Extremely**

A1	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	**A2**
A1	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	**A3**
A2	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	**A3**

Similarly, three digital technology levels in the Data Processing (**BIM)** Category

B1: **BIM Level 0/1** – 2D drawing shared electronically/paper based, limited concept 3D models

B2: **BIM Level 2** – 2D & 3D information, Increased Spatial Coordination, models shared electronically between members.

B3: **BIM Level 3 –** Collaborative, online Model that includes sequencing (4D), Cost Info. (5D), Lifecycle Info (6D) and more.

2. Which data processing digital technology (BIM) level is more effective in enhancing the virtual environment of construction projects?

Extremely				Equal Importance				Extremely	

B1	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	**B2**
B1	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	**B3**
B2	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	**B3**

Also, three digital technology levels in the Data **Communication** Category

C1: Phone calls & Emails.

C2: Phone calls, Emails & **Video Conferencing**

C3: Phone calls, Emails, Video Conferencing & **Cloud Computing (Live Data Servers)**

3. Which data communication digital technology level is more effective in enhancing the virtual environment of construction projects?

Extremely				Equal Importance				Extremely	

C1	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	**C2**
C1	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	**C3**
C2	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	**C3**

Section 3: AHP pairwise comparisons between the three data phase categories

In this section, you will compare between the effectiveness of the three categories of data acquisition, data processing (BIM) and data communication in enhancing the virtual environment of construction projects. The following table explains the scale:

4. Which data phase category is more effective in enhancing the virtual environment of construction projects?

Extremely				Equal Importance				Extremely	

Data collection	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	**Data Processing Through BIM**
Data collection	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	**Data Communication**
Data Communication	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	**Data Processing Through BIM**

Section 4: Rate Your Firm's Level of Virtualization

In this section, you will be asked to choose the level of digital technology in each of the three data phase categories (data collection, data processing (BIM) and data communication) achieved by your firm over the recent construction projects.

5. Over the recent construction projects at your firm, which data collection digital technology level has your firm achieved?
   □ A1 (staff manually collecting data from site.)
   □ A2 (CCTVs, Phone cameras, Site Tablets, Voice, multimedia
   □ A3 (3D Laser scanning, Photogrammetry, Drones, RFID, GIS/GPS)

6. Over the recent construction projects at your firm, which data processing (BIM) digital technology level has your firm achieved?
   □ B1 (2D drawing shared electronically/paper based, limited concept 3D models)
   □ B2 (2D & 3D information, Increased Spatial Coordination, models shared electronically between members)
   □ B3 (Collaborative, online Model that includes sequencing (4D), Cost Info. (5D), Lifecycle Info (6D) and more)

7. Over the recent construction projects at your firm, which data communication digital technology level has your firm achieved?
   □ C1 (Phone calls and emails)
   □ C2 (Phone calls, emails and video conferencing)
   □ C3 (Phone calls, emails, video conferencing and cloud computing)

8. In your opinion, do you believe that utilizing more advanced digital technology and hence, more virtualization, contributes to the overall project success?

   □ Strongly Agree
   □ Agree
   □ Neutral
   □ Disagree
   □ Strongly disagree

Vita

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In January 2021, he joined the Construction Management master's program at the American University of Sharjah as a Graduate Teaching Assistant. During his master's program, he successfully published his first academic article titled "Impacts of COVID-19 on the Use of Digital Technology in Construction Projects in the UAE". Meanwhile, in early 2023, Omar is currently working on his second academic publication about the impacts of digital technology on virtual environments within AEC firms. Also, he is currently employed as an assistant project manager at Jacobs Engineering. His research interests are in digital technologies in the AEC industry, Virtual environments, Building Information Modelling (BIM).