THESIS

USE OF REALITY CAPTURE TECHNOLOGIES IN THE US CONSTRUCTION INDUSTRY

Submitted by

Ali Karbasiahvazi

Department of Construction Management

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Fall 2021

Master's Committee:

Advisor: Svetlana Olbina
Co-Advisor: Jonathan W. Elliott

Laura Malinin

ABSTRACT

USE OF REALITY CAPTURE TECHNOLOGIES IN THE US CONSTRUCTION INDUSTRY

The construction industry has traditionally been slow to adopt new technologies. Reality capture technologies (RCT), including laser scanning and photogrammetry, have been around for many years; however, the benefits, obstacles, and application areas of these technologies in the construction industry have not been investigated nor quantified in detail. Clarifying the benefits and obstacles to implementing RCT by different construction project stakeholders could encourage decision-makers to invest in these technologies for their projects.

This study aimed to explore the use of RCT within the commercial building sector of the US construction industry. A survey was used to investigate the extent of RCT use, including different commercial project types and throughout project lifecycles, and the benefits and obstacles of using RCT. The survey was distributed to owners/developers, designers, contractors, and construction managers/owner representatives across the US.

Descriptive statistics indicated that most survey participants were familiar with RCT. Using ANOVA and t-tests, statistical comparisons revealed no significant differences by project stakeholders regarding the proposed benefits or obstacles of RCT use in commercial building projects. However, results showed a statistically significant difference for RCT benefits by project type, suggesting that participants' perceived RCT use was more beneficial for additions, renovations, or maintenance projects than new construction projects. Additionally, statistical analysis revealed that participants perceived the use of RCT was less beneficial during the operation and maintenance (O&M) phase compared to other phases of project lifecycle. This

research contributes to the body of knowledge by providing perspectives of US construction project stakeholders regarding RCT use. RCT providers and manufacturers can use the research findings to better fit their products to the needs of construction project stakeholders. The findings can also help AEC firms in the commercial building sector to implement RCT on their projects.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

The construction industry has traditionally been slow to adopt new technologies, which led to it suffering from low productivity (McCoy & Yeganeh, 2021). However, recent years have shown a significant increase in the acceptance of Building Information Modeling (BIM) as one of the top information and communication technologies within the Architecture, Engineering, and Construction (AEC) industry (Boton & Forgues, 2018; McGraw-Hill Construction, 2014; Smith, 2014). According to Dodge Data & Analytics (2015), many design and construction companies in the United States (US) have gained BIM experience and have confirmed positive impacts of adoption. Relevant literature in the last decade on the topic also indicates a surge in the number of research articles about creating as-built BIMs (i.e., BIM models generated in the construction phase), and as-is BIMs (i.e., BIM models generated when the project is in the operation and maintenance phase). Data acquisition is considered the first, and one of the most challenging, step of creating both as-is BIMs in existing buildings and as-built BIMs in new construction projects. The emergence of several data capturing technologies, also known as Reality Capture Technologies (RCT), in recent years indicates the importance of collecting accurate and efficient geometric data on both new construction and renovation projects.

Research on RCT has been rapidly growing in the last two decades (Wang & Kim, 2019). Volk et al. (2014) classified data capturing and building surveying methods into non-contact and contact techniques. Contact techniques refer to traditional surveying methods, which are mostly manual processes such as tape measurement methods, calipers, and mechanical theodolites. Image-based and range-based techniques are considered non-contact methods in their classification. Reality Capture is a process that uses hardware, such as laser scanners or camera-mounted Unmanned Aerial Vehicles (UAVs), to collect spatially accurate surface points of an existing object, building or site and generate a three-dimensional (3D) representation of real-world conditions in the form of textured, high-resolution, geometrically precise 3D point cloud data or meshes (Almukhtar et al., 2021; Autodesk, 2021). Traditional surveying methods included manual, time-consuming and inaccurate processes, which resulted in incomplete and inaccurate documentation of existing field conditions. RCT was developed to overcome the limitations of traditional surveying methods and enhance construction productivity.

Point cloud data generated from RCTs can be used for different construction applications including, but not limited to: 3D model reconstruction, construction progress tracking, construction Quality Assurance and Quality Control (QA/QC), construction safety management, restoration of historical heritage, building performance analysis, and renovation purposes (GSA, 2009; Wang & Kim, 2019). According to Wang & Kim (2019), the emergence of numerous commercial laser scanning hardware and software in recent years is due, in part, to the realization of the advantages of this technology over traditional surveying methods. New laser scanning devices have integrated image-based technologies with scanning technology, providing more detailed information (i.e., surface material, color, etc.) about the captured environment. Based on the literature, a large portion of recent laser scanning-related studies in the construction industry have focused on automation of 3D model reconstruction from point cloud data and processing procedures in this regard. Other studies investigated one specific application of laser scanning technologies on design and construction projects. However, no study was found that explored the use of RCT by construction project stakeholders and their perception of the benefits and obstacles to wider adoption of these technologies in different projects. In addition, at the time of conducting this study, no published article was found that investigated the experience and perspectives of architects, engineers, contractors, and owners regarding the applications of RCT during different phases of project lifecycles.

The literature review of this study begins by introducing different data capturing approaches used in the construction industry. Laser scanning technology and photogrammetry (also known as image-based technique) are the primary methods of reality capturing and are elaborated and categorized based on their working platforms. The realized benefits and obstacles to wider adoption of each data capturing technique are also investigated based on previous studies. Finally, a comprehensive review of the application areas of RCT in the Architecture, Engineering, Construction, Operation and Maintenance (AECOM) industry is provided.

1.1 Problem Statement

In summary, the relevant literature on the topic indicated a scarcity of research on the perceptions and experiences of construction project stakeholders regarding the use of RCT. Many questions remain unanswered due to the nascent nature of RCT, , which consequently contributes to the slow adoption of these technologies by construction project stakeholders (Almukhtar et al., 2021). Previous studies indicate several applications of laser scanning and photogrammetry technologies are the main methods of reality capturing in the AECOM industry from a theoretical perspective. Case study was the major research methodology used in the related studies. However, no research was found exploring current perspectives of construction project stakeholders on RCT use. A large proportion of the current reality capture-related research in the construction industry has focused on the automation of 3D model reconstruction of structures from point cloud data. However, limited studies have focused on the realized and perceived benefits and obstacles of RCT use by project stakeholders for different applications and project lifecycles. This lack of research motivated the author to perform a comprehensive survey study to explore familiarity, perceptions, and experiences of US construction project stakeholders that listed commercial buildings as their primary market sector with the use of RCT on new construction projects as well as renovation construction projects.

1.2 Research Purpose and Scope

The goal of this study was to explore the use of RCT by construction project stakeholders, including owners/developers, designers, contractors, construction managers (CM), and owner representatives on new constructions, additions, renovations, and/or interior fit-out projects. Specifically, the goal was to investigate areas of application for RCT throughout project lifecycles, including different stakeholders' realized and perceived benefits and obstacles of RCT use, as well as the extent of use. In this research, RCT refers to laser scanning, photogrammetry, and the integration of these two technologies. The literature indicates several applications of RCT throughout project lifecycles, which can be used by different project stakeholders. Also, based on the literature, RCT has applications in different construction market sectors, including residential, commercial, and heavy civil projects. However, this study was focused on the use of reality capture by US construction project stakeholders that listed commercial buildings as their primary market sector. Previous studies indicated multiple potential application areas of RCT in different construction types, including new construction projects, renovations, additions, demolitions, and facilities management projects. The scope of this research did not include the use of RCT on facilities management and demolition projects. Instead, the study focused on comparing RCT use in new construction versus renovation, addition, and interior fit-out projects. While new construction projects have shaped the major portion of the construction market in the US, the emergence of new sustainability trends has led to the renovating of existing buildings gaining more importance by increasing the building's lifecycle and reducing energy consumption. The term renovation is used to refer to the renovation, addition, and/or interior fit-out project types in the rest of this study.

1.3 Research Questions

This study aimed to answer the following five research questions. As shown below, several sub-research questions were developed based on the main research questions and were used to generate the survey questionnaire. Responses to the sub-research questions were used to provide a holistic response to each research question.

1. To what extent are reality capture technologies used by US construction project stakeholders (i.e., owners/developers, designers, contractors, CM and owner representatives) in the commercial building sector?
    - 1.1. What percentage of US construction project stakeholders have heard of reality capture technologies?
    - 1.2. What percentage of US construction project stakeholders have personal experience with reality capture technologies?
    - 1.3. What percentage of US construction project stakeholders mentioned their companies had had experience with reality capture technologies?
    - 1.4. On what commercial project types do US construction project stakeholders report using reality capture technologies?
    - 1.5. What percentage of the US construction project stakeholders who have experience with reality capture technologies use reality capture technologies on new construction projects and renovation projects?

2. Do the US construction project stakeholders in the commercial building sector agree that the use of reality capture technologies provides benefits on different project types (i.e., new construction and renovation projects)?
    2.1. Do the US construction project stakeholders agree that the use of reality capture technologies provides benefits on new construction projects?
    2.2. Do the US construction project stakeholders agree that the use of reality capture technologies provides benefits on addition, renovation, and/or interior fit-out projects?
    2.3. Is there a significant difference between the US construction project stakeholders' opinions regarding the benefits of using reality capture technologies when compared by project type?
3. Do the US construction project stakeholders in the commercial building sector agree that the use of reality capture technologies provides benefits during different phases of a project lifecycle?
    3.1. Do the US construction project stakeholders agree that the use of reality capture technologies provides benefits during the design/preconstruction phase of a project?
    3.2. Do the US construction project stakeholders agree that the use of reality capture technologies provides benefits during the construction/fabrication phase of a project?
    3.3. Do the US construction project stakeholders agree that the use of reality capture technologies provides benefits during the operation and maintenance phase of a project?
    3.4. Is there a significant difference between the US construction project stakeholders' opinions regarding the benefits of using reality capture technologies during different phases of project lifecycle when compared by project stakeholder?

3.5. Is there a significant difference between the US construction project stakeholders' opinions regarding the benefits of using reality capture technologies when compared by project lifecycle phase?

4. What are the benefits of using reality capture technologies based on the US construction project stakeholders' opinions in the commercial building sector?

   4.1. What are the benefits of using reality capture based on US construction stakeholders' opinions?

   4.2. Is there a significant difference between the US construction project stakeholders' opinions regarding the benefits of using reality capture technologies when compared by project stakeholder?

5. What are the obstacles to using reality capture technologies in the commercial building sector based on the US construction project stakeholders' opinions?

   5.1. What are the obstacles to the adoption/or wider adoption of reality capture technologies based on US construction project stakeholders' opinions?

   5.2. Is there a significant difference between the US construction project stakeholders' opinions regarding the obstacles preventing the adoption/wider adoption of reality capture technologies when compared by project stakeholder?

CHAPTER 2: LITERATURE REVIEW

A comprehensive literature review on the topic is presented in this chapter. The first part presents a review of the most used data capturing approaches and building surveying techniques. The advantages and disadvantages of each technique are identified based on the existing literature. After providing background information about different data capturing approaches, the study elaborates on laser scanning technologies as the leading technology used in reality capturing. This review classifies laser scanning into three main categories based on their working platform, and then the challenges of using each technology in the construction industry domain are explained. In the next section, the application areas of RCT are investigated by reviewing recent studies in the field, and the benefits of using RCT for each application during different phases of the project lifecycle are elaborated. Next, the study covers the use of RCT by construction project stakeholders on new construction projects as well as additions, renovations, and/or tenant interior/fit-out projects. Finally, the literature review chapter closes by elaborating on the obstacles preventing RCT adoption/wider adoption in the construction industry.

2.1 Data Capturing Approaches in the Construction Industry

Building information modeling (BIM) has proven to be a vital communication and information technology impacting the construction industry worldwide (Boton & Forgues, 2018; Eastman et al., 2011). The BIM process encourages the development of smart data that can be used throughout a building's life cycle (Azhar, 2011). In recent years, BIM implementation in new construction has increased in the US and worldwide. BIM adoption and use in North America grew from 28% to 71% between 2007 and 2012, which indicates the importance and acceptance of using this technology in construction projects (McGraw-Hill Construction, 2014; Smith, 2014). However, despite the proven benefits of using BIM in a building's life cycle, a large portion of existing buildings do not have BIMs because they were constructed prior to BIM expansion. Existing buildings would benefit from a semantic BIM file in their remaining life-cycle stages, including the operation and maintenance (O&M) phase, refurbishment, deconstruction and demolition. Geometric data acquisition of existing conditions is considered the first, and one of the most challenging, step of creating the as-is BIMs (i.e., BIMs generated when the project is in the operation and maintenance stage) in existing buildings and as-built BIMs in new construction projects.

The lack of documented non-geometric data in existing buildings is always a big challenge, and it usually takes time to attain the required data. Gathering physical data also has technical difficulties in renovation projects. In general, old buildings do not have pre-existing 3D BIM models; thus, the design team needs to rely on available 2D CAD/paper drawings. Nevertheless, even 2D drawings are not always available for renovation projects, making the process even more complicated. Moreover, available drawings do not always reflect the building's actual condition due to the differences between the as-designed and as-built conditions (Lu & Lee, 2017). Thus, AEC firms utilize different data capturing approaches to fill this gap and produce accurate 3D models of existing buildings. Despite the considerable achievements in data collection by introducing advanced data capturing technologies, the transition process of creating a semantically rich BIM model from the captured data still requires a lot of human intervention, which results in an inefficient process and spending a considerable amount of time and money (Pătrăucean et al., 2015; Volk et al., 2014).

Volk et al. (2014) classified data capturing and building surveying methods into non-contact and contact techniques. Contact techniques refer to traditional surveying methods, which are mostly manual processes such as tape measurement methods and calipers. Image-based and range-based techniques were considered non-contact methods in their classification. Laser scanning, which includes Light Detection and Ranging (LiDAR) and Laser Detection and Ranging (LADAR), is considered one of the main methods for as-built 3D building modeling in recent years. On the other hand, one of the other non-contact techniques called tagging has primarily been used in new buildings and construction projects for progress monitoring. In another study, Omar and Nehdi (2016) classified radio-frequency identification (RFID), barcoding, ultra-wideband (UWB), geographic information system (GIS), and global positioning system (GPS) under the geospatial category. Due to the limitation of installing tags in renovation projects, RFID tags and barcoding technologies have rarely been used for as-built 3D modeling. Thus, tagging methods are not covered in the scope of this study.

Although 3D model reconstruction has been identified as the main application of RCT in many studies, the literature indicated other potential applications of using RCT throughout project lifecycles (Wang & Kim, 2019). Clarifying project objectives before choosing the data capturing approach ensures that the project manager gets what is required in a cost-effective manner (GSA, 2009). As RCT matures in the future, it could be expected that creating as-is BIMs for existing buildings would be feasible with minimum cost. The following sections cover a comprehensive discussion on the major geometric data capturing and construction surveying techniques and elaborates on the advantages and disadvantages of each approach.

2.1.1 Manual Methods

Creating as-built documentation is an important part of construction projects. Contractors must recognize the differences between the as-designed plans and what already has been constructed to create as-built drawings for different phases of construction. Representing the building geometry via documents is typically the most important application of building surveying. Traditionally, manual surveying tools, including measuring tapes and optical theodolites, have been used in construction surveys (Klein et al., 2011). The result of this type of surveying was typically a set of 2D drawings in the form of floor plans, sections, and elevations. To generate the as-built documents of a building using conventional field surveying methods, all building components such as walls, doors, and windows needed to be measured manually. Therefore, the process was time-consuming, labor-intensive, and error-prone (Jung et al., 2014; Klein et al., 2012).

Measuring angles and distances are the two most basic parts of the surveying field. To measure angles, mechanical theodolites were invented based on a traditional instrument called "transit," which were previously used by surveyors for measuring angles. With the development of technology, the mechanical parts of theodolites were replaced with electronics, which resulted in higher precision (Schofield & Breach, 2007). Since the 1980s, electronic distance measurement (EDM) devices, which work based on calculating the time-of-flight (TOF) of an energy wave, have replaced the use of tapes for measuring long distances by surveyors. "Triangulation" and "traverses" are the two common techniques used to determine the position of an element based on distances and angles. The combination of electronic theodolites and EDM devices led to the invention of "total stations," which is currently one of the main instruments for surveying urban and infrastructure (Schofield & Breach, 2007).

To capture the 3D geometry of existing components, more advanced technologies and devices were developed. Image-based and laser-scanner-based techniques are the two main categories for capturing the geometry of existing buildings in recent years. However, a large portion of contractors, facility managers, and other stakeholders in the construction industry still use manual or semi-manual methods of surveying as well (Klein et al., 2011).

2.1.1.1 Advantages and Disadvantages of Using Manual Methods

Despite the simplicity in function and economics of manual instruments, these techniques had a high possibility of error. In tape measuring, sagging problems, particularly over long distances, effects of temperature on accuracy, and difficulty in measuring around obstacles are some of the many limitations of this method (ME et al., 2019). Optical theodolites are accurate compared to tape measurement. However, it is generally a time-consuming and relatively expensive process, requiring extensive human resources (M.E. et al., 2019).

Laser distance meters and digital cameras are considered recent advancements to instruments in the construction industry. The new devices provide more precision and are easier to utilize compared to previous types of equipment. However, the central part of the process remained manual and time consuming (Jung et al., 2014). Moreover, architects and engineers needed to obtain a degree of specialized knowledge and education of geodetic surveying techniques before utilizing the instruments, and the equipment was typically expensive (Petzold et al., 2004).

2.1.2 Image-Based Techniques (Photogrammetry and Videogrammetry)

Using computer vision techniques, researchers in the field of computer graphics and photogrammetry have conducted a large amount of research on creating 3D models from images (Pollefeys et al., 2004; Snavely et al., 2008). Moravec (1981) inspired several researchers in the image processing field by developing a corner detector that was able to pick optimal windows. Schmid and Mohr (1997) utilized photometric information and local computation to process images with partial visibility (Lu & Lee, 2017). Later, Lowe (1999) introduced the scale invariant feature transform (SIFT), which enhanced the matching and recognition of local attributes among images.

In recent years, image-based modeling (IBM) has gained importance, especially in the field of architecture and urban planning. Modern photogrammetry and remote sensing techniques, in combination with Unmanned Aerial Systems (UAS), represent new research trends covering a wide range of studies, including technology, safety, and regulation (Colomina & Molina, 2014). In this regard, Teller et al. (2003) employed thousands of calibrated images to remodel the MIT campus in their project. Pollefeys et al. (2004) proposed a method to generate several types of visual models using images from an uncalibrated camera. Dick et al. (2004) presented an automatic method for 3D modeling of architectural buildings. In large-scale urban scene reconstruction, Schindler et al. (2007) attempted to model the city of Atlanta from historical photographs and address the location recognition issue in a large image dataset. In a more recent study, Lu & Lee (2017) identified different types of configurations for image-based data capturing techniques including commercial digital cameras, multicamera Rigs, thermographic cameras, camera stereo setups, Microsoft Kinect, and Google Tango. These configurations and equipment are the most used methods of reality capturing in the photogrammetry and videogrammetry domains.

Several algorithms such as SIFT, speeded up robust features (SURF), maximally stable external regions (MSER), and DAISY (i.e., a fast local descriptor for dense matching) have been proposed by researchers in the field of computer vision to identify objects in images (Lu & Lee, 2017; Morris, 2004). Researchers in civil engineering started to utilize these algorithms for image-based recognition of buildings and civil infrastructures. Lu and Lee (2017) categorized image-based recognition and construction approaches into five groups, including feature representation-based methods, wide baseline matching-based methods, dimensionality reduction-based methods, clustering-based methods, and methods for 3D construction from image-based point clouds.

Despite several efforts and developments in the field, it seems that image-based techniques are not widely used for the purpose of creating 3D as-built models in the construction industry due to insufficient accuracy of the output and a lack of an automated approach for generating 3D models from the captured data (Pătrăucean et al., 2015; Volk et al., 2014).

2.1.2.1 Advantages and Disadvantages of Using Image-Based Techniques

By utilizing image-based modeling techniques, AEC firms do not encounter common problems like data noise and missing textures that are usually faced while using laser scanners (Fathi et al., 2015). Moreover, the price range of using image-based methods is more reasonable for capturing large-scale complex projects compared to the price range of using laser scanning-based techniques. This makes image-based methods remain competitive as an effective surveying tool in the construction industry. Although the output data of image-based techniques is not as accurate as laser scanning technologies, image-based techniques have been proven as an effective and economical solution for creating as-built and as-is BIM models, working as a complement to other data capturing methods (Dimitrov & Golparvar-Fard, 2014).

2.1.3 Laser Scanning-Based Techniques (LiDAR)

3D Laser scanning, also known as Light Detection And Ranging (LiDAR) is a range-based technique that is based on measurements of time-of-flight (TOF). It is one of the most valid and widely used methods for attaining 3D point clouds of a space or object (Volk et al., 2014; Wang et al., 2020). The scanners emit laser light pulses to the scene surface and calculates the surface distance by recording the laser light pulse's round trip time The laser scanner then returns data in a point cloud format and renders it using related software. Users can interact with the scanned objects in a virtual environment using these applications (Golparvar-Fard et al., 2011; Jaselskis et al., 2003). Laser scanning is an effective way of creating as-is models and can be conducted in different ways, including terrestrial, mobile, and aerial (Becerik-Gerber et al., 2011). Terrestrial laser scanning (TLS), also called ground-based LiDAR, is one of the most used laser scanning technologies in the construction industry. It can generate a point cloud of the captured area either in single or multiple scan positions. LiDAR accomplishes the critical step of registering the point clouds while capturing from multiple scan positions and processing the data.

Looking for new methods to automatically create 3D models from scanned point clouds has become a trend in new research since 2007. Li et al. (2008) proposed a way to create BIMs from laser scanning that was compatible with International Foundation Class (IFC) files. Bosche et al. (2009) presented an innovative and practical method of object recognition in a 3D atmosphere by combining planning and field technologies. Brilakis et al. (2010) provided an efficient way of generating automatic parametric BIM models based on hybrid video and laser scanning data. Murphy et al. (2013) implemented laser scanning to make a renowned historic building information model. Xiong et al. (2013) came up with an approach for converting point cloud data from several laser scanners in different positions into an automated rich information model. However, none of the previous methods were fully automated or comprehensive. The literature revealed that most related studies were specific to one case study (e.g., automatic creation of structural columns), or the process still required human intervention and was error-prone.

2.1.3.1 Advantages and Disadvantages of Using Laser Scanning-based Techniques

The construction industry market benefits from a variety of scan-to-BIM applications that allow 3D modelers to convert point cloud data into as-is geometric models. A large portion of these programs were designed to allow modelers to replace scanned points with BIM software components. However, the modeling task has remained highly manual and repetitive, particularly on projects requiring the acquisition of MEP equipment consisting of several objects. As a result, the process of transforming laser scanning data into a semantic BIM file takes a lot of time and effort (Volk et al., 2014).

Bringing different sets of data into one global coordinate system (registration procedure) is essential to generate 3D point clouds. Registering laser scans is faster and more accurate compared to other data capturing techniques. Lu and Lee (2017) evaluated different processes of creating as-is BIMs by conducting a comprehensive review of recent publications. The results demonstrated that laser scanning is still a top priority method for generating as-is BIMs. The main advantages of using laser scanners are high-resolution outputs, standardization of the generated point cloud models, and accuracy (Golparvar-Fard et al., 2011).

However, scanning the building from different positions and angles is needed, which requires a high amount of time and effort, and in some cases where the construction site is tight, using traditional laser scanners is impossible (Wang et al., 2015a). In addition to positioning constraints, the 3D point cloud generated by a ground-based laser scanner usually has several holes and noise, specifically in complex and detailed structures. Moreover, laser scanning-based techniques still do not address the problem of capturing unwanted hidden geometries (e.g., pipelines and ducts behind ceilings), which remains a serious obstacle to creating accurate as-is BIM models. Another limitation of using scanners in the construction industry is during inclement weather conditions, like rainfall. Due to the light interference, using a laser scanner in areas with uncontrolled ambient light (e.g., outdoor environments) can increase the noise and reduce the final quality of point cloud data. However, with the overall advancement of technology, laser scanning technology has become more widespread and is replacing traditional surveying methods (Golparvar-Fard et al., 2011).

2.1.3.2 Different Types of Laser Scanning Technologies

3D laser scanning is an effective way of creating as-is models of buildings, construction sites, and infrastructure and can be conducted on different working platforms (Becerik-Gerber et al., 2011). Phase-shift and TOF are the two main range measurement techniques used in laser scanners. For scanners using the phase-shift technique, an amplitude modulated continuous wave (AMCW) is emitted to the target object, and the phase shift between emitted and reflected signals is measured. For TOF, the scanner emits a laser pulse and calculates the traveling time of the reflected pulse to measure the distances from the target object (Wang et al., 2020).

Laser scanning technologies are commonly grouped into three different categories based on their working platforms and spatial location of the scanner: Aerial Laser Scanning (ALS), Terrestrial Laser Scanning (TLS), and Mobile Laser Scanning (MLS) (Wang et al., 2020). Figure 1 shows the number of journal and conference articles related to these three laser scanning technologies published in the last decade. The literature search was conducted in the 'Web of Science' using keyword search. Related literature on the topic showed that the number of articles published between 2010 to 2020 in the construction industry area with 'terrestrial laser scanning' as a keyword was approximately twice the number of articles with 'mobile laser scanning' or 'aerial laser scanning' as keywords. Figure 1 also shows an increase in the number of articles published about TLS in the last ten years, which indicates that the importance of the TLS research topic is trending up in the construction industry. The literature also reveals the trend over the last decade of looking for new methods to automatically create 3D BIM models from scanned point clouds.

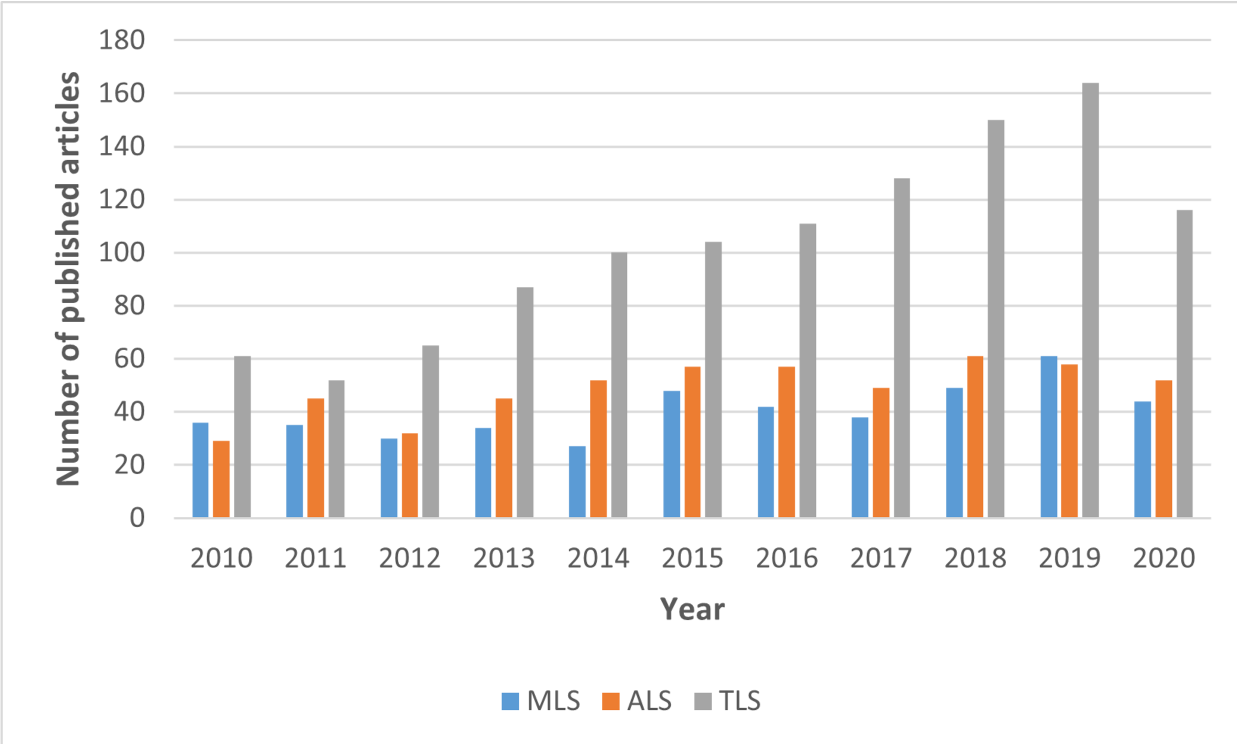


Figure 1. The Number of Journal and Conference Papers Per Year Regarding Mobile Laser Scanning, Aerial Laser Scanning, and Terrestrial Laser Scanning in the Context of the Construction Industry.

2.1.3.2.1 Aerial Laser Scanning (ALS)

Aerial laser scanning, also called airborne/aerial LiDAR, has been widely used for capturing large-scale areas (e.g., cities, forests, etc.) due to its high mobility. Traditionally, optical imagery was utilized for the analysis of urban land mapping for many years. In the late 1990s, ALS replaced the traditional approach by generating point clouds of urban areas (Yan et al., 2015). In early versions of the ALS system, the LiDAR equipment was mounted on an airplane or helicopter flying around the scene to capture the data. The advent of ALS has completely revolutionized the field of topographic surveying and continues to show promising applications in different fields such as urban planning, archeology, forest management, and landscape studies. The data acquisition system in ALS consists of several components including, a laser scanner device, internal measurement unit (IMU), onboard global positioning system

(GPS), ground GPS, and digital camera (Coluzzi et al., 2010). A combination of LiDAR technology and Global Positioning System (GPS) in ALS systems has provided the option of creating a 3D point cloud of a scene (e.g., a city scanned). In this method, an Unmanned Aerial Vehicle (UAV), which carries the LiDAR equipment, is utilized to fly around a scene and capture geometric data (Wang et al., 2015a).

Researchers have developed creative ways to automatically produce urban planning and as-built 3D building modeling from ALS data. In the field of computer vision, Frueh and Zakhor (2003) came up with an automated approach for generating textured 3D city models using both terrestrial and aerial-based LiDAR point clouds. Rottensteiner (2003) introduced an approach to generate 3D building models using LiDAR point clouds automatically. Several research studies investigated creating automatic 3D building models that emphasized rooftop modeling from aerial LiDAR data. Yu et al. (2010) illustrated an automated object-based method to determine building density for urban design use by utilizing airborne LiDAR data.

LiDAR remote sensing technology was a revolutionary approach for urban planning and surveying because the sampled surface elevation of urban areas captured through ALS was more accurate than those from photogrammetric techniques (Yu et al., 2010; Zhang et al., 2006). Additionally, one advantage of ALS compared to ground-based LiDAR is that it can generate a Digital Surface Model (DSM) of inaccessible areas such as building roofs.

2.1.3.2.1.1 Obstacles to Using ALS in the Construction Industry

Although ALS technology is considered one of the most accurate techniques for creating 3D models of cities and urban planning, it is not as accurate as a terrestrial laser scanning system for the purpose of as-built 3D modeling in the construction industry. Lee and Park (2019) analyzed the performance of UAV images and UAV LiDAR technologies for creating 3D geospatial information. Based on the results of their study, the accuracy of the captured data by UAV images showed a deviation of up to 8.4 cm from the reference points. The accuracy of UAV LiDAR data was about 5 cm, which indicates a higher accuracy compared to UAV image technology. Both methods indicated satisfactory accuracy to produce digital maps (e.g., digital maps with a scale of 1:1000). However, the accuracy of both methods is not sufficient for other purposes, such as construction quality control and as-built 3D modeling of the buildings. Therefore, the lack of accuracy of ALS presents an obstacle to its broader implementation in the construction industry (Lee & Park, 2019).

2.1.3.2.2 Terrestrial Laser Scanning (TLS)

Terrestrial laser scanning (TLS), also called ground LiDAR, is the most commonly used laser scanning technology in the AECOM industry due to its high accuracy, a key factor for many applications in the construction industry (Wang et al., 2020; Yang et al., 2020). A typical TLS system has a scanner mounted on a tripod placed at a fixed position, while the scanner head and mirror can freely rotate both horizontally and vertically, capturing the surrounding environment by emitting laser beams. The TLS output point cloud data of the observed environment has high density and accuracy (Vosselman & Maas, 2010). Shan and Toth (2018) classified ground-based or terrestrial laser scanners into static and dynamic categories. In this study, the term TLS is used for static terrestrial laser scanners and the term MLS for dynamic terrestrial laser scanners. The MLS system will be discussed in detail in the next section of this study.

TLS systems are also categorized based on the range or distance the TLS can be used: short-range laser scanners using phase measurement, medium-range laser scanners using pulse ranging, long-range laser scanners also using pulse ranging, and total stations with scanning capabilities (Shan & Toth, 2018). TOF and amplitude-modulated continuous-wave (AMGW) are the most common range principles used in TLS systems. TOF is usually used in long-range scanners where lower accuracy is acceptable. On the other hand, scanners with higher accuracy typically use the AMGW measuring principle and can capture geometries in environments with maximum ranges from 50 to 450 meters (Shan & Toth, 2018; Yang et al., 2020).

TLS systems are used in architecture, civil engineering, cultural heritage, virtual reality, plant design, the automobile industry, and others (Holopainen et al., 2013; Vosselman & Maas, 2010). The AEC industry uses TLS mainly for 3D reconstructions of facilities. Thanks to recent developments, newer TLS devices have built-in cameras that enable the system not only to capture visual features, but also intrinsic properties of the environment such as building materials. Due to its high accuracy, researchers have extensively used TLS for constructing as-is BIMs that represent as-is conditions of buildings.

2.1.3.2.2.1 Obstacles to Using TLS in the Construction Industry

Despite many advantages of the TLS system, its practical use remained limited for many years because of several obstacles preventing its adoption, such as relatively high equipment costs and the high expertise required to work with the system (Nowak et al., 2020). With advancements in technology and commercial versions of laser scanners, the cost of TLS systems has decreased significantly in recent years. Newer TLS devices are also easier to operate as well. However, other obstacles still exist. TLS function becomes limited with reflective surfaces or glass elements. TLS scanners can obtain high-quality data, but suffer from low mapping efficiency because of laborious scan station resetting and registration procedures (Cui et al., 2019). To generate accurate point clouds of large-scale buildings, scans must be taken from hundreds of positions with small distances from each other (about 5-10 meters). Next, data from all the measuring points need to be processed and compiled into one final point cloud using the “point to cloud registration. Registration is a critical step in TLS systems, because the captured data is not applicable for construction purposes without registration.

The quality of the laser scanner and expertise of the operator still remain important factors affecting the final result (Nowak et al., 2020). Therefore, time-consuming processes and labor-intensive tasks remain potential obstacles to adopting TLS technologies in the commercial building sector. This results in keeping costs of TLS implementation high, which prevents wider adoption of this technology in the AEC industry. Additionally, TLS functionality is limited when used in unfavorable weather conditions (e.g., rain, snow, etc.), high temperatures, or jobsites with vibration. These obstacles, which are common in construction, could also prevent wider adoption of TLS in the industry (Filgueira et al., 2017; Nowak et al., 2020).

2.1.3.2.3 Mobile Laser Scanning (MLS)

While the high performance and reliability of TLS and ALS technologies in the construction industry are undeniable, they also have some clear limitations. For instance, it is impossible to use TLS in locations with size or shape limitations, such as narrow corners. Moreover, capturing 3D information of indoor environments using ALS is not practical in many cases due to safety issues and technical limitations of ALS (Chen et al., 2019; Fryskowska et al., 2015; Kedzierski & Fryskowska, 2014). The Mobile Mapping System (MMS) concept was introduced in the early 1990s as a solution to address the inconvenience caused by stationary TLS and ALS (Barber et al., 2008). In this approach, the scanner is mounted on a vehicle to capture the 3D information of the existing environment, providing densities and accuracies closer to TLS and speeds closer to ALS techniques. As a result, the MLS is considered a flexible, cost-effective and time-saving alternative. A typical vehicle-based MLS system consists of one or more laser scanners, a global navigation satellite system (GNSS), an inertial measurement unit (IMU) component, and digital cameras. Similar to ALS, the MLS makes use of GNSS positioning. However, the details of positioning in MLS are different. The common positioning method for mobile mapping systems is the combination of IMU with GPS and other sensors (Boavida et al., 2012; Chen et al., 2019). MLS systems have been commercially available for two decades and can achieve an accuracy of a few centimeters (Boavida et al., 2012; Haala et al., 2008).

The primary application of MLS is in urban areas for large-scale outdoor point cloud acquisition. Traditionally, optical imagery was utilized for many years to analyze urban land and urban mapping. In the late 1990s, ALS replaced traditional approaches to generate point clouds of urban areas (Yan et al., 2015). In recent years, the MLS system has gained attention in urban scene mapping and modeling for its ability to extract finer-scale objects with more detailed information compared to ALS. Thanks to the high speed and accuracy of MLS, new urban applications have emerged, such as road environment reconstruction, single stem tree modeling, furniture detection, and building roof segmentation (Sairam et al., 2016; Xiang et al., 2018). Wang et al. (2019) provided a summary of the latest mobile mapping systems from manufacturers such as Topcon, Trimble, Leica, and RIEGL. The main applications of these commercial systems include surveying and mapping for urban road inventories, infrastructure monitoring, city surveying, and pavement management.

Although the main application of MLS is currently in urban areas, recent developments in MLS technology shows promising results for 3D indoor mapping. MLS systems can be applied to indoor scenes that have complex layouts and can minimize occlusion effects. They can continuously obtain point clouds while moving. This is why easy-to-use and affordable indoor

MLS systems are now mostly used for data acquisition of large indoor scenes (Cui et al., 2019; Wang et al., 2013). Indoor Mobile Mapping Systems (IMMS) are very similar to vehicle-based mobile mapping systems, but use other positioning methods such as Simultaneous Location and Mapping (SLAM) instead of using GNSS, which is not available in indoor environments (Thomson et al., 2013). Therefore, IMMS are considered a modified version of mobile mapping systems for the specific function of capturing geometric data of indoor environments.

2.1.3.2.3.1 Obstacles to Using MLS in the Construction Industry

Despite rapid advances in MLS technology, the accuracy and density of the point cloud generated from MLS is still lower than TLS systems (Thomson et al., 2013). Therefore, a lack of accuracy remains an obstacle that prevents broader adoption of MLS in indoor environments. Due to the high speed of data capturing using the IMMS approach, Thomson et al. (2013) investigated the use of these systems to create as-is BIMs. They found the point cloud generated from IMMS indicated a few centimeters deviation from the reference survey, which makes the system unacceptable for applications requiring millimeter level accuracy. Chen et al. (2019) developed an innovative method for capturing indoor environments using MLS, but the process was error-prone, and the final point cloud was less accurate than TLS systems. In another recent study, Cui et al. (2019) proposed an automatic approach to reconstruct a complex indoor environment from MLS point clouds. The recall and precision of the reconstructed surface models were evaluated to be more than 60% (close to five centimeters). Despite promising results obtained from using MLS for 3D model reconstruction, moving objects, multiple reflections, and occlusion are some remaining challenges of using MLS systems for creating 3D models of indoor environments. Therefore, the lack of accuracy of MLS in capturing different environments presents an obstacle to its broader adoption in the construction industry (Cui et al., 2019; Thomson et al., 2013).

2.1.4 Integration of Data Capturing Techniques

Researchers from the fields of computer vision, geometry processing, and civil engineering have practiced different methods to achieve more accurate and efficient means of 3D as-built modeling. Efficient interdisciplinary communication between researchers from different fields and the integration of different approaches are essential factors to advance as-built and as-is BIM technologies (Pătrăucean et al., 2015). Several researchers have tried to integrate different data acquisition approaches and streamline the process of as-built 3D modeling. In this regard, Guarnieri et al. (2013) combined photogrammetry and TLS to capture geometry data of a complex civil infrastructure. Dore and Murphy (2014) proposed a semi-automated method for generating 3D geometry of a façade using a laser scanner and image data. In the field of buildings energy simulation, Ham and Golparvar-Fard (2015) constructed as-is BIM elements of an existing building by integrating thermal imagery and digital imagery techniques. Lu and Lee (2017) identified photogrammetry and its integration with other methods as a feasible and promising alternative, which has the potential to compete with laser scanning techniques.

The general process of creating an as-built BIM model from the combination of laser scanning-based techniques and photogrammetry methods is demonstrated in Figure 2. As shown in Figure 2, the point cloud generated by each method needs to be gathered into a central 3D environment as the first step of the process. Registration procedure plays a crucial role in bringing different point clouds to an integrated coordinate system. Pătrăucean et al. (2015) defined point cloud processing as the second step in the as-built modeling process. Eliminating outliers, reducing noise, and dealing with missing input data are main goals of the processing stage of the as-built modeling process. The next step in the as-built modeling process can be achieved in two different ways. The first scenario happens when an as-designed BIM model of the project exists. Therefore, the as-designed model needs to be updated by being compared with the captured point cloud data. In the second scenario, the as-designed BIM model does not exist, and the 3D model of the building needs to be constructed from scratch. Therefore, recognizing the elements (e.g., floors, walls, doors) from the point cloud and identifying relationships between them is a crucial part of as-built modeling in this approach.

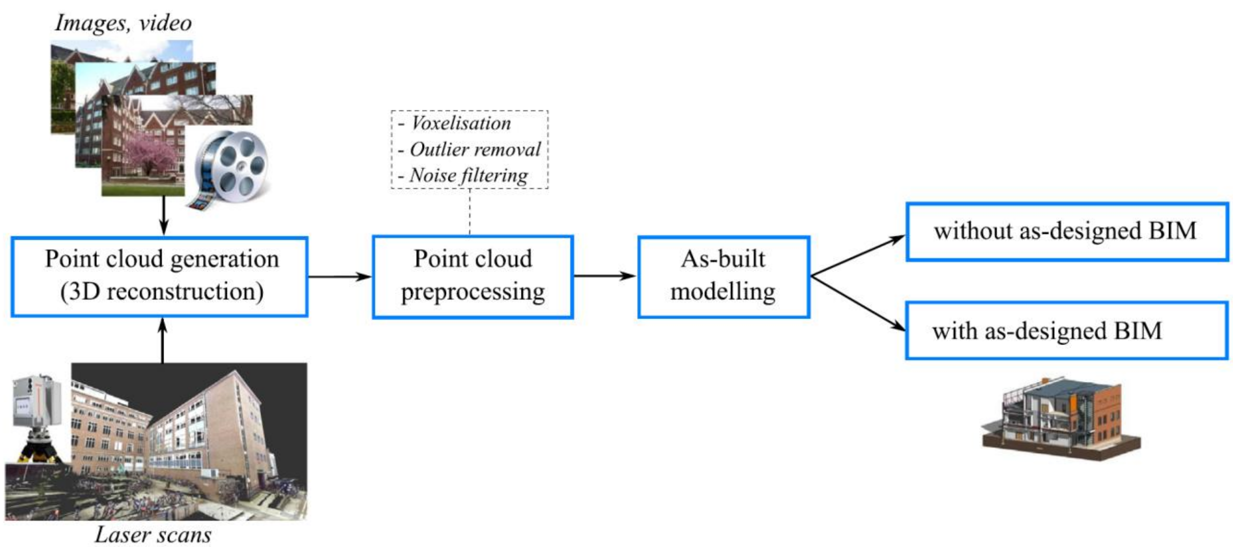


Figure 2. As-Built/As-Is 3D Modeling Process, Source: (Pătrăucean et al., 2015)

2.1.4.1 Advantages and Disadvantages of Integration of Data Capturing Approaches

The integration of different data capturing technologies could overcome the limitations of each individual technology (Karsch et al., 2014). Laser scanning-based technologies are considered some of the most advanced and common methods of capturing data by generating high-resolution 3D point clouds of structures. Accuracy and range are the main strength of these methods. However, a lot of time and effort is required to achieve a complete and accurate scan of a building, specifically for complicated structures that require scanning from different positions.

On the other hand, image-based techniques such as photogrammetry, videogrammetry, and range images are affordable and user-friendly methods of data acquisition (Omar & Nehdi, 2016). Therefore, several researchers have tried to integrate photography and laser scanning for generating as-is BIM of existing structures (Dore & Murphy, 2014; Murphy et al., 2013). Although laser scanning technology is still considered a top priority method of generating as-is BIMs, the integrated approach has gained acceptance in recent years as a promising alternative (Lu & Lee, 2017).

The integration of different data acquisition approaches seems to be a promising method to reduce the limitations of each individual technique. However, the integration of different technologies requires collaboration of researchers from different fields. Multidisciplinary information exchange, the wide range of technological elements needed for integration, and the perseverance to use new methods are inportant challenges facing the development of integration approaches. Moreover, the captured data (e.g., point clouds, images, etc.) using each method must be processed to be integrated, which is an extra and complicated step. Therefore, geometric data acquisition using integration of data capturing approaches can be lengthy and time-consuming, preventing broader adoption of these techniques in the construction industry (Khaddaj & Srour, 2016; Lu & Lee, 2017).

2.2 Application Areas of RCT in the Construction Industry

Traditionally, construction information was collected through site visits and manual measurements, which was labor-intensive, time-consuming, and error-prone. With recent advancements, 3D point clouds generated from photogrammetry and remote sensing technologies such as laser scanning has become a superior approach providing accurate and efficient information about construction sites, work, and equipment (Marks et al., 2013; Wang &

Kim, 2019; Wang et al., 2020). 3D point cloud data generated from RCT can provide accurate and fast records of construction-related objects and environments. Therefore, laser scanners have been widely used for different AEC applications in recent years. The next four sections provide a detailed introduction to the most common application areas of RCT based on the literature review.

2.2.1 Creating 3D Models of Existing Facilities

3D model reconstruction of construction-related objects using point cloud data is one of the main applications of RCT in the construction industry. The literature review showed research on 3D model reconstruction using point cloud data shaped approximately 50% of point cloud-related articles published from 2004 to 2018 (Wang & Kim, 2019). 3D model reconstruction can be classified based on the construction type into different categories, including buildings, construction sites, civil infrastructure, and urban/city modeling. The construction site refers to the use of RCT to model the earthwork, site geologies, construction equipment, and scaffolds. The 3D model reconstruction of the building includes modeling the building's entire interior and exterior with all their components. The literature also revealed diverse reality capture applications for 3D modeling of infrastructure elements, including roads, highways, bridges, tunnels, and large-scale industrial instruments (Wang & Kim, 2019). Generating 3D models of cities started in the late 1990s, using airborne images and laser scans. However, research on automatic city modeling is still an active area of study (Buyukdemircioglu et al., 2018; Chen et al., 2018; Wu et al., 2018).

Based on the literature, early research studies on 3D model reconstruction using point cloud data were limited to reconstruction of solely geometry models, without any semantic information (e.g., material, manufacturer, warranty, etc.) about the elements that shape the whole

3D model. When reconstructing the geometry models, transferring the original sensing data from the laser scanner into a complete point cloud of the target object was the sole goal. Registering the scans taken from multiple positions into a shared coordinate system is the key task in this regard. A detailed explanation of the registration process is provided in the following sections.

On the other hand, reconstructing semantic models (3D models with information about different elements, e.g., BIM models) from the point cloud data is a more complex task that includes an extra step of object recognition. Planes are the most common geometry in buildings. Utilizing different algorithms, object recognition aims to classify the points with the same characteristics into object categories such as walls, floors, doors, and windows (Wang & Kim, 2019). A comprehensive explanation of object recognition has been provided in the point cloud processing section.

2.2.1.1 3D Model Reconstruction Benefits in Different Project Phases

One of the primary current applications of RCT in the construction industry is creating 3D models of existing objects using point cloud data. A large portion of the research literature of the past two decades has been dedicated to this topic. 3D model reconstruction can benefit all project lifecycle phases, including planning, design, construction (including fabrication), and O&M (including renovation). For example, generating a 3D model of an existing structure/environment during planning and design phases can help the project team make better decisions that will result in improved design quality and productivity. Based on the literature, 3D model reconstruction is currently the only application of point cloud data used in the planning and design phases of construction projects. For fabrication and construction phases, as-is 3D models of construction projects can be used as the base tool for other construction applications such as construction safety management, construction automation, etc. The as-is 3D model of the project in the construction phase improves construction quality, productivity, and safety. Finally, during the O&M phase, the reconstruction of the 3D model of existing facilities can be used for different FM purposes. Particularly, it can help FM practitioners make informed decisions to provide better maintenance and extend the service life of the facility. Considering renovation as part of the O&M phase, 3D model reconstruction application of laser scanning and photogrammetry technologies provides several benefits in the renovation stage as well by enhancing the quality and efficiency of the process (Wang & Kim, 2019).

2.2.2 Geometry Quality Inspection

According to the literature, geometry quality inspections of buildings and infrastructure are one of the main applications of point cloud data in the construction industry. On-time and accurate quality inspection mitigates risk associated with defects and imperfections in construction projects and reduces project time and cost (Omar & Nehdi, 2016). According to Nahangi and Haas (2014), construction rework related to late detection of deficiencies accounts for about 10% of the total project budget in industrial projects. However, proper quality assurance (QA) and quality control (QC) have been considered labor-intensive and time-consuming processes in construction projects for many years. In the last two decades, TLS has increasingly gained interest in dimensional QC by addressing limitations of traditional surveying methods. Thanks to TLS technology, inspectors can capture dense and accurate point cloud data of the entire construction surface in an efficient way (Puri et al., 2018).

Wang and Kim (2019) classified research articles on geometry quality inspection into three categories, including (1) dimensional, (2) surface, and (3) displacement. An as-designed BIM file is a critical component of dimensional quality inspection since the point cloud data has to be compared with the 3D model of the structure prepared by the design team. Several research studies related to damage detection on heritage sites and inspections related to the size, shape, position, and orientation of buildings and civil infrastructure, these can be included in the dimensional quality inspection group (Kashani & Graettinger, 2015; Kim et al., 2016; Wang et al., 2016).

Surface quality inspection is another trending application area of point cloud data in the construction industry. For example, concrete work is one of the major tasks in construction projects, the inspection team can test floor flatness using laser scanners to help evaluate the concrete contractor's performance (Puri et al., 2018). Based on the literature, flatness/waviness, deformation, surface cracks, and spalling are main problems regarding concrete surface quality inspections. Since most of the surfaces in construction projects are planar, typically, no as-designed BIM model is needed for surface quality inspections. For displacement inspections, the focus is on the change of the relative position of a structure (e.g., displacement of landslides, dams, etc.). To detect the displacement of a structure, point cloud data is collected at several intervals and compared to each other (Riveiro et al., 2013). Only a few research articles were found related to this application of point clouds.

Wang and Kim (2019) also investigated QA/QC applications of point clouds in different stages of construction projects, including preconstruction, construction, and O&M phases. For preconstruction, the main application of TLS was quality inspection of precast concrete elements and prefabricated objects to ensure smooth installation and prevent rework. In addition, the goal of inspection in the construction phase is to make sure the project is built based on the as-designed model and discrepancies are within required tolerance values. The main inspection occurs right after the construction work of a specific scope of the project is finished. Finally, routinely conducting geometry inspections in the O&M phase helps to detect structure defects early and repair them before they become costlier issues later. The main inspection targets of QA/QC in the O&M phase of construction projects include steel structures, concrete structures, heritage sites, post-disaster buildings, tunnels, and landslides (Wang & Kim, 2019).

2.2.2.1 Geometry Quality Inspection Benefits in Different Project Phases

Applications of geometry quality inspections using point cloud data are primarily utilized in construction/fabrication and O&M phases. On-time and accurate quality inspections using RCT mitigates risks and improves construction quality and productivity. Point cloud data also can be used to check geometry quality of prefabricated construction elements to support smooth installation of components. Using RCT in the O&M phase, FM teams can regularly check facilities and repair any deficiencies on time. Therefore, virtual 3D environments can improve FM efficiency and aid in accurately inspecting the condition of facilities (Wang et al., 2015a).

2.2.3 Construction Progress Tracking

Construction progress tracking is a critical element of project control, but is always challenging due to the complexity of construction projects (Omar & Nehdi, 2016). Progress tracking provides information to the project team to know if they are meeting schedule and budget guidelines, and helps them to make necessary adjustments to achieve the project's goals. Traditionally, progress tracking was based on a large amount of information from different sources that were provided in a wide variety of forms, particularly visual inspections and daily or weekly reports. Therefore, the process was mostly manual, time-consuming, and error-prone (Bosché et al., 2015; Turkan et al., 2012).

Capturing data related to the as-is condition of the construction site in different time frames during the construction phase is a critical component of progress tracking. Omar and Nehdi (2016) classified data acquisition technologies related to progress tracking into four groups: (1) enhanced IT-based communication tools; (2) geospatial; (3) imaging; and (4) augmented reality. Enhanced IT communication technologies refer to the tools, such as multimedia tools (e.g., digital photographs and videos), email services, voice-based tools, and hand-held computers/tablets that improve communication on construction sites to address the challenges of site information tracking. Geospatial technologies refer to the tools, such as barcoding, radio frequency identification (RFID), global positioning system (GPS), and ultra-wideband (UWB) tags that help the project team in visualizing construction objects on site and help documentation processes. Omar and Nehdi (2016) included technologies such as photogrammetry, videogrammetry, laser scanning, and range images into the imaging category. However, other researchers have separated laser scanning-based technologies from other imaging techniques (Lu & Lee, 2017; Volk et al., 2014).

Finally, augmented reality (AR) was identified by Omar and Nehdi (2016) as the last data acquisition technology used in construction progress tracking. Wang et al. (2014) defined AR as "a live, direct or indirect view of a physical, real-world environment whose elements are augmented by virtual, computer-generated imagery". Using AR, project managers can compare the status of different projects or phases by overlaying the reality (in this case, as-built data generated from laser scanners) with a 4D BIM model of the project (Golparvar-Fard et al., 2009). Despite the application of AR in construction progress monitoring, AR cannot be categorized as a geometry data capturing approach based on its definition. Among all the categories mentioned above, laser scanning and photogrammetry are the only data acquisition technology groups identified by Omar and Nehdi (2016) that focuses specifically on capturing the 3D geometry of existing structures.

The considerable growth of commercial laser scanning software and hardware in recent years confirms the acceptance of this technology in the AEC/FM industry (Bosché et al., 2015). Due to the high density and accuracy of point cloud data generated from laser scanning systems, research on construction progress tracking using laser scanning technologies has grown steadily in the last two decades (Chen et al., 2019; Dimitrov & Golparvar-Fard, 2014; Omar & Nehdi, 2016). TLS has been identified by many as the best fit technology for capturing 3D geometry of construction projects.

Akinci et al. (2006) developed a framework for active quality control on construction sites using sensing technologies. Recent articles in the literature primarily focus on the automation of construction progress monitoring by developing algorithms for processing 3D point cloud data. In this regard, Turkan et al. (2012) proposed a system that integrates schedule information with 3D object recognition technology to provide the project team with a 4D object-oriented progress tracking system. Results from testing the system on a concrete structure were promising, showing more accuracy than manual progress tracking methods. However, the quality and comprehensiveness of the scanned data was an important factor impacting the final results. Bosché et al. (2015) proposed an automated approach comparing as-built data taken from TLS and 3D models of cylindrical MEP work by combining two previously studied techniques. Maalek et al. (2019) provided a method to automatically extract structural elements from TLS point cloud data using relation-based reasoning between objects and geometric primitive. The framework was also able to detect changes between consecutive scans by removing redundant points. Based on the reviewed studies, automation of object recognition from point cloud data is the key factor in automatic progress tracking (Wang & Kim, 2019).

2.2.3.1 Construction Progress Tracking Benefits in Different Project Phases

Construction progress tracking is a major application area of RCT in the construction industry. This application is primarily in the construction phase of the lifecycle, helping the construction team to monitor and control progress of the construction projects in a more efficient manner. In a recent pilot study, RCT was implemented to track the progress and quantify the earned value of work put-in-place in a medical office building by one of the leading general contractors in the US (Rubenstone, 2020). The goal was to integrate the 3D model, construction schedule and cost. The pilot study showed promising results, tracking 50% to 60% of work performed on the site. Billing and cash flow requirements in construction projects are long processes, leaving subcontractors to wait months to get paid. General contractors may benefit from using RCT workflow to quantify work and submit construction invoices to their clients in a faster and more efficient way (Rubenstone, 2020; Turkan et al., 2013).

Using RCT can reduce the number of site visits to collect data by providing an automated/semi-automated approach for construction progress tracking (Leica Geosystems AG, 2017). Additionally, RCT use has shown promising results in reducing the time required to document construction progress (Almukhtar et al., 2021). Increased accuracy of the collected data is another benefit of using RCT compared to traditional construction progress tracking approaches. While quality and accuracy of progress data collected manually depends on individuals' skills, experiences, and personal interpretations, RCT use provides a higher level of accuracy for construction progress tracking purposes (Turkan et al., 2012). Construction professionals may benefit from using RCT to capture a large area of the construction site in a short amount of time, resulting in reduced overall time and cost of a project. Moreover, the collected data using RCT can be peer-reviewed, yielding a more reliable and trusted output than the traditional approach. Construction project managers can use these data in decision-making to make corrective actions, increasing the overall efficiency and productivity of the projects (Omar & Nehdi, 2016; Tang et al., 2010).

2.2.4 Other Applications of RCT

The application areas of RCT in the construction industry continue to grow over time. 3D model reconstruction and geometry quality inspection using point cloud data have been the focus of AEC researchers, accounting for about 75% of journal articles related to point cloud data applications in the last 15 years (Wang & Kim, 2019). Construction project stakeholders have started using RCT for a wide range of applications. For instance, according to the literature review, major applications of RCT by general contractors include enhancing communication between office and job sites, 3D model coordination among trades, and creating as-built documents (Autodesk, 2021; Leica Geosystems AG, 2017). Contractors can monitor installations and catch discrepancies earlier by overlaying scans on the 3D design model. Owners and clients, on the other hand, primarily seek RCT services for visualization purposes (Rubenstone, 2020). This could be due to being unaware of other RCT applications, as well as uncertainties regarding the ROI for RCT implementation. Additionally, several studies indicated that RCT use could specifically help designers, in addition to renovations and fit-out projects, to avoid uncertainties due to the lack of geometric information and design with confidence (Coburn et al., 2017; Autodesk, 2021).

Wang and Kim (2019) determined other applications of point cloud data in the construction industry including, building/infrastructure performance analysis, construction safety management, building renovation, construction automation, heritage applications, and robot navigation. However, no clear boundary can be identified between different applications of point cloud data taken from laser scanners. For instance, 3D model reconstruction, which is presented as the main application of laser scanners in many studies, overlays with most of the other applications in this area.

Infrastructure assessment and building performance analysis, as one of the application areas of laser scanning, including structural analysis, infrastructure assessment, building energy analysis, etc. In this regard, Balado et al. (2017) diagnosed building accessibility by automating the detection of inaccessible steps in building entrances using point cloud data from the MLS system. For structural analysis, Lee and Park (2011) used point cloud data taken from the TLS system to monitor and estimate the stress level of a steel beam. The method showed high accuracy (error range of 2.2-7.2%), while addressing the limitations of conventional sensors.

For infrastructure assessment, Riveiro et al. (2016) used the point cloud data generated from TLS systems to monitor the structural health of masonry arch bridges. This study expanded the use of laser scanning technology in civil engineering communities by developing and testing an automatic geometric segmentation method of masonry bridges. Building energy analysis is the other main application area of point cloud data found in the literature. For building energy analysis, Lagüela et al. (2011) identified laser scanning technologies as an optimal complement for thermographic measurement due to their abilities in providing metric information. In another study, Cho et al. (2015) reviewed the state-of-the-art building energy modeling and diagnostics approaches. Based on this study, laser scanning methods can be used as the basis of energy modeling and retrofit assessment applications in existing buildings.

Safety management in the construction industry is moving from reactive to proactive, which requires an efficient safety information flow. RCT shows promising results in enhancing this information flow by facilitating the collection of safety information (Zhou et al., 2015).

Marks et al. (2013) used TLS data to measure the blind spots for construction equipment and evaluated the design of different equipment models, which resulted in increased visibility of equipment operators. The validated design showed promising results in reducing fatalities caused by worker collisions with construction equipment. In an attempt to address the insufficiencies of current safety inspections at excavation sites, Wang et al. (2015b) proposed a semi-automated approach to identify and locate fall hazards. Point clouds collected from the excavated pits were linked with existing safety measures in a BIM environment, helping the design and installation of safety equipment.

2.2.4.1 Other Applications and Benefits of RCT in Different Project Phases

From the other application areas of point cloud data discussed in the previous section, the applications relating to the construction phase can be identified as construction safety management and construction automation (Wang & Kim, 2019). Research indicated the use of point cloud data for analyzing the construction site and implementing safety protocols (Pradhananga, 2014). The literature also showed several studies that utilized laser scanning technologies to propose frameworks for construction automation. Designers may benefit from using RCT to enhance their design process in areas such as building performance analysis, building renovation, and heritage applications. RCT provides accurate as-is condition information that gives designers access to accurate and reliable information during the design phase of a project. Finally, in the O&M phase, the point cloud data generated from RCT can be used for building energy analysis, structural analysis of buildings and infrastructure, building renovation, heritage applications, and robot navigation.

2.3 Use of RCT in Different Project Types

With the expansion of BIM, the need for accurate and up-to-date information about the project has increased across the construction industry (Lu & Lee, 2017). The use of RCT on a project helps AEC professionals in decision-making by providing a full understanding of the project. Using laser scanners or photogrammetry, AEC professionals can collect accurate 3D-datasets of a building, structure, or an environment and compare what exists versus what is planned. The following two sections cover the use of RCT in new building construction projects as well as additions, renovations, and/or tenant interior/fit-out projects.

2.3.1 New Construction Projects

The world population is increasing by tens of millions every year. In the US alone, the annual percent change in the population is estimated to be 0.7% in 2021, which is about 2.3 million more people per year (CIA, 2021). Consequently, more construction is needed to accommodate rapid growth. The building sector accounts for 36% of energy consumption and 39% of total energy-related CO_2 emissions worldwide (UNEP, 2018). It is forecasted that global energy consumption will increase by 91% in developing countries and 31% in developed countries by 2025 (Ibp, 2015; Najjar et al., 2017). The global AEC industry is facing a challenge to accommodate the growing population and is looking for intelligent and efficient ways to create buildings that are smarter and more resilient. RCT is amongst the leading technologies used to enhance traditional construction practices in various applications.

As BIM is becoming the norm in new construction projects around the world, RCT implementation on new construction projects could bring added value by providing accurate information throughout the lifecycle. Contractors can use RCT for object recognition purposes by aligning point cloud data with as-designed BIM models and identifying the discrepancies

(Wang & Kim, 2018). Using RCT throughout different phases of a new construction project enables construction tasks to conform to the drawings and specifications, and it helps the project team avoid deviations and identify problems early to avoid additional costs downstream. Creating 3D as-built models using scans, providing site awareness to the project team, clash detection, deviation reporting, construction verification, and visualization are some areas in which RCT use can be beneficial on new building construction projects. Contractors may benefit from using RCT in different ways including, generating accurate as-built drawings, monitoring construction progress without constant visits to the site, early detection of clashes, effective communication with the design team and informing them of the required changes (Autodesk, 2021; Leica Geosystems AG, 2017). RCT has the potential to solve many communication issues by providing means to connect what is happening in the field to the office. General contractors may benefit from an efficient collaboration with their trade partners (e.g., mechanical trade, electrical trade, structural trade, etc.) using RCT alongside the BIM workflow. Early detection of errors during construction can reduce reworks, mitigate risk, and enhance the overall quality (Rubenstone, 2020).

Implementing RCT also helps designers to gain accurate information about the site condition and adjacent structures during the design phase of new construction projects. Accurate geometric data of the existing environment reduces uncertainties during the design phase. Additionally, designers can avoid numerous site visits by referring to the point cloud data, saving time and money (Autodesk, 2021; Leica Geosystems AG, 2017). Despite the various applications of RCT, the literature indicates that owners typically ask for RCT services for visualization purposes. Data visualization helps owners in decision-making. Increasing the owners' awareness regarding the benefits of using RCT throughout the project lifecycle could increase the demand for RCT services on new construction projects (Deutsch, 2015; Gerges et al., 2017).

2.3.2 Additions, Renovations, and/or Tenant Interior/Fit-Out Projects

Buildings age and become obsolete over time. Technological changes, poor design, and changing occupant needs are main factors that intensify the need to change existing conditions of buildings. According to the American Housing Survey by the US Census Bureau (USCB, 2019), the median year in which US houses were built was 1978, which consequently makes them inefficient in terms of energy performance, function, and space quality. By consuming 16-50% of energy resources, the building sector constantly depletes energy resources worldwide (Pombo et al., 2016). Scientists and designers are constantly studying different strategies to reduce this impact, including improving the energy efficiency of building operations, utilizing more renewable energy sources, and reducing building material production process impacts. Compared to new building construction, renovation of existing buildings is a more sustainable method, resulting in reduced global energy consumption, greenhouse gas emissions, and construction material waste (Hasik et al., 2019; Ma et al., 2012). However, based on the American Housing Survey (USCB, 2019), only about 12% of US householders with homes built prior to 2009 indicated that they renovated in the last ten years. The survey also revealed that energy efficiency was the main reason for home improvement. AEC professionals may face multiple challenges during renovation of an existing building, such as the intervention of various stakeholders and professionals, complexity from the aging of building systems, potential usage of the building during the time of renovation, and owners' lack of awareness about financial benefits (Ma et al., 2012; Sanhudo et al., 2018).

Environmental impacts of demolition scenarios followed by new construction, versus renovation and repurposing of the existing structures, have been investigated and compared in the last 20 years (Cha et al., 2012; Dong et al., 2002). Demolition and rebuilding increases the amount of construction waste materials compared to the renovation approach. Consequently, more raw materials are consumed during the construction process as well. Hasik et al. (2019) utilized multiple case studies to compare renovation and new construction projects, they found a 53-75% reduction of different environmental impacts in renovation over new construction because of reduced new building materials. Green renovation, which is aligned with sustainable practices, should always be considered a valuable option by designers, policymakers, and building owners.

Despite several advantages of green renovation, it is rarely implemented in the construction industry due to various reasons. Jagarajan et al. (2017) summarized factors affecting the implementation of green renovations into eight categories: financial resources, experts in green building, policy support, green development quantification, green awareness, communication, internal leadership and green material and technology. Developing cost-effective methods of green retrofitting, in conjunction with increasing public awareness, are critical elements of promoting green renovation in the construction industry. Gathering geometric and non-geometric data (e.g., aging of the materials and systems) of the existing building from multiple stakeholders is one of the main obstacles slowing down green retrofits and renovation processes. Consequently, green renovation is typically considered more challenging than constructing new green buildings (Ham & Golparvar-Fard, 2013). However, recent developments in data capturing techniques and BIM technology have introduced promising results to address some of the difficulties of green renovation processes.

Construction project stakeholders may benefit from using RCT on renovations, additions, and/or tenant interior/fit-out projects. According to the Energy Performance of Buildings Directive of the EU (EPBD, 2012) and its later revisions, identification of critical information for renovations, collection and proper interpretation of monitored data, handling of uncertainties, and the high effort to create BIM of an existing building are some of the major challenges in renovation projects to achieve near-zero energy housing at cost-optimal levels. Inaccurate assumptions about existing conditions of a building resulting from a lack of existing documents might lead to unintended errors or even accidents (Lu & Lee, 2017). The design teams may benefit from complete as-built documents as a starting point to develop their design with confidence. Recent advancements in RCT provide an efficient way for capturing the existing condition of buildings. Architects and engineers can use this information to reduce uncertainties, reduce errors, and avoid reworks on their projects.

Implementing RCT in initial survey stages of renovation projects can assist designers to obtain accurate dimensions where there may be a lack of as-built plans. It can also aid in generating an accurate visualization of a design and the existing context, ensuring reality matches the 3D model, reducing the number of visits to the job site, and enabling effective collaboration among the stakeholders throughout the project (Autodesk, 2021; Leica Geosystems AG, 2017). Re-design and renovation of building facades, interior design, energy performance retrofits, and refurbishment are some applications of RCT in renovation projects found in the literature. In this regard, Aydin et al. (2014) used RCT to capture the existing façades of a building. Accurate geometric information helped to redesign the building facades in harmony with the existing environment.

RCT can empower AEC professionals to capture site conditions before, during, and on completion of projects, ensuring buildings conform with design intent. Despite the need for point clouds and/or meshes of data of existing buildings for the purposes of building renovation, the literature review indicated that less than 9% of the current literature on RCT focuses on renovation projects (Almukhtar et al., 2021; Wang & Kim, 2019). Recent advancements in RCT, alongside increasing demand to capture geometric information in existing buildings, indicate the need for conducting more research to explore application-oriented data acquisition frameworks. In construction inspection, for instance, if the density of the point cloud data is low, it could lead to missing important geometric data. On the other hand, a denser point could data requires extra time to capture and process, leading to additional costs. Therefore, more studies are required to define practical RCT frameworks for capturing and processing point cloud data for multiple applications (Wang & Kim, 2019).

2.4 Obstacles to RCT Adoption in Construction Projects

Despite considerable advancements in RCT in recent years, obstacles remain that could prevent its adoption/wider adoption in the construction industry. To evaluate the adoption of a new technology in a specific domain, researchers propose technology assessment theories, including but not limited to, Technology Acceptance Model (TAM), Diffusion of Innovation (DOI), and Task-Technology Fit (TTF) (Peansupap & Walker, 2005). Mutai (2009) used these theories to develop a group of constructs to investigate the perception of construction project stakeholders about BIM in the construction industry domain. These factors were classified into three categories: human factors, technological factors, and cultural/legal factors. These factors may impact construction stakeholders, preventing them from adopting new technologies (e.g., BIM, RCT, etc.). Based on these constructs, lack of management support, lack of training, lack of current employee expertise, and lack of relevance to the project at hand can be human-related obstacles to RCT implementation. The high cost of software and hardware, not being user-friendly, lack of interoperability, and insufficient output quality are other potential technological-related obstacles. Finally, risk liability and limitation regarding the scope of work are placed in legal-related obstacles (Mutai, 2009). In a more recent study, Hatem et al. (2018) conducted a survey study exploring the benefits and obstacles to BIM use among construction professionals in Iraq. The results identified a lack of government support and management, lack of awareness about the benefits of BIM, and unwillingness to change as the three main factors hampering BIM implementation in that country. Despite the abundance of survey studies about BIM, no survey study was found that explores the benefits and obstacles to RCT adoption by different construction project stakeholders.

In another study, Lu and Lee (2017) proposed a model to evaluate image-based technologies used for creating as-is BIM by defining four groups of factors, including economy, accuracy, efficiency, and practicability. These factors, if not met, could prevent the adoption/wider adoption of RCT in construction. Economy, here, is defined by the cost of equipment, cost of software, and cost of hiring experts or training human resources to utilize the technology. The data capturing approach needs to be economical and cost-effective to become widespread. In this classification, efficiency, refers to implementing RCT with the least possible resources, which results in minimizing time and cost. Finally, practicability stands for being compatible with other applications and having a smooth operation. However, this proposed model by Lu and Lee (2017) has no clear boundary among the proposed criteria. For instance, efficiency encompasses economic aspects; thus, there is no solid boundary between practicability and efficiency. Despite the efforts to define the factors influencing new technology implementation, more practical studies are needed to explore if the proposed factors are perceived as obstacles to RCT adoption by construction stakeholders.

Reality capture technologies such as laser scanning have shown promising results in many outdoor environment case studies (Cheng et al., 2018). However, several technical limitations could hinder the use of RCT for indoor mapping, including but not limited to site constraints, portability constraints, and the high cost of using RCT on a project. The less expensive an innovation, the more likely it will be adopted (Rogers, 2010). The cost of implementing a new technology has been defined as a major obstacle to widespread adaption in many previous studies. Cost is an important factor that creates several obstacles to RCT use on a project including, the equipment is expensive, the related software is expensive, cost of hiring employees with the required skills, and cost of training current employees (Bohn & Teizer, 2010; Mutai, 2009). Time and resource constraints are other obstacles to innovative technology adoption, which are related to the cost. If the data collection or data processing using RCT is too time-consuming, additional costs could arise and prevent widespread adaption of these technologies by construction project stakeholders (Sepasgozar & Shirowzhan, 2016).

In addition, if an innovation is not user-friendly, it is less likely to be widely used. Rogers (2010) defined complexity as “the degree to which the innovation is perceived as relatively difficult to understand and use.” Therefore, if the equipment is not user-friendly, and the related software is not user-friendly, these are potential obstacles to RCT implementation within the construction industry (Fathi et al., 2015).

Lack of awareness of the benefits is another critical barrier to the widespread adaption of innovative technologies. Due to the relatively nascent nature of RCT in the construction industry, many AEC firms struggle to decide which technology best fits their projects. According to

Gerges et al. (2017), lack of awareness and uncertainty about the return on investment is one of the major barriers to BIM adoption in several countries. If construction project stakeholders are not confident about the benefits of using an innovative technology, it may lead to lower demand for that technology, preventing the adoption/wider adoptions of new technologies on their projects. Also, a lack of a comprehensive framework for RCT use for a specific construction application could keep AEC professionals hesitant to adopt RCT on their projects (Almukhtar et al., 2021).

Finally, new construction contract types will be required to accommodate the requirements to use RCT on a project. According to Rubenstone (2020), a lack of a business case was an obstacle preventing general contractors from justifying the benefits of using RCT on a project. Thus, including requirements for RCT adoption into the project workflows in construction contracts could lead to broader adoption of this technology within the construction industry.

CHAPTER 3: RESEARCH METHODOLOGY

The purpose of this study was to explore the use of RCT by US construction project stakeholders in the commercial building sector. A comprehensive literature review was conducted to identify recent research studies on RCT, including laser scanning and photogrammetry, in the construction industry. In addition, areas of RCT application were discussed, and realized and perceived benefits and obstacles were investigated. According to the literature review, RCT has several applications throughout project lifecycles, including but not limited to, 3D model reconstruction, geometry quality inspection, construction progress tracking, construction safety management, construction automation, building performance analysis, renovation and refurbishment. Exploration of the literature helped identify research trends and topics, as well as gaps in the research.

This chapter provides detailed information about the methods and procedures utilized for answering the research questions of this study. Based on the literature, a survey instrument was developed to investigate US construction project stakeholders' experiences and perceptions of RCT use on new construction and renovation projects in the commercial sector.

3.1 Survey Instrument

Since RCT is still relatively new in the construction industry, limited studies have explored the use of RCT from AECOM professionals' perspectives. A quantitative research method was employed to provide a better understanding of the experiences and perceptions of US construction industry project stakeholders about the use of RCT on commercial projects. A cross-sectional survey instrument was developed and utilized as the primary research method. The survey was designed to target a wide range of construction project stakeholders in the US and to determine the participants' experiences and perceptions regarding adopting RCT throughout a project’s lifecycle. At the time of conducting this study, no survey studies were found that explore the use of RCT from AECOM professionals’ points of view. Therefore, survey studies on relevant topics such as BIM and digital cameras were reviewed to construct the questionnaire of this study (Bohn & Teizer, 2010; Chan et al., 2019; Moreno et al., 2019; Ozorhon & Karahan, 2017).

The online survey was developed in Qualtrics and hosted on the Qualtrics website through an account funded by Colorado State University; it was kept open for four weeks. The potential participants were reached in two different ways. First, the survey link was distributed via email to a sample of 13,971 Construction Management Association of America (CMAA) members and a convenience sample of 418 members of the International Facility Management Association (IFMA) working in the US. At the time of conducting this study, 13,971 were all of the US CMAA members that could be determined based on their company’s location.
Second, an anonymous survey link was shared with the author's connections through his LinkedIn account, who were all engaged in the design and construction industry.

3.1.1 Participants

According to the literature, RCT can be applied in different areas throughout the project lifecycle. Collected data from the existing condition of the buildings, structures, and surrounding project sites can be utilized in different project types including, new construction, renovations, additions, tenant interior/fit-out, facilities management, and demolition projects. However, the scope of this study was limited to the use of RCT in new construction, renovations, additions, and interior fit-out projects. In this study, the term “renovation” was used to refer to all additions, renovations, and tenant interior fit-out projects. Moreover, for the purpose of this study, the scope was limited to firms that listed commercial buildings as their primary sector, and respondents from other sectors were not included in the analysis.

The author utilized different approaches to garner the most responses from the US construction project stakeholders as possible. Since the author was a member of the CMAA Colorado chapter, the CMAA member directory, which contains more than 16,200 AECOM professionals worldwide and sorted by their firm type, was utilized to reach out to the email addresses of potential participants. An Excel file containing the list of all CMAA members at the time of conducting this study was created, and the list was sorted based on company location. Construction professionals who did not identify their company's location or were working outside the US were removed from the list. After sorting and cleaning the email addresses from the CMAA member directory, a list of 13,971 construction professionals was finalized for the survey distribution phase. Also, a convenience sample of 418 IFMA Foundation members was also included in the study. The author was a member of the IFMA Foundation, Rocky Mountain Chapter. Therefore, he had access to the member directory of the IFMA foundation and was able to distribute the survey to potential participants via email addresses.

To garner maximum participation, the author also used social media (i.e., LinkedIn) to reach out to his professional connections who were working in the construction industry. The survey link was posted on LinkedIn, and potential participants with experience in the US construction industry were invited to initiate the survey. Additionally, the invitation text, including the survey link, was sent as a private message to 651 of the author's LinkedIn connections, inviting them to participate in the study. Collected data from the survey were sorted based on the respondents' role, primary market sector, and annual revenue of their company using the demographic questions. Only the responses from construction professionals that listed commercial buildings as their primary sector were considered for the data analysis stage of this study.

3.1.2 Data Collection

To answer the research questions, quantitative data were collected by developing a close-ended web-based questionnaire. Open-ended questions were also included in several sections (e.g., realized or perceived benefits, realized or perceived obstacles) to gather the participants' additional opinions and specific comments about the topic. The web-based questionnaire was chosen as the data collection method of this study due to the extensive use of the web by construction professionals and the ease of quickly collecting data from a large and diverse sample. The survey instrument was initially approved by the Colorado State University Institutional Review Board (IRB) on March 19, 2021 (See APPENDIX A). The invitation email was sent to the sample population through Qualtrics distribution tool on May 3rd, 2021, and the survey was open for four weeks. Potential respondents were asked to consent to participate before the initiation of the questionnaire. The first reminder email was sent five business days after the invitation email (May 10th, 2021). The second reminder was sent 14 business days after the invitation email was sent (May 17th, 2021), the email was intended to remind potential respondents to take a few minutes and participate in the survey.

The questionnaire of this study was developed in collaboration with Jonathan W Elliot and Svetlana Olbina, Associate Professors in the Department of Construction Management at Colorado State University; therefore, the author acknowledges both as authors of the survey questionnaire. Based on the information from the literature review and the research questions, 76 survey questions were developed (see APPENDIX C). These questions were categorized into eight sections: 1) consent and definitions, 2) demographics and general questions, 3) general perception and experience with RCT, 4) realized benefits and realized obstacles using RCT, 5) perceived benefits and perceived obstacles using RCT, 6) factors affecting general contractors' decisions to use RCT on a project, 7) effectiveness of RCT use in new construction projects by project lifecycle phase, and 8) effectiveness of RCT use, in additions, renovations and/or interior fit-out projects by project lifecycle phase.

In Section 1, respondents were asked for their consent to participate in the study according to the IRB protocols. Also, the technical terms used in the questionnaire were defined in this section to avoid potential misconceptions. Questions in the second section were demographic and general questions, they were primarily derived from previous BIM-related survey studies (Chan et al., 2019; Ozorhon & Karahan, 2017). These questions were added to empower the researcher to filter and sub aggregate the results based on different categories (e.g., respondents' role on a typical construction project, annual revenue of company, primary market sector of company, etc.). Moreover, the author later used stakeholders' classification to conduct ANOVA and student t-tests, comparing the means of responses between different groups of stakeholders.

Section 3 focused on the familiarity and experiences of respondents with RCT. The respondents were asked if they or their company had used RCT on a project in the past. Skip logic was built into the survey to direct respondents without RCT experience to Section 5 (perceived benefits and obstacles). Also, respondents who had never heard of RCT were directed to the end of the questionnaire. Hence, respondents who were allowed to proceed to Section 4 (realized benefits and obstacles) had personal experience with RCT, or they knew of their company's experience with these technologies. Therefore, they were able to provide valid responses. Note that, as shown in APPENDIX C, in matrix table questions (i.e., Likert scale and slider type questions), the participants had the "N/A" option to choose if they have not used the specific RCT application.

Table 1 summarizes specific questions designed in the survey questionnaire to respond to identified research questions of this study. As shown in the table, each research question was developed into more detailed sub-questions, which were addressable by the analysis. For example, to address Research Question 1, five sub-questions were developed and the relevant questions in the questionnaire were used for the analysis (see APPENDIX C). As stated, the literature revealed limited research has been conducted investigating the use of RCT by construction project stakeholders. Therefore, the information and proposed choices for the subjective questions in the questionnaire were derived from the most relevant literature and similar survey studies, as suggested by Naoum (2012).

Table 1

Research Questions and the Corresponding Questions in the Survey Questionnaire

Research Questions and Sub-Questions	**Survey Questions (See APPENDIX C)**
1. To what extent are reality capture technologies used by US construction (Architects, Engineers, Contractors, Owners/developers) stakeholders in the commercial building sector?	
1.1. What percentage of US construction project stakeholders have heard of reality capture technologies?	RCE1
1.2. What percentage of US construction project stakeholders have personal experience with reality capture technologies?	RCE2
1.3. What percentage of US construction project stakeholders mentioned their companies had experience with reality capture technologies?	RCE3
1.4. On what commercial project types do US construction project stakeholders report using reality capture technologies?	SEG2.1

1.5. What percentage of the US construction project stakeholders who have experience with reality capture technologies use reality capture technologies on new construction projects and renovation projects?	Q23, Q31
2. Do the US construction project stakeholders in the commercial building sector agree that the use of reality capture technologies provides benefits on different project types (i.e., new construction and renovation projects)?	
2.1. Do the US construction project stakeholders agree that the use of reality capture technologies provides benefits on new construction projects?	RCE0
2.2. Do the US construction project stakeholders agree that the use of reality capture technologies provides benefits on additions, renovations, and/or interior fit-out projects?	RCE0
2.3. Is there a significant difference between the US construction project stakeholders' opinions regarding the benefits of using reality capture technologies when compared by project type?	RCE0
3. Do the US construction project stakeholders in the commercial building sector agree that the use of reality capture technologies provides benefits during different phases of the project lifecycle?	
3.1. Do the US construction project stakeholders agree that the use of reality capture technologies provides benefits during the design/preconstruction phase of a project?	RCE0, SEG1
3.2. Do the US construction project stakeholders agree that the use of reality capture technologies provides benefits during the construction/fabrication phase of a project?	RCE0, SEG1
3.3. Do the US construction project stakeholders agree that the use of reality capture technologies provides benefits during the operation and maintenance phase of a project?	RCE0, SEG1
3.4. Is there a significant difference between the US construction project stakeholders' opinions regarding the benefits of using reality capture technologies during different phases of project lifecycles when compared by project stakeholder?	RCE0, SEG1
3.5. Is there a significant difference between the US construction project stakeholders' opinions regarding the benefits of using reality capture technologies when compared by project lifecycle phase?	RCE0, SEG1
4. What are the benefits of using reality capture technologies based on the US construction project stakeholders' opinions in the commercial building sector?	
4.1. What are the benefits of using reality capture identified by the US construction stakeholders?	CHSPB1, Q29
4.2. Is there a significant difference between the US construction project stakeholders' opinions regarding the benefits of using	CHSPB1, Q29

reality capture technologies when compared by project stakeholder?	
5. What are the obstacles to using reality capture technologies in the commercial building sector based on the US construction project stakeholders' opinions?	
5.1. What are the obstacles to the adoption/or wider adoption of reality capture technologies based on the US construction project stakeholders' opinions?	CHPO1, Q33
5.2. Is there a significant difference between the US construction project stakeholders' opinions regarding the obstacles preventing the adoption/wider adoption of using reality capture technologies when compared by project stakeholder?	CHPO1, Q33

3.1.2.1 Data Analysis

For the first step, descriptive statistics were conducted to quantitatively describe the sample and to provide a general idea of the distribution of the collected data. This step helped identify associations among different variables and where to conduct more elaborate statistical analyses in the following steps (Creswell, 2015). The statistical analyses in this study was conducted in *IBM SPSS 27* statistical software. The survey results were exported from *Qualtrics* into *Excel* to be cleaned and coded. The responses from participants working primarily in the commercial building sector were identified and prepared for further analysis. The data were modeled in the form of bar charts, histograms, and tables to provide informative results.

Table 2 shows the types of analyses used to address each of the research sub-questions. As shown in the table, research sub-questions 1.1 through 1.5 were addressed using descriptive statistics. In summary, the frequency counts and frequency percentages of stakeholders having RCT experience were compared with those who have not used these technologies yet. For research sub-questions 2.1 and 2.2, the means of responses for the RCT benefits on each project type (i.e., new construction projects and additions, renovations, or maintenance projects) were calculated, and these results were classified by stakeholder. Sub-question 2.3 was analyzed by exploring the differences between participants' opinions about the benefits of using RCT on new construction or renovation projects. Since the comparison needed to be performed between only two groups, the student t-test analysis was utilized on the sample data to compare the mean of responses in one group (i.e., respondents' opinions about benefits of RCT use in new construction projects) to the mean of responses in the other group (i.e., respondents' opinions about benefits of RCT use in renovation projects).

For research sub-questions 3.1, 3.2, and 3.3, descriptive statistics were employed to investigate the opinions of US construction project stakeholders regarding RCT benefits during the preconstruction (or design) phase, construction (or fabrication) phase, and O&M phase of a project. Research Question 3.4 was addressed using the ANOVA test to explore if there was a difference between the stakeholders' opinions about the benefits of using RCT during different project lifecycle phases. For research sub-question 3.5, three separate student t-tests were conducted to see if differences between respondents' perceptions would be found about benefits of using RCT in the preconstruction (or design) phase, construction (or fabrication) phase, and O&M phase of the project lifecycle. The student's t-test was used to conduct this statistical analysis due to the lack of a dependent variable and having wide-format data.

Research Questions 4 and 5 investigated the perceptions of participants about the benefits of RCT and obstacles preventing RCT use on their projects. As shown in Table 2, part one of each question was addressed by calculating the means of responses for all the identified RCT benefits and obstacles, and then ranking the variables (i.e., 21 RCT benefits, and 19 RCT obstacles) accordingly. For part two of Research Questions 4 and 5, ANOVA tests were utilized to explore if there was a statistically significant difference between the perceptions of different stakeholders regarding the identified benefits and obstacles to RCT use.

Table 2

Research Questions and the Corresponding Statistical Analysis

Research Questions and Sub-Questions	Analysis Strategy
1. To what extent are reality capture technologies used by US construction (Architects, Engineers, Contractors, Owners/developers) stakeholders in the commercial building sector?	
1.1. What percentage of US construction project stakeholders have heard of reality capture technologies?	Descriptive statistics (frequency count and percentage frequency distribution by stakeholder)
1.2. What percentage of US construction project stakeholders have personal experience with reality capture technologies?	
1.3. What percentage of US construction project stakeholders mentioned their companies have had experience with reality capture technologies?	
1.4. On what commercial project types do US construction project stakeholders report using reality capture technologies?	
1.5. What percentage of the US construction project stakeholders who have experience with reality capture technologies use reality capture technologies on new construction projects and renovation projects?	
2. Do the US construction project stakeholders in the commercial building sector agree that the use of reality capture technologies provides benefits on different project types (i.e., new construction and renovation projects)?	
2.1. Do the US construction project stakeholders agree that the use of reality capture technologies provides benefits on new construction projects?	Calculate the means of responses for each project type and by stakeholder. Making inference based on the means
2.2. Do the US construction project stakeholders agree that the use of reality capture technologies provides benefits on addition, renovation, and/or interior fit-out projects?	
2.3. Is there a significant difference between the US construction project stakeholders' opinions regarding the benefits of using reality capture technologies when compared by project type?	Comparison of means of responses using Student t-test (comparing new construction vs. renovation)
3. Do the US construction project stakeholders in the commercial building sector agree that the use of reality capture technologies provides benefits during different phases of the project lifecycle?	
3.1. Do the US construction project stakeholders agree that the use of reality capture technologies provides benefits during the design/preconstruction phase of a project?	Calculate the means of responses for each project phase and by

3.2. Do the US construction project stakeholders agree that the use of reality capture technologies provides benefits during the construction/fabrication phase of a project?	stakeholder and making inference based on the means
3.3. Do the US construction project stakeholders agree that the use of reality capture technologies provides benefits during the operation and maintenance phase of a project?	
3.4. Is there a significant difference between the US construction project stakeholders' opinions regarding the benefits of using reality capture technologies during different phases of project lifecycle when compared by project stakeholder?	Comparison of means of responses using ANOVA test (Kruskal Wallis test if the data is not normally distributed)
3.5. Is there a significant difference between the US construction project stakeholders' opinions regarding the benefits of using reality capture technologies when compared by project lifecycle phase?	Two by two comparison of means of responses using the One-Sample t-test
4. What are the benefits of using reality capture technologies based on the US construction project stakeholders' opinions in the commercial building sector?	
4.1. What are the benefits of using reality capture technologies based on the US construction stakeholders' opinions?	Calculate the means of responses for each variable and rank the means in descending order.
4.2. Is there a significant difference between the US construction project stakeholders' opinions regarding the benefits of using reality capture technologies when compared by project stakeholder?	Comparison of means of responses using ANOVA test (Kruskal Wallis test if the data is not normally distributed)
5. What are the obstacles to using reality capture technologies in the commercial building sector based on the US construction project stakeholders' opinions?	
5.1. What are the obstacles to the adoption/or wider adoptions of reality capture technologies based on US construction project stakeholders' opinions?	Calculate the means of responses for each variable and rank the means in descending order.
5.2. Is there a significant difference between the US construction project stakeholders' opinions regarding the obstacles preventing the adoption/wider adoptions of reality capture technologies when compared by project stakeholder?	Comparison of means of responses using ANOVA test (Kruskal Wallis test if the data is not normally distributed)

CHAPTER 4: RESULTS AND ANALYSIS OF DATA

4.1 Description of Participant Information

The survey was distributed on May 3rd, 2021, and responses were collected for four weeks. During this period, a total of 611 responses were collected from CMAA, IFMA Foundation, and LinkedIn connections. Table 3 shows the distribution of respondents who participated in the survey. CMAA members comprised a majority of respondent data (88%). As shown in the table, 13,971 invitation emails were sent to US CMAA members, and 538 of the members initiated the survey and consented to participate in the study. The calculation of the exact response rate was not possible due to the snowball sampling strategy (i.e., some of the respondents shared the anonymous survey link with other construction professionals in the US).

Table 3

Survey Distribution and Collected Data

	Audience Size	**Consent to Participate (n)**	**%**
CMAA	13971	538	88
IFMA	416	18	2.9
LinkedIn	651*	55	9.1
Total	14987	611	100

*651 indicates the number of invitation messages sent to the researcher's LinkedIn connections

Descriptive statistics were used to demonstrate the distribution of the 611 collected responses based on survey questions in Section 2 (demographic and general questions). First, respondents were categorized based on their company's primary market sector. As shown in Figure 3, infrastructure (42%) and commercial building (38%) were the two largest portions of the market sectors. Then, the 187 commercial building participants were further explored by analyzing their responses to questions in Section 3 (general perceptions and experiences with RCT).

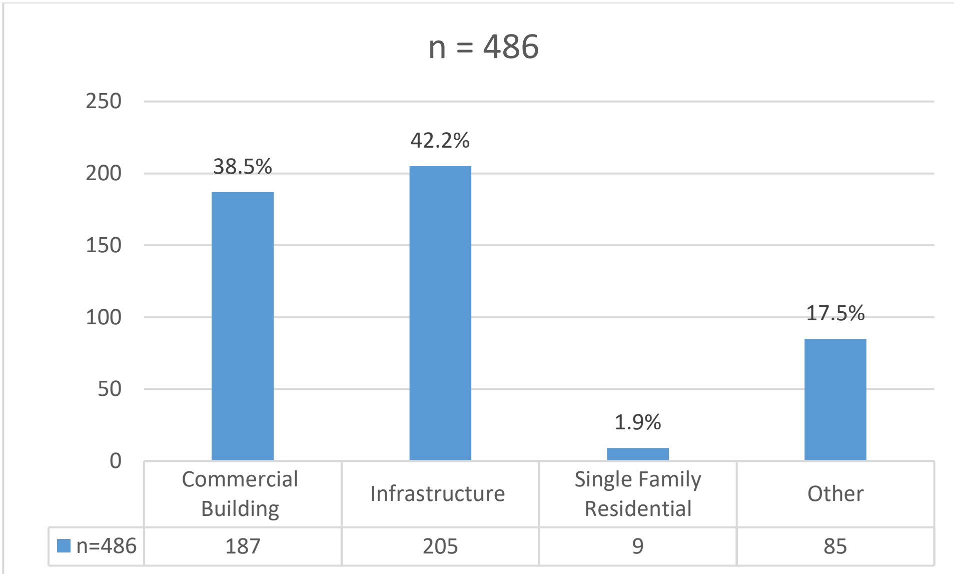


Figure 3. Description of Participants by Their Company's Primary Market Sector

4.2 Data Cleaning and Data Coding Procedures

Raw data were exported from *Qualtrics* into *Excel* to be cleaned and prepared for further analysis. Since the scope of the study was delimited to US construction project stakeholders working in the commercial building sector, participants working in other sectors were removed from the *Excel* file. Of the 187 participants from the commercial building sector, 11 did not respond to the industry segment (item SEG1) survey question (see APPENDIX C), which asked about their role on a typical construction project, yielding 176 responses. The participants were coded into four groups based on their response to the SEG1 survey question, including 1) owner/developer, 2) designer (including architect and engineer), 3) contractor (including general contractor and subcontractor), and 4) CM and owner representative. APPENDIX B shows the coding instruction used in this study. The respondents who chose "other" as their role were sub aggregated into one of the four categories based on their text entry to the survey question. For instance, if they chose "other" for their role, but their text entry identifying their role was "construction manager," or "owner representative," then they were classified into group four. As shown in Figure 4, four of the remaining 176 participants were also removed from the data set because their text entry responses could not be fit into any of the defined categories, resulting in 172 responses.

Also, data columns that were unrelated to the scope of the study were removed (e.g., variables exploring participants from other market sectors). Since the variables were independent, pairwise deletion was employed, resulting in a different number of responses (N) for each analysis. Figure 4 shows the demographic characteristics of the cleaned sample of the commercial building stakeholders, which was imported into *SPSS* for further statistical analysis.

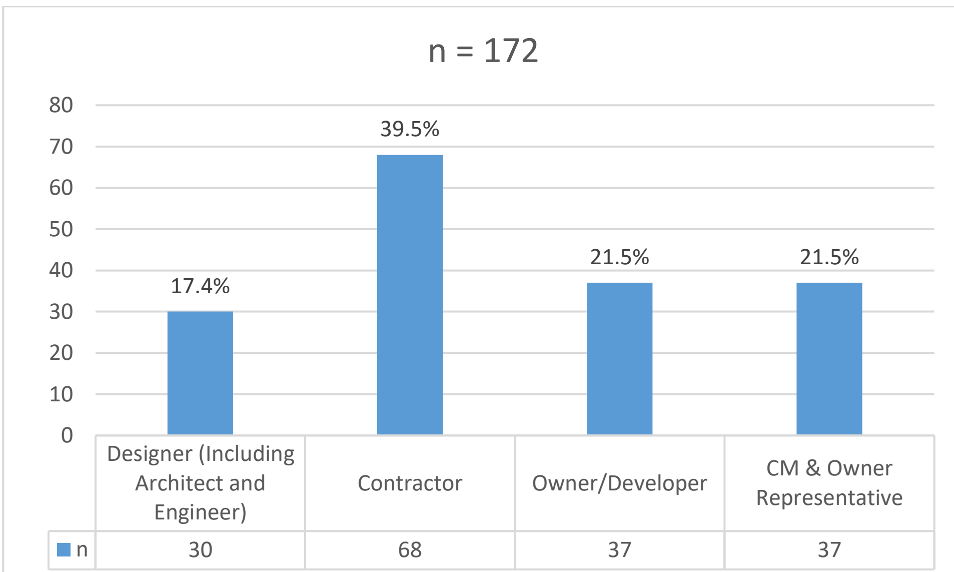


Figure 4. Description of Commercial Building Sector Participants by Their Role

The author used *IBM SPSS Statistics 27* software to analyze the data set. The imported data was coded in *SPSS* by assigning numeric values to each item (see APPENDIX B). These unique names helped the author to find and utilize the data for further analysis efficiently. Also, the level of measurement, including nominal, ordinal, and scale, were defined for each question. For instance, demographic and general questions were measured at the nominal level since these questions classified the respondents into different categories. On the other hand, 5-point Likert scale variables were measured at the scale level as suggested by Morgan et al. (2020).

4.3 Results

This section provides the results of the statistical analysis to address each research question. As discussed in Chapter 1, each research question was split into sub-questions that were more specific to performing statistical analysis. Note that since the variables defined in the survey were independent, pairwise deletion was employed in this study. Therefore, the number of responses (N) for each question is different.

4.3.1 Results for Research Question 1

Research Question 1 aimed to investigate the extent of using RCT by responding US construction project stakeholders in the commercial building sector. Specifically, Research Subquestion 1.1 explored the percentage of stakeholders who had heard of RCT. As shown in Figure 5, out of 160 participants who responded to this question, a majority (128, 80.0%) indicated that they had heard of RCT. About 83% of contractors, 81% of designers, 77% of CM & owner representatives, and 76% of owners/developers had heard of RCT. It should be noted that the definition of RCT in this study was clarified at the beginning of the survey instrument to avoid any misconceptions and increase the reliability of the results. The survey findings indicated that most construction project stakeholders, regardless of their role, reported hearing about RCT.

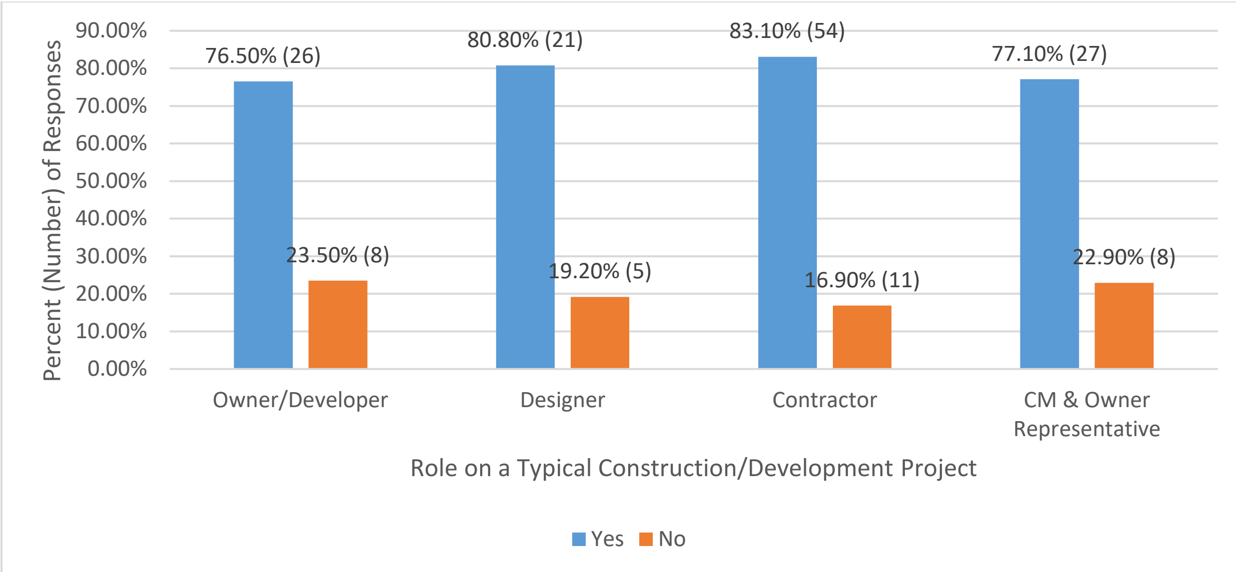


Figure 5. Descriptive Statistics: Respondents Who Had Heard of RCT (N_T = 160)

Research subquestion 1.2 investigated the percentage of construction project stakeholders that had personal experience with RCT. As shown in Figure 6, about half (68, 53.1%) of the 128 participants who responded to this question indicated personal RCT experience. Almost 70% of contractors and about half of owners/developers (52%) had personal experience with RCT, as compared to one-third of designers (33.3%) and 37% of CMs and owner representatives. Note that of all the survey respondents who had experience with RCT (68 respondents), 55.9% were contractors, while 19.1% were owners/developers, 14.7% CM and owner representatives, and 10.3% were designers. As shown in the literature, adopting RCT on a project requires using both physical equipment (i.e., laser scanners, cameras, etc.) for capturing geometric data and software applications for data processing. Therefore, as expected, a larger portion of contractors, who are more involved in field activities, had personal experience with RCT compared to other stakeholders.

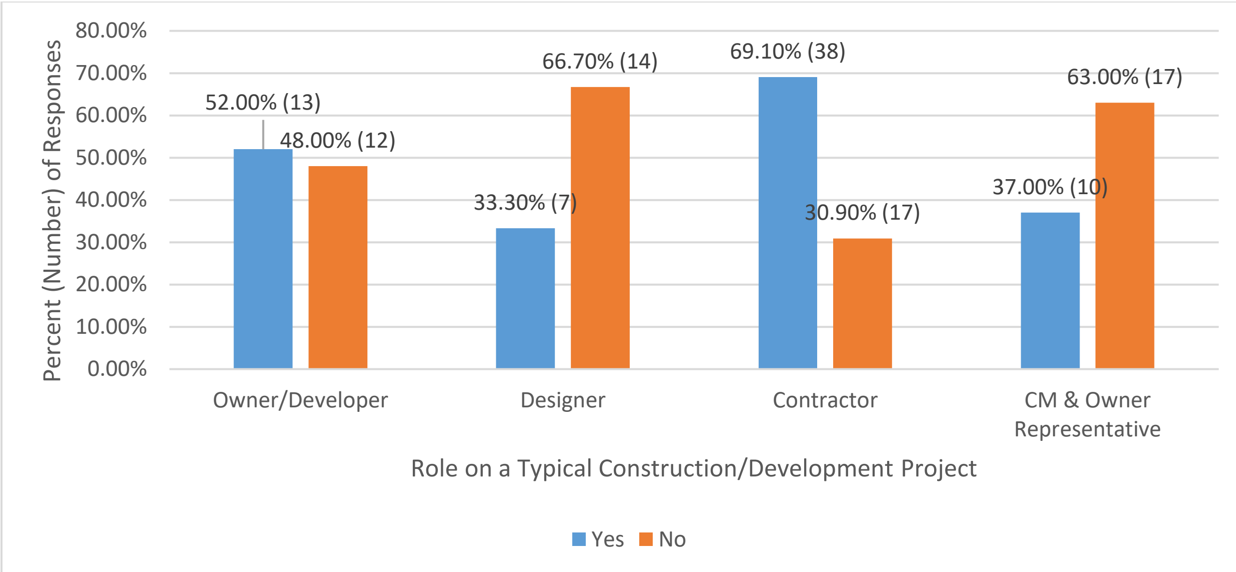


Figure 6. Descriptive Statistics: Respondents Who Had Personal Experience with RCT (N_T = 128)

Research subquestion 1.3 explored the experiences of participants' companies with RCT. The survey results indicated that of 128 participants who responded to this question, more than half (79, 61.7%) reported that their company had experience with using RCT on their projects, about one-fourth (29, 23%) indicated their company had no experience with RCT, and about 16% were not sure about their company's experience with RCT. As shown in Figure 7, a majority of the contractors (43, 78%) stated that their company had experience with RCT, while a minority of the designers made the same statement, and about half of the owners/developers (13, 52%) and CM and owner representatives (15, 56%) stated that their company had experience with RCT. This is an important finding since it suggests that RCT use is more common among contracting firms compared to other stakeholders. These findings correspond to recent studies on BIM (as a new technology in the construction industry) in which contractors exceeded designers in implementing BIM on their projects (McGraw Hill, 2014). Results to research subquestions 1.1-1.3 show that despite a majority of survey participants having heard of

RCT, many of them had not used RCT personally, nor had their company implemented RCT on projects.

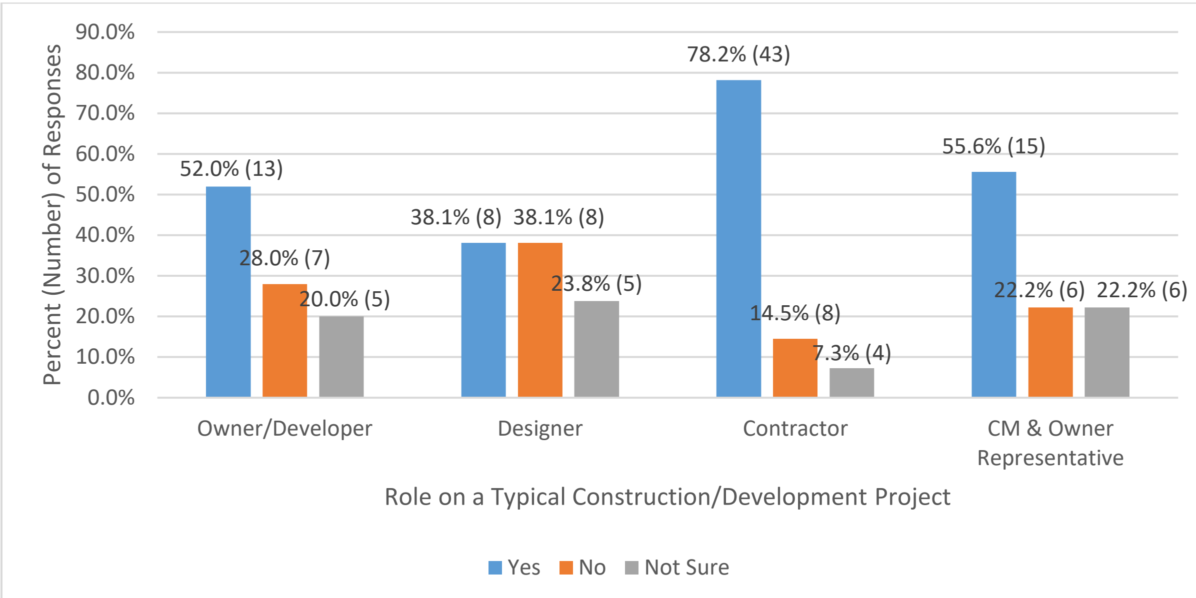


Figure 7. Descriptive Statistics: Respondent Company's Experience with RCT (N_T=128)

Research subquestion 1.4 investigated participants' experiences with RCT on specific commercial project types, including core and shell buildings, multi-family residential, retail, mixed-use, education, healthcare, interior/tenant fit-out, and other types of projects. The respondents were asked to select the commercial project types in which they used RCT. Note that respondents were asked to "select all that apply" when answering this question (see APPENDIX C). Figure 8 indicates RCT uses on different commercial project types regardless of participants' roles on a typical construction/development project. Almost half (78, 49.4%) of the 158 participants who responded to the question stated that they used RCT on core and shell projects. Also, about 45% of 148 respondents reported they used RCT on healthcare projects. Interestingly, less than a quarter of 146 respondents (33, 22.6%) used RCT on multi-family residential projects. This is an important finding that suggests construction project stakeholders tended to use RCT on more complex projects (e.g., healthcare projects and core and shell buildings) compared to simple projects (e.g., multi-family residential and retail). This finding corresponds to the results of previous studies about emerging construction technologies in which construction project stakeholders were more willing to use technologies on complex structures (Dodge Data & Analytics, 2015; McGraw Hill Construction, 2014).

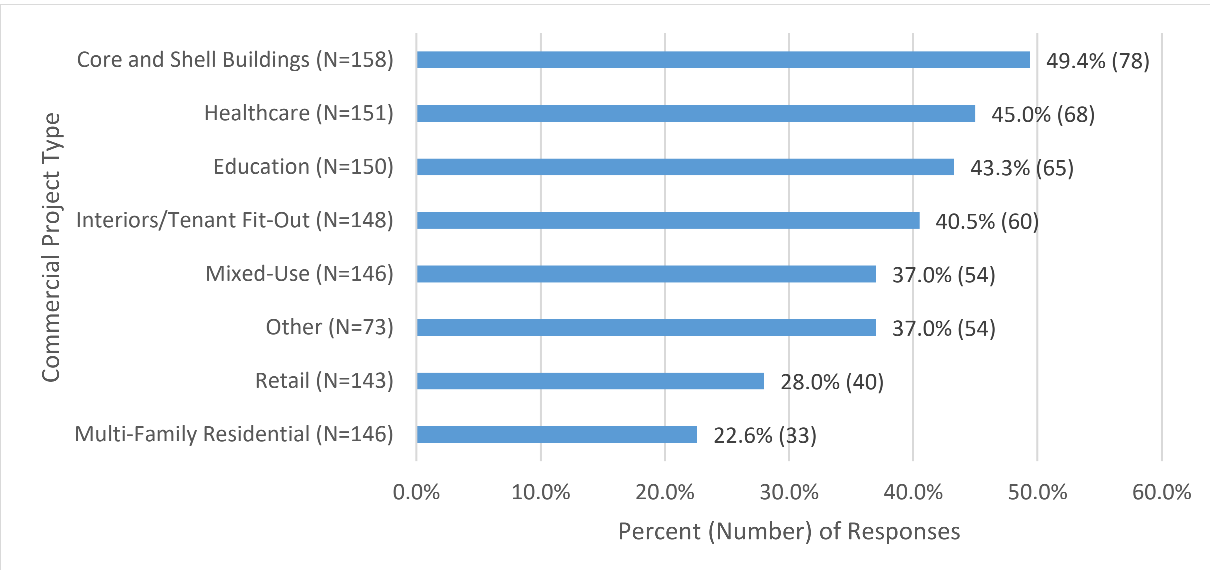


Figure 8. Descriptive Statistics: RCT Use on Specific Commercial Project Types: All Respondents

Table 4 shows the frequencies and percentages of RCT use on different commercial project types by owners/developers. As discussed earlier in this chapter, pairwise deletion was employed in this study. Thus, the total number of responses collected for each variable was different. For instance, as shown in the table, the total number of owners/developers who responded to the use of RCT on “core and shell buildings” (N = 34) was different from the number of designers who responded to RCT use on “retail” projects (N = 30). When asked about using RCT on specific commercial project types, the largest portion of owner/developers (14, 42.4%) reported using it on education projects. Core and shell buildings (12, 35.3%) and healthcare (10, 31.3%) were the other commercial project types on which owner/developers indicated a relatively high percentage of RCT use, while one respondent (3.3%) had experience with using RCT on retail projects.

Table 4

Descriptive Statistics: Owner/Developer Perception of Using RCT on Specific Commercial Project Types

Commercial Project Types							
Core and Shell Buildings (N = 34)	Multi-Family Residential (N = 31)	Retail (N = 30)	Mixed-Use (N = 30)	Education (N = 33)	Healthcare (N = 32)	Interiors/ Tenant Fit-Out (N = 33)	Other (N = 18)
12 (35.3%)	2 (6.5%)	1 (3.3%)	4 (13.3%)	14 (42.4%)	10 (31.3%)	8 (24.2%)	5 (27.8%)

Regarding the use of RCT on specific commercial project types by designers, about half (13, 46.4%) of 28 designers who responded to this question stated that they used RCT on core and shell buildings, and about 42% indicated that they had experience with RCT on both healthcare and mixed-use projects. Similar to the results for RCT use in retail projects by owners/developers, designers reported the smallest portion of RCT experience on retail projects (7, 26.9%).

Table 5

Descriptive Statistics: Designer Perception of Using RCT on Specific Commercial Project Types

Commercial Project Types							
Core and Shell Buildings (N=28)	Multi-Family Residential (N=27)	Retail (N=26)	Mixed-Use (N=26)	Education (N=27)	Healthcare (N=26)	Interiors/Tenant Fit-Out (N=25)	Other (N=10)
13 (46.4%)	8 (29.6%)	7 (26.9%)	11 (42.3%)	11 (40.7%)	11 (42.3%)	10 (40.0%)	3 (30.0%)

When asked about the use of RCT on specific project types, a majority of contractors (38, 62.7%) indicated RCT use on healthcare projects, almost the same proportion (62%) reported that they used RCT on core and shell buildings, and more than half indicated that they used RCT on mixed-use projects. However, about a third (32%) stated using RCT on multi-family projects.

Table 6

Descriptive Statistics: Contractor Perception of Using RCT on Specific Commercial Project Types

Commercial Project Types							
Core and Shell Buildings (N=61)	Multi-Family Residential (N=57)	Retail (N=56)	Mixed-Use (N=58)	Education (N=57)	Healthcare (N=59)	Interiors/Tenant Fit-Out (N=56)	Other (N=24)
38 (62.3%)	18 (31.6%)	24 (42.9%)	32 (55.2%)	30 (52.6%)	37 (62.7%)	27 (48.2%)	9 (37.5%)

Finally, when asked about RCT use on commercial project types, about half (47.6%) of CM and owner representatives reported RCT use on ‘other’ project types. Some examples of ‘other’ project types they indicated in the provided text entry box in the questionnaire included defense facilities, museums, and offices. In addition, 15 (44%) of 34 CM & owner representatives indicated RCT use on interiors/tenant fit-out projects, while less than one-sixth (5, 16.1%) of them reported to have experience with RCT on multi-family residential projects.

Table 7

Descriptive Statistics: CM & Owner Representative Perception of Using RCT on Specific Commercial Project Types

Commercial Project Types							
Core and Shell Buildings (N=35)	Multi-Family Residential (N=31)	Retail (N=31)	Mixed-Use (N=32)	Education (N=33)	Healthcare (N=34)	Interiors/Tenant Fit-Out (N=34)	Other (N=21)
15 (42.9%)	5 (16.1%)	8 (25.8%)	7 (21.9%)	10 (30.3%)	10 (29.4%)	15 (44.1%)	10 (47.6%)

Exploring the participants’ opinions about using RCT on specific commercial project types by stakeholder revealed that “core and shell buildings” was always among the top three project types on which stakeholders reported using RCT. Also, except for CMs and owner representatives, all other construction project stakeholder groups identified healthcare among the top three project types that have adopted RCT. These findings correspond to previous research on implementing new technologies within the construction industry, that AEC professionals were more willing to use new technologies on complex commercial projects than simple projects. Technology providers and manufacturers can use this data to tailor their products based on AEC professionals' perceptions about RCT use on specific project types.

For research subquestion 1.5, a cross-tabulation approach was employed to compare stakeholders' RCT use on new construction projects versus renovation projects. As shown in Figure 9, a majority (51, 65.4%) of 78 respondents with RCT experience reported using RCT on new construction projects. About three-fourth (31, 75.6%) of the contractors, 57% of CM and owner representatives, 56% of designers, and half of the owners/developers indicated that they had experience with RCT on new construction projects. It should be noted that, except for contractors, the number of participants responding to this question was relatively low.

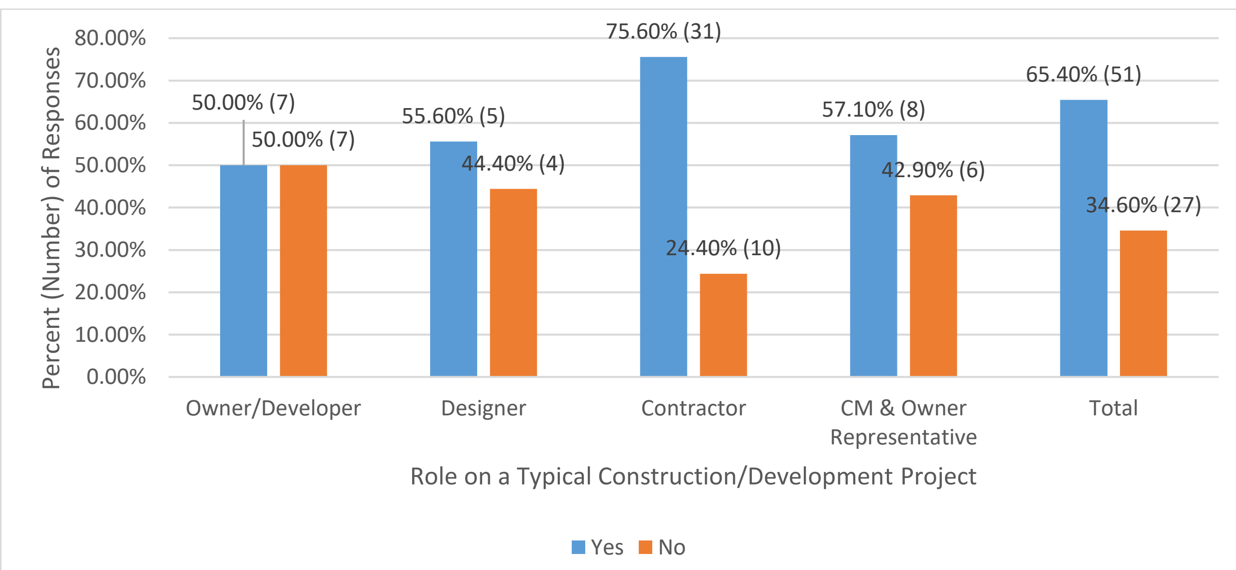


Figure 9. Descriptive Statistics: Respondents Experience with RCT Use on New Construction Projects (N_T=78)

Regarding the use of RCT on additions, renovations and/or interior fit-out projects, as shown in Figure 10, 49 (68.1%) of 72 respondents with RCT experience indicated they used RCT on additions, renovations and/or interior fit-out projects. About three-fourths (74.3%) of the contractors, 64% of CM and owner representatives, 64% of owners/developers, and about half of the designers (55.6%) reported RCT use on additions, renovations, and/or interior fit-out projects.

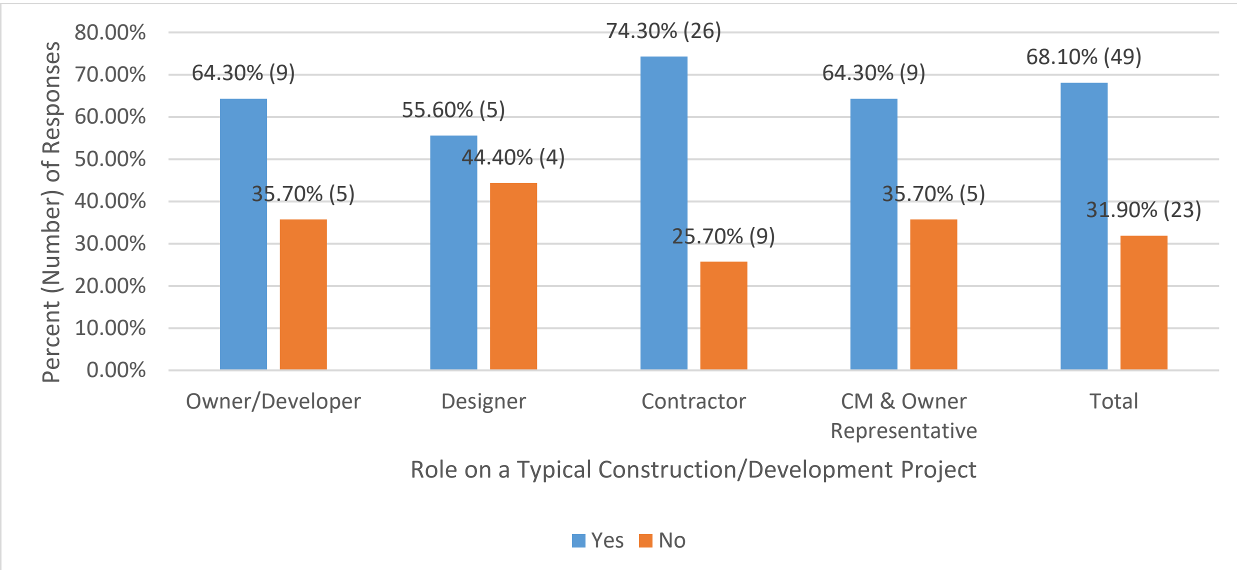


Figure 10. Descriptive Statistics: Respondents Experience with RCT Use on Addition, Renovation, and/or Interior Fit-Out Projects (N_T=72)

Despite the smaller number of renovation projects as compared to new construction projects, which was also previously shown in the literature, the survey results indicated that the majority of participants had experience with RCT on both new construction and renovation projects. The comparison of the stakeholders' experiences with RCT use by project type suggests that stakeholders (e.g., contractors, CMs and owner representatives) who reported more experience with RCT on new construction projects also indicated a higher degree of RCT use on renovation projects as well. These findings suggest that RCT is used on both new construction projects and renovation projects. Therefore, once a company establishes the foundation for adopting RCT, they can benefit from using RCT on all of their projects, regardless of type.

4.3.2 Results for Research Question 2

Research subquestion 2.1 investigated the level of agreement of these construction project stakeholders who had heard of RCT regarding RCT benefits on new construction projects. Survey participants were asked to use a 5-point Likert scale (1 = strongly disagree, 2 = disagree, 3 = neither agree nor disagree, 4 = agree, and 5 = strongly agree) to express their level of agreement with the statement that RCT use provides benefits on new construction projects (see APPENDIX C). Table 8 shows the analysis of these responses by stakeholders. The number of responses (N), mean score (M), standard deviation (SD), and 95% confidence interval for mean (95% CI) were calculated for each of the stakeholder groups. To analyze the results, the means of responses were classified into ranking categories in which the means between 1.00 and 1.80 were considered as strongly disagree, means between 1.81 and 2.60 were counted as disagree, the means between 2.61 and 3.40 were considered for neither agree nor disagree, means between 3.41 and 4.20 were considered as agree, and means above 4.21 were interpreted as strongly agree. As shown in Table 8, the mean scores indicated that all the participants, regardless of their role, agreed with the statement that RCT provides benefits on new construction projects. Contractors, more than other stakeholders, agreed that the use of RCT was beneficial for new construction projects (M = 4.02), while designers indicated the lowest level of agreement compared to other stakeholders (M = 3.60).

Table 8

Descriptive Statistics: Stakeholder Agreement with the Statement that RCT Provides Benefits on New Construction Projects (RQ2.1)

Stakeholder	N	M	SD	95% CI

Owner/Developer	24	3.71	1.46	[3.09, 4.32]
Designer	20	3.60	1.46	[2.91, 4.29]
Contractor	52	4.02	1.20	[3.69, 4.35]
CM & Owner Representative	27	3.85	1.20	[3.38, 4.33]
Total	123	3.85	1.30	[3.62, 4.08]

Research subquestion 2.2 investigated the level of agreement of the survey participants, regardless of their role, who had heard of RCT regarding the RCT benefits on additions, renovations or maintenance projects. Table 9 shows the analysis of responses to the 5-point Likert scale question used in the questionnaire (see APPENDIX C). As shown in the table, the total mean score (M = 4.24) indicated that, on average, survey participants strongly agreed that RCT provides benefits on additions, renovations or maintenance projects. More specifically, the CM and owner representatives agreed, and all other groups of stakeholders strongly agreed that RCT benefits addition, renovation or maintenance projects. For this type of project, interestingly, the designers, more than other stakeholders, agreed that RCT provides benefits on additions, renovations, or maintenance projects (M = 4.40). Note that all four groups of stakeholders who participated in this study indicated a higher level of agreement on RCT benefits for additions, renovations, or maintenance projects than for new construction projects. This is an important finding that suggests construction project stakeholders perceived that implementing RCT is more beneficial on additions, renovations, and/or maintenance projects. The literature revealed that a lack of accurate and complete construction documents in existing buildings is one of the primary challenges in renovation projects (Lu & Lee, 2017). Generating 3D models of existing buildings is one of the main applications of RCT, so these results support its usefulness to construction project stakeholders on renovation projects.

Table 9

Descriptive Statistics: Stakeholder Agreement with the Statement that RCT Provides Benefits on Additions, Renovations or Maintenance Projects (RQ2.2)

Stakeholder	**N**	**Mean**	**SD**	**95% CI for Mean**
Owner/Developer	24	4.29	1.042	[3.85, 4.73]
Designer	20	4.40	1.095	[3.89, 4.91]
Contractor	52	4.23	1.182	[3.90, 4.56]
CM & Owner Representative	27	4.11	1.396	[3.56, 4.66]
Total	123	4.24	1.183	[4.03, 4.46]

For Research subquestion 2.3, the researcher used a paired samples t-test to explore the differences between participants' perceptions regarding the benefits of RCT on new construction or renovation projects. Note that all 123 respondents provided a level of agreement on RCT benefits on new and renovation project types. As shown in Table 10, the mean score for RCT benefits on additions, renovations or maintenance projects was 4.24; which indicated that on average, the participants strongly agreed with the statement that RCT provides benefits on additions, renovations or maintenance projects. However, the mean score for RCT benefits on new construction project (M = 3.85) indicated that, on average, participants agreed that RCT also provides benefits on new construction projects.

Table 10

Paired Samples Statistics: Comparison of Participants' Opinions About RCT Benefits by Project Type (RQ2.3)

		N	**M**	**SD**	**95% CI**
Pair 1	RCT Provides Benefits on New construction projects	123	3.85	1.291	[3.62, 4.08]
	RCT Provides Benefits on Addition, renovation or maintenance projects	123	4.24	1.183	[4.03, 4.46]

The following hypotheses were defined for addressing Research subquestion 2.3:

- Null hypothesis (H0): There is no statistically significant difference between the respondents' opinions about the benefits of RCT use on new construction projects versus benefits of RCT use on additions, renovations or maintenance projects.
- Alternative hypothesis (Ha): There is a statistically significant difference between the respondents' opinions about the benefits of RCT use on new construction projects versus benefits of RCT use on additions, renovations or maintenance projects.

Paired samples t-tests were used to compare the means of responses about the benefits of using RCT by project type (i.e., new construction projects versus additions, renovations or maintenance projects). The assumption of normality was explored before conducting the t-test. For the test of normality, as recommended by Morgan et al. (2020), the absolute value of the skewness and Kurtosis for each variable was compared to the threshold. As shown in APPENDIX D, the skewness statistic values for both RCT benefits on new construction projects and renovation projects were between -1 and 1, and the absolute Kurtosis value was lower than two. Thus, the assumption of normality was satisfied. Note that the two-tailed t-test is robust to the violation of normality if the sample size is large (Morgan et al. 2020). As shown in Table 11, a paired samples t-test indicated that participants opinions about RCT benefits on renovation projects was, on average, significantly different from their opinions regarding RCT benefits on new construction projects, $t(123) = 3.305$, $p = 0.001$. Although the difference between the means was statistically significant, the effect size (d = 0.19) was medium based on Cohen's (1988) guidelines. This is an important finding, revealing evidence indicating RCT use is perceived to be more beneficial on additions, renovations, or maintenance projects compared to new construction projects. This could be due to the lack of existing building construction documents in renovation projects. As the literature showed, creating 3D models of existing facilities is considered one of the main applications of RCT, which could benefit construction project professionals specifically on additions, renovations or maintenance projects (Wang et al., 2019). However, survey results for research subquestion 1.5 revealed that construction project stakeholders with RCT experience on new construction projects also were likely to adopt RCT on renovation projects as well. In other words, although RCT use is perceived to be more beneficial on renovation projects compared to new construction projects, once the company establishes the framework for RCT adoption, they tend to use RCT on both new construction projects and renovation projects.

Table 11

Paired Samples t-Test: Comparison of Participants' Opinions About the Benefits of RCT by Project Type (RQ2.3)

Paired Samples Test									
		Paired Differences					t	df	Sig. (2-tailed)
		M	SD	SE	95% CI				
					Lower	Upper			
Pair 1	New construction - Addition, renovation or maintenance projects	.390	1.310	.118	.156	.624	3.305	122	.001

4.3.3 Results for Research Question 3

Research subquestion 3.1 explored the opinions of US construction project stakeholders regarding RCT benefits during the design/preconstruction phase of a project. Table 12 shows the means of responses to the 5-point Likert scale question used in the questionnaire (see APPENDIX C). As shown in the table, the total mean score (M = 3.84) indicated that, on average, all the survey participants agreed that RCT provides benefits during the design/preconstruction phase of a project. It should be noted that contractors, who are more involved in the preconstruction phase of a project, agreed less than other stakeholders (M = 3.77) with the statement that RCT provides benefits during the design/preconstruction phase of a project, while CM and owner representatives showed the highest level of agreement (M = 4.04) compared to other stakeholders.

Table 12

Descriptive Statistics: Stakeholder Agreement with the Statement That RCT Provides Benefits During the Design/Preconstruction Phase of a Project

Stakeholder	N	Mean	SD	95% CI for Mean
Owner/Developer	24	3.79	1.250	[3.26, 4.32]
Designer	19	3.79	.976	[3.32, 4.26]
Contractor	52	3.77	1.308	[3.41, 4.13]
CM & Owner Representative	27	4.04	.980	[3.65, 4.42]
Total	122	3.84	1.174	[3.63, 4.05]

Research subquestion 3.2 investigated the perceptions of US construction industry project stakeholders regarding RCT benefits during the construction/fabrication phase of a project. The survey participants were asked to use a 5-point Likert scale question to express their level of agreement with the statement that RCT use provides benefits during the construction/fabrication phase of a project. As shown in Table 13, the mean scores indicated that all of the responding professionals, regardless of their role on a project, agreed that using RCT provides benefits during the construction/fabrication phase of a project. Contractors are directly involved in the construction/fabrication phase of a project and, therefore, can experience the impact of using RCT on construction. They agreed that using RCT is beneficial during the construction/fabrication phase (M = 3.98). The CM and owner representatives indicated almost the same level of agreement (M = 4.00), while the owner/developers indicated the lowest level of agreement with the statement (M = 3.58) among the four groups of stakeholders.

Table 13

Descriptive Statistics: Stakeholder Agreement with the Statement That RCT Provides Benefits During the Construction/Fabrication Phase of a Project

Stakeholder	N	Mean	SD	95% CI for Mean
Owner/Developer	24	3.58	1.283	[3.04, 4.12]

Designer	20	3.70	1.174	[3.15, 4.25]
Contractor	52	3.98	1.111	[3.67, 4.29]
CM & Owner Representative	27	4.00	1.301	[3.49, 4.51]
Total	123	3.86	1.196	[3.65, 4.08]

Research Subquestion 3.3 investigated perceptions of US construction industry project stakeholders regarding RCT benefits during the O&M phase of a project. Table 14 shows the mean scores of the responses to the 5-point Likert scale question used in the questionnaire (see APPENDIX C). As shown in the table, the total mean score (M = 3.48) indicated the participants agreed with the statement that RCT provides benefits during the O&M phase of a project. Note that the designers, more than other stakeholders, agreed that RCT provides benefits during this phase (M = 3.95); while the owner/developers, who are involved the most in the O&M phase compared to the other stakeholders, indicated the lowest level of agreement (M = 3.00). In other words, owners/developers neither agreed nor disagreed with the statement that RCT provides benefits during the O&M phase. Therefore, although the literature review indicated several potential application areas for RCT use during the O&M phase, in practice, the stakeholders most involved in O&M activities have not perceived considerable benefits for RCT implementation in that phase. Additionally, with the exception of designers, the average mean score for all the other stakeholders regarding RCT benefits during O&M was lower than their mean score for other project phases, suggesting RCT was perceived by stakeholders to be less beneficial during the O&M phase compared to other phases.

Table 14

Descriptive Statistics: Stakeholder Agreement with the Statement That RCT Provides Benefits During the O&M Phase of a Project

Stakeholder	N	Mean	SD	95% CI for Mean
Owner/Developer	24	3.00	1.383	[2.42, 3.58]
Designer	20	3.95	1.146	[3.41, 4.49]
Contractor	52	3.56	1.092	[3.25, 3.86]

CM & Owner Representative	27	3.41	.797	[3.09, 3.72]
Total	123	3.48	1.133	[3.28, 3.68]

Research subquestion 3.4 investigated differences in participants' perceptions regarding RCT benefits during different phases of project lifecycles when compared by stakeholder. To address the question, the assumptions of normality and homogeneity of variance were explored before conducting the ANOVA test. To test normality, the absolute value of the skewness for each variable (i.e., RCT provides benefits during design/preconstruction, RCT provides benefits during construction/fabrication, and RCT provides benefits during O&M phases) was compared to the threshold of one, as recommended by Morgan et al. (2020). As shown in APPENDIX E, skewness statistic values for all three variables were between -1 and 1. Thus, it was assumed that the data was approximately normally distributed and conducting an ANOVA test was justified. Also, the visual inspection of the RCT benefits P-P Plot indicated a good possibility that the data was approximately normally distributed (see APPENDIX E). Levene's test was conducted to check the assumption of homogeneity of variance for ANOVA. As shown in APPENDIX F, Levene's tests were not significant ($P > .05$). Thus, the assumption of homogeneity of variance is not violated. As shown in Table 15, ANOVA revealed no significant difference among the four groups of stakeholders' opinions about the benefits of RCT use during the design/preconstruction phase and construction/fabrication phase of the project lifecycle. However, a significant difference ($P = 0.042$, $F = 2.821$) was observed on the means of the responses among the four stakeholder groups regarding the RCT benefits for the O&M phase.

Table 15

One-Way ANOVA test: Stakeholder Agreement with the Benefits of RCT Use During Different Phases of Project Lifecycle

Variable		**SS**	**df**	**MS**	**F**	**P**
	Between Groups	1.411	3	.470	.336	.799

Benefits during the design/preconstruction phase	Within Groups	165.310	118	1.401		
	Total	166.721	121			
Benefits during the construction/fabrication phase	Between Groups	3.636	3	1.212	.843	.473
	Within Groups	171.014	119	1.437		
	Total	174.650	122			
Benefits during the operation and maintenance phase	Between Groups	10.404	3	3.468	2.821	.042
	Within Groups	146.295	119	1.229		
	Total	156.699	122			

The Post Hoc test (Tukey HSD) was implemented to determine where the statistical difference occurred. The Tukey HSD revealed a statistical difference between the owner/developers and designers mean perceptions for RCT benefits during the O&M phase of a project (see APPENDIX G). As shown in Table 15, the designers' mean score was significantly higher (M = 3.95) than the owner/developers' mean score (M = 3.00). The results suggest that designers indicated a higher expectation of RCT benefits during the O&M phase, while owners/developers, on average, neither agreed nor disagreed with the statement.

Research subquestion 3.5 aimed to explore the difference between the respondents' perceptions of RCT benefits when compared by project lifecycle phase. Table 16 shows the means of responses to the 5-point Likert scale question. As shown in the table, the highest mean score for the RCT benefits was allocated to the construction/fabrication phase (M=3.86), followed by the design/preconstruction phase (M=3.84), and O&M phase (M=3.48).

Table 16

Descriptive Statistics by Project Phase: RCT Benefits During Different Phases of a Project Lifecycle

Project Lifecycle Phase	**N**	**M**	**SD**	**95% CI**
RCT provides benefits during the design/preconstruction phase of a project	122	3.84	1.174	[3.63, 4.05]
RCT provides benefits during the construction/fabrication phase of a project	123	3.86	1.196	[3.65, 4.08]

RCT provides benefits during the operation and maintenance phase of a project	123	3.48	1.133	[3.28, 3.68]
Valid N (listwise)	122			

Since three different questions (RCT benefits during the design/preconstruction phase, construction/fabrication phase, and O&M phase) were asked from the same group of participants, multiple paired sample t-tests were employed to investigate if any significant differences between the means of responses could be found. As shown in Table 17, no statistically significant differences were observed between the means for the design/preconstruction phase and construction/fabrication phase (P = 0.753). However, the t-test results indicated a statistically significant difference between the means of responses for the design/preconstruction phase and the O&M phase (P = 0.004). Also, as shown in the table, a statistically significant difference was observed between the means of responses for the construction/fabrication phase and the O&M phase (P = 0.001). The results revealed that participants perceived that RCT use would be less beneficial during the O&M phase compared to the design/preconstruction phase and construction/fabrication phase. Despite recent research trends on using BIM and new technologies during the O&M phase, these findings suggest that construction project stakeholders still believe that using RCT during the O&M phase is less beneficial than using it during other phases of a project lifecycle (Pärn et al., 2017).

Table 17

Paired Samples Tests by Project Phase: Comparing the Means of Responses Among Design/Preconstruction Phase, Construction/Fabrication Phase, and O&M Phase

Paired Samples Test									
		M	SD	SE	95% CI		t	df	Sig. (2-tailed)
					Lower	Upper			
Pair 1	Design/preconstruction phase – O&M phase	-.033	1.149	.104	-.239	.173	-.315	121	.753

Pair 2	Design/preconstruction phase – O&M phase	.352	1.336	.121	.113	.592	2.915	121	.004
Pair 3	Construction/fabrication phase – O&M phase	.382	1.211	.109	.166	.598	3.498	122	.001

4.3.4 Results for Research Question 4

Research subquestion 4.1 explored the level of agreement of the construction project stakeholders regarding the benefits (i.e., perceived/realized benefits) of using RCT on a project. Based on the relevant studies (i.e., survey studies on new construction technologies such as BIM, 360 cameras, and laser scanners), 21 benefits for using RCT on a project were developed and utilized in the questionnaire. Participants were asked to state their level of agreement with each benefit using a 5-point Likert scale. As shown in Table 18, on average, participants strongly agreed with increased accuracy of existing condition documentation ($M = 4.36$), reduced time required to document existing conditions ($M = 4.29$), and increased accuracy of the as-built documents ($M = 4.22$) as the major benefits of using RCT on a project. Also, except for reduced project duration ($M = 3.3$, i.e. neither agree nor disagree), participants agreed with the rest of the RCT benefits provided in the questionnaire. Table 18 shows the ranking of all 21 RCT benefits used in the questionnaire based on the total mean scores. On average, participants' level of agreement was lower for the following benefits: the reduced time required for quality assurance processes, reduced time required for quality control process, increased speed of installation of construction elements, reduced overall project cost, and reduced project duration. Note that the means of stakeholders' perceptions for all 21 RCT benefits were positive ($M > 3$).

Table 18

Descriptive Statistics: Ranking of RCT Benefits Based on Total Responses' Mean Score

Descriptive Statistics			
RCT Benefits	**N**	**M**	**SD**
1. Increased accuracy of existing condition documentation	111	4.36	.861

2. Reduced time required to document existing conditions	112	4.29	.999
3. Increased accuracy of the as-built documents	111	4.22	.928
4. Reduced number of site visits to collect data	113	4.10	1.000
5. Reduced time required to generate 3D models	113	3.99	1.073
6. Reduced project risk	113	3.94	.938
7. Increased speed of as-built document creation	110	3.94	1.052
8. Increased accuracy of construction documents	112	3.93	.984
9. Increased accuracy of the constructed system locations	112	3.91	1.000
10. Increased accuracy of surveying/layout	108	3.90	1.023
11. Increased speed of surveying/layout	109	3.83	1.032
12. Increased accuracy of installed work	111	3.81	.968
13. Reduced rework during design	113	3.80	1.079
14. Reduced rework to correct errors in the field	112	3.77	1.040
15. Increased construction quality	111	3.77	.963
16. Increased accuracy of prefabricated elements	111	3.77	1.044
17. Reduced time required for quality assurance processes	112	3.63	1.004
18. Reduced time required for quality control processes	112	3.56	1.055
19. Increased speed of installation of constructed elements	112	3.54	1.048
20. Reduced overall project cost	113	3.41	1.015
21. Reduced project duration	113	3.30	.981
Valid N (listwise)	103		

Table 19 shows the means of stakeholders' responses to the 21 RCT benefits used in the questionnaire. As shown in the table, the increased accuracy of existing condition documentation item had 111 collected responses, and the total mean score was 4.36. This indicates, on average, all the participants strongly agreed with this benefit of RCT. The results revealed that owners/developers, more than other stakeholders, agreed that using RCT could increase the accuracy of existing condition documentation (M = 4.55), while designers showed the lowest level of agreement. Interestingly, on 11 of the 21 RCT benefit items used in the questionnaire (including the top three benefits identified in Table 17), owners/developers indicated the highest level of agreement compared to other stakeholders.

Additionally, it was interesting that designers, more than other stakeholders, agreed with the benefits related to the construction phase, including: reduced rework to correct errors in the field, increased accuracy of installed work, increased accuracy of the as-built documents, increased speed of surveying/layout, and increased speed of installation of constructed elements.

Contractors, more than other stakeholders, agreed with the following benefits of RCT use: the reduced time required for quality assurance processes, reduced time required for quality control processes, and increased construction quality. Time, quality, and cost are three important objectives in planning and controlling construction projects. Interestingly, all three benefits mentioned earlier for contractors were related to project quality. Finally, CM and owner representatives, more than other stakeholders, agreed with statements that the use of RCT on a project could reduce rework during design (M = 4), as well as RCT could increase the accuracy of surveying/layout (M = 4.08).

Table 19

Descriptive Statistics: Stakeholder Agreement with the Benefits of Using RCT on a Project

RCT Benefits		**N**	**M**	**SD**	**95% CI**
Increased accuracy of existing condition documentation	Owner/Developer	20	4.55	.605	[4.27, 4.83]
	Designer	20	4.15	.933	[3.71, 4.59]
	Contractor	45	4.44	.785	[4.21, 4.68]
	CM & Owner Representative	26	4.23	1.070	[3.80, 4.66]
	Total	111	4.36	.861	[4.20, 4.52]
Reduced time required to document existing conditions	Owner/Developer	20	4.45	.826	[4.06, 4.84]
	Designer	20	4.20	1.105	[3.68, 4.72]
	Contractor	46	4.43	.807	[4.20, 4.67]
	CM & Owner Representative	26	3.96	1.280	[3.44, 4.48]
	Total	112	4.29	.999	[4.10, 4.47]
Increased accuracy of the as-built documents	Owner/Developer	20	4.25	.851	[3.85, 4.65]
	Designer	20	4.45	.759	[4.09, 4.81]
	Contractor	46	4.15	.988	[3.86, 4.45]
	CM & Owner Representative	25	4.12	1.013	[3.70, 4.54]
	Total	111	4.22	.928	[4.04, 4.39]
Reduced number of site visits to collect data	Owner/Developer	20	4.30	.733	[3.96, 4.64]
	Designer	20	4.00	1.214	[3.43, 4.57]
	Contractor	47	4.11	.983	[3.82, 4.40]
	CM & Owner Representative	26	4.00	1.058	[3.57, 4.43]
	Total	113	4.10	1.000	[3.91, 4.28]
	Owner/Developer	20	4.35	.745	[4.00, 4.70]

Reduced time required to generate 3D models	Designer	20	3.90	1.210	[3.33, 4.47]
	Contractor	47	3.91	1.158	[3.57, 4.25]
	CM & Owner Representative	26	3.92	1.017	[3.51, 4.33]
	Total	113	3.99	1.073	[3.79, 4.19]
Reduced project risk	Owner/Developer	20	4.10	.912	[3.67, 4.53]
	Designer	20	3.60	.995	[3.13, 4.07]
	Contractor	47	4.00	.933	[3.73, 4.27]
	CM & Owner Representative	26	3.96	.916	[3.59, 4.33]
	Total	113	3.94	.938	[3.76, 4.11]
Increased speed of as-built document creation	Owner/Developer	20	4.15	.933	[3.71, 4.59]
	Designer	20	3.70	1.174	[3.15, 4.25]
	Contractor	45	3.87	1.036	[3.56, 4.18]
	CM & Owner Representative	25	4.08	1.077	[3.64, 4.52]
	Total	110	3.94	1.052	[3.74, 4.14]
Increased accuracy of construction documents	Owner/Developer	20	4.00	.918	[3.57, 4.43]
	Designer	20	3.95	.945	[3.51, 4.39]
	Contractor	46	3.87	1.108	[3.54, 4.20]
	CM & Owner Representative	26	3.96	.871	[3.61, 4.31]
	Total	112	3.93	.984	[3.74, 4.11]
Increased accuracy of the constructed system locations	Owner/Developer	20	4.10	.788	[3.73, 4.47]
	Designer	20	4.00	1.076	[3.50, 4.50]
	Contractor	46	3.91	1.029	[3.61, 4.22]
	CM & Owner Representative	26	3.69	1.050	[3.27, 4.12]
	Total	112	3.91	1.000	[3.72, 4.10]
Increased accuracy of surveying/layout	Owner/Developer	19	3.95	1.079	[3.43, 4.47]
	Designer	19	3.89	1.100	[3.36, 4.43]
	Contractor	45	3.78	1.042	[3.46, 4.09]
	CM & Owner Representative	25	4.08	.909	[3.70, 4.46]
	Total	108	3.90	1.023	[3.70, 4.09]
Increased speed of surveying/layout	Owner/Developer	20	4.00	.973	[3.54, 4.46]
	Designer	19	4.00	1.054	[3.49, 4.51]
	Contractor	46	3.63	1.082	[3.31, 3.95]
	CM & Owner Representative	24	3.96	.955	[3.56, 4.36]
	Total	109	3.83	1.032	[3.64, 4.03]
Increased accuracy of installed work	Owner/Developer	20	3.65	1.089	[3.14, 4.16]
	Designer	20	4.00	1.026	[3.52, 4.48]
	Contractor	46	3.89	.924	[3.62, 4.17]
	CM & Owner Representative	25	3.64	.907	[3.27, 4.01]
	Total	111	3.81	.968	[3.63, 3.99]
Reduced rework during design	Owner/Developer	20	3.95	.945	[3.51, 4.39]
	Designer	20	3.60	1.188	[3.04, 4.16]
	Contractor	47	3.70	1.140	[3.37, 4.04]
	CM & Owner Representative	26	4.00	.980	[3.60, 4.40]
	Total	113	3.80	1.079	[3.60, 4.00]
	Owner/Developer	20	3.70	1.031	[3.22, 4.18]

Reduced rework to correct errors in the field	Designer	20	3.90	1.021	[3.42, 4.38]
	Contractor	46	3.70	1.030	[3.39, 4.00]
	CM & Owner Representative	26	3.85	1.120	[3.39, 4.30]
	Total	112	3.77	1.040	[3.57, 3.96]
Increased construction quality	Owner/Developer	20	3.75	.786	[3.38, 4.12]
	Designer	20	3.80	1.105	[3.28, 4.32]
	Contractor	45	3.87	.869	[3.61, 4.13]
	CM & Owner Representative	26	3.58	1.137	[3.12, 4.04]
	Total	111	3.77	.963	[3.58, 3.95]
Increased accuracy of prefabricated elements	Owner/Developer	20	3.50	1.051	[3.01, 3.99]
	Designer	19	4.11	1.100	[3.57, 4.64]
	Contractor	46	3.87	.980	[3.58, 4.16]
	CM & Owner Representative	26	3.54	1.067	[3.11, 3.97]
	Total	111	3.77	1.044	[3.57, 3.96]
Reduced time required for quality assurance processes	Owner/Developer	20	3.65	1.137	[3.12, 4.18]
	Designer	20	3.50	1.100	[2.99, 4.01]
	Contractor	46	3.78	.917	[3.51, 4.05]
	CM & Owner Representative	26	3.46	.989	[3.06, 3.86]
	Total	112	3.63	1.004	[3.45, 3.82]
Reduced time required for quality control processes	Owner/Developer	20	3.55	1.050	[3.06, 4.04]
	Designer	20	3.50	1.235	[2.92, 4.08]
	Contractor	46	3.83	.902	[3.56, 4.09]
	CM & Owner Representative	26	3.15	1.084	[2.72, 3.59]
	Total	112	3.56	1.055	[3.36, 3.76]
Increased speed of installation of constructed elements	Owner/Developer	20	3.55	.945	[3.11, 3.99]
	Designer	20	3.95	1.050	[3.46, 4.44]
	Contractor	46	3.50	1.090	[3.18, 3.82]
	CM & Owner Representative	26	3.27	1.002	[2.86, 3.67]
	Total	112	3.54	1.048	[3.34, 3.73]
Reduced overall project cost	Owner/Developer	20	3.75	.851	[3.35, 4.15]
	Designer	20	3.40	1.188	[2.84, 3.96]
	Contractor	47	3.34	1.048	[3.03, 3.65]
	CM & Owner Representative	26	3.27	.919	[2.90, 3.64]
	Total	113	3.41	1.015	[3.22, 3.60]
Reduced project duration	Owner/Developer	20	3.60	.940	[3.16, 4.04]
	Designer	20	3.30	1.081	[2.79, 3.81]
	Contractor	47	3.28	.971	[2.99, 3.56]
	CM & Owner Representative	26	3.12	.952	[2.73, 3.50]
	Total	113	3.30	.981	[3.12, 3.48]

Research Subquestion 4.2 investigated differences between respondents' opinions regarding the benefits of using RCT on commercial building projects when compared by project stakeholder group. The following hypotheses were defined for addressing this research question:

- Null hypothesis (H_0): There is no statistically significant difference among perceptions of the four stakeholder groups regarding the benefits of using RCT on commercial building projects.
- Alternative hypothesis (H_A): There is a statistically significant difference among perceptions of the four stakeholder groups regarding the benefits of using RCT on commercial building projects.

ANOVA tests were used to compare the means of responses to address the research question. The assumptions of normality and homogeneity of variance were explored before conducting the ANOVA test. To test normality, the absolute value of the skewness for each benefit was compared to the threshold of one, as recommended by Morgan et al. (2020). As shown in APPENDIX H, the skewness statistic values for 17 of the 21 proposed benefits (variables) were between -1 and 1. Thus, it was assumed that the data for those 17 variables were approximately normally distributed and conducting an ANOVA test was justified. For the four variables that violated the assumption of normality, the Kruskal-Wallis test was employed, which is a non-parametric alternative for ANOVA.

In addition to the test of normality, Levene's test was conducted to check the assumption of homogeneity of variance for ANOVA. As shown in APPENDIX I, Levene's tests were not significant for any of the variables ($P > .05$). Thus, the assumption of homogeneity of variance is not violated. According to Table 20, ANOVA tests revealed no statistically significant difference among the stakeholders' perceptions of RCT benefits ($P < 0.05$). Thus, the null hypothesis could not be rejected.

There is no evidence of a statistically significant difference among the perceptions of the four stakeholder groups (i.e., owner/developer, designer, contractor, and CM and owner representative) regarding the benefits of using RCT on commercial building projects. These findings suggest that all of the construction project stakeholders have similar opinions about each RCT benefit item provided in the questionnaire. This could be due to the increased awareness of all AECOM professionals regarding new construction technologies in recent years. Also, the results suggest conflicts are unlikely among the perceptions of different construction project stakeholders about a specific RCT benefit on a project.

Table 20

ANOVA Test: Comparing the Means of Responses for RCT Benefits

RCT Benefits		**SS**	**df**	**MS**	**F**	**P**
Reduced rework during design	Between Groups	2.739	3	.913	.780	.508
	Within Groups	127.580	109	1.170		
	Total	130.319	112			
Reduced number of site visits to collect data*	Between Groups	1.261	3	.420	.414	.743
	Within Groups	110.668	109	1.015		
	Total	111.929	112			
Reduced time required to generate 3D models	Between Groups	3.135	3	1.045	.905	.441
	Within Groups	125.856	109	1.155		
	Total	128.991	112			
Reduced overall project cost	Between Groups	3.056	3	1.019	.989	.401
	Within Groups	112.219	109	1.030		
	Total	115.274	112			
Reduced project duration	Between Groups	2.712	3	.904	.938	.425
	Within Groups	105.058	109	.964		
	Total	107.770	112			
Reduced project risk	Between Groups	3.005	3	1.002	1.142	.335
	Within Groups	95.562	109	.877		
	Total	98.566	112			
Reduced time required for quality assurance processes	Between Groups	2.153	3	.718	.706	.551
	Within Groups	109.838	108	1.017		
	Total	111.991	111			

Reduced time required for quality control processes	Between Groups	7.619	3	2.540	2.366	.075
	Within Groups	115.943	108	1.074		
	Total	123.563	111			
Reduced time required to document existing conditions*	Between Groups	4.441	3	1.480	1.502	.218
	Within Groups	106.416	108	.985		
	Total	110.857	111			
Reduced rework to correct errors in the field	Between Groups	.841	3	.280	.254	.858
	Within Groups	119.124	108	1.103		
	Total	119.964	111			
Increased accuracy of existing condition documentation*	Between Groups	2.359	3	.786	1.062	.368
	Within Groups	79.226	107	.740		
	Total	81.586	110			
Increased accuracy of construction documents	Between Groups	.300	3	.100	.101	.959
	Within Groups	107.129	108	.992		
	Total	107.429	111			
Increased accuracy of installed work	Between Groups	2.261	3	.754	.800	.496
	Within Groups	100.767	107	.942		
	Total	103.027	110			
Increased accuracy of the as-built documents*	Between Groups	1.536	3	.512	.587	.625
	Within Groups	93.275	107	.872		
	Total	94.811	110			
Increased speed of as-built document creation	Between Groups	2.765	3	.922	.829	.481
	Within Groups	117.790	106	1.111		
	Total	120.555	109			
Increased accuracy of surveying/layout	Between Groups	1.525	3	.508	.479	.698
	Within Groups	110.355	104	1.061		
	Total	111.880	107			
Increased speed of surveying/layout	Between Groups	3.352	3	1.117	1.050	.374
	Within Groups	111.676	105	1.064		
	Total	115.028	108			
Increased accuracy of the constructed system locations	Between Groups	2.117	3	.706	.699	.555
	Within Groups	108.991	108	1.009		
	Total	111.107	111			
Increased speed of installation of constructed elements	Between Groups	5.342	3	1.781	1.650	.182
	Within Groups	116.515	108	1.079		
	Total	121.857	111			
Increased accuracy of prefabricated elements	Between Groups	5.442	3	1.814	1.695	.172
	Within Groups	114.468	107	1.070		
	Total	119.910	110			
Increased construction quality	Between Groups	1.414	3	.471	.502	.682
	Within Groups	100.496	107	.939		
	Total	101.910	110			

*The assumption of normality for these four variables was not satisfied.

A Kruskal-Wallis non-parametric test was conducted on the variables not normally distributed, including: reduced number of site visits to collect data, reduced time required to document existing conditions, increased accuracy of existing condition documentation, and increased accuracy of the as-built documents. As shown in Table 21, results for each item were as follows: reduced number of site visits to collect data, χ^2 (3, N=113) = 0.661, p = 0.882; reduced time required to document existing conditions, χ^2 (3, N=112) = 2.504, p = 0.475; increased accuracy of existing condition documentation, χ^2 (3, N=111) = 2.427, p = 0.489; and finally, increased accuracy of the as-built documents, χ^2 (3, N=111) = 1.735, p = 0.629. Thus, the Kruskal-Wallis test results confirmed the findings of ANOVA tests, indicating no statistically significant differences among the perceptions of the four stakeholder groups regarding the four non-normally distributed benefits (see APPENDIX H).

Table 21

Kruskal-Wallis Test: Comparing the Means of Responses for the Four Non-Normally Distributed RCT Benefits

Test Statistics[a,b]				
	RCT Benefits: Reduced number of site visits to collect data	RCT Benefits: Reduced time required to document existing conditions	RCT Benefits: Increased accuracy of existing condition documentation	RCT Benefits: Increased accuracy of the as-built documents
Kruskal-Wallis H	.661	2.504	2.427	1.735
df	3	3	3	3
Asymp. Sig.	.882	.475	.489	.629
a. Kruskal Wallis Test				
b. Grouping Variable: Role on a 'Typical' Construction/Development Project				

4.3.5 Results for Research Question 5

Research subquestion 5.1 investigated the level of agreement of construction project stakeholders regarding the obstacles preventing the use of RCT on projects. Nineteen obstacles preventing the adoption/or wider adoption of RCT were identified and utilized in the questionnaire. The participants were asked to state their level of agreement with each obstacle using a 5-point Likert scale. As shown in Table 22, on average, participants agreed with eight of 19 obstacles provided in the questionnaire. The top five obstacles to wider adoption of RCT according to participants' opinions were: lack of owner/client demand (M = 3.84), lack of project-level budget (M = 3.81), lack of in-house expertise (M = 3.74), lack of training (M = 3.56), and lack of company budget (M = 3.56). These findings correspond to previous studies on adopting new technologies such as BIM in the AEC industry. For example, lack of training and lack of in-house expertise were also some of the major obstacles to BIM adoption according to prior research (Hatem et al, 2018; McGraw Hill Construction, 2014; Smith, 2014). On the other hand, as shown in the table, participants neither agreed nor disagreed with the rest of the obstacles. The obstacles with the lowest level of agreement based on the means of responses were: not important for the projects I work on, the equipment is not user-friendly, data collection is too time-consuming, and risk/liability concerns.

Table 22

Descriptive Statistics: Ranking of RCT Obstacles Based on Total Responses Mean Scores

Descriptive Statistics			
RCT Obstacles	**N**	**Mean**	**SD**
1. Lack of owner/client demand	106	3.84	.997
2. Lack of project-level budget	107	3.81	1.158
3. Lack of in-house expertise	106	3.74	1.054
4. Lack of training	106	3.56	.947
5. Lack of company budget	108	3.56	1.163
6. It is not a company priority	108	3.50	1.055

7. The equipment is expensive	108	3.48	1.009
8. Cost of hiring employees with the required skills	106	3.45	.996
9. No time for training	106	3.36	.997
10. The related software is expensive	107	3.31	.873
11. Cannot bill Reality Capture costs to my projects	107	3.21	1.166
12. Cannot justify the return on investment	107	3.21	1.114
13. Lack of software interoperability	106	3.09	.889
14. The related software is not user-friendly	106	3.09	.857
15. Data processing is too time consuming	106	3.07	.998
16. Not important for the projects I work on	108	2.97	1.188
17. The equipment is not user-friendly	106	2.93	.908
18. Data collection is too time consuming	106	2.91	1.010
19. Risk/liability concerns	106	2.83	.951
Valid N (listwise)	100		

Table 23 shows the analysis of responses to the 5-point Likert scale question related to RCT obstacles used in the questionnaire by stakeholders. As shown in the table, the highest rated obstacle based on the total mean score was the lack of owner/client demand, with 106 responses collected on the item and a total mean score of 3.84, which indicated, on average, participants agreed with this as an obstacle. Additionally, the results revealed that owners/developers, alongside CM and owner representatives, more than other stakeholders agreed that lack of owner/client demand prevents wider adoption of RCT on projects (M = 4), while designers showed the lowest level of agreement with this obstacle as compared to other stakeholders (M = 3.65). Interestingly, for nine of the 19 RCT obstacles used in the questionnaire, owners/developers indicated the highest level of agreement compared to other stakeholders. Designers, more than other stakeholders, agreed that return on investment could not be justified for RCT use, preventing wider implementation of RCT (M = 3.29).

Meanwhile, contractors, more than other stakeholders, agreed with five of the 19 obstacles used in the questionnaire including: not important for the projects I work on, the equipment is expensive, the related software is expensive, data processing is too time-consuming, and no time for training. Lastly, CM and owner representatives indicated the highest level of agreement with: lack of owner/client demand (alongside the owner/developer stakeholders), cannot bill reality capture costs to my projects, the related software is not user-friendly, data collection is too time-consuming, and lack of training.

Table 23

Descriptive Statistics: Stakeholder Agreement with the Obstacles to the Adoption/Wider Adoptions of RCT on a Project

RCT Obstacles		N	Mean	SD	SE	95% CI
Lack of owner/client demand	Owner/Developer	20	4.00	.649	.145	[3.70, 4.30]
	Designer	17	3.65	1.169	.284	[3.05, 4.25]
	Contractor	44	3.75	1.144	.172	[3.40, 4.10]
	CM & Owner Representative	25	4.00	.816	.163	[3.66, 4.34]
	Total	106	3.84	.997	.097	[3.65, 4.03]
Lack of project-level budget	Owner/Developer	20	4.20	.696	.156	[3.87, 4.53]
	Designer	18	3.44	1.381	.326	[2.76, 4.13]
	Contractor	44	3.73	1.246	.188	[3.35, 4.11]
	CM & Owner Representative	25	3.92	1.077	.215	[3.48, 4.36]
	Total	107	3.81	1.158	.112	[3.59, 4.04]
Lack of in-house expertise	Owner/Developer	20	3.85	1.040	.233	[3.36, 4.34]
	Designer	17	3.65	1.320	.320	[2.97, 4.33]
	Contractor	44	3.77	1.008	.152	[3.47, 4.08]
	CM & Owner Representative	25	3.64	.995	.199	[3.23, 4.05]
	Total	106	3.74	1.054	.102	[3.53, 3.94]
Lack of training	Owner/Developer	20	3.50	.946	.212	[3.06, 3.94]
	Designer	17	3.53	1.179	.286	[2.92, 4.14]
	Contractor	44	3.52	.952	.144	[3.23, 3.81]
	CM & Owner Representative	25	3.68	.802	.160	[3.35, 4.01]
	Total	106	3.56	.947	.092	[3.37, 3.74]
Lack of company budget	Owner/Developer	20	4.05	.887	.198	[3.63, 4.47]
	Designer	18	3.33	1.283	.302	[2.70, 3.97]
	Contractor	45	3.44	1.159	.173	[3.10, 3.79]
	CM & Owner Representative	25	3.52	1.229	.246	[3.01, 4.03]
	Total	108	3.56	1.163	.112	[3.33, 3.78]
It is not a company priority	Owner/Developer	20	3.95	.887	.198	[3.53, 4.37]
	Designer	18	3.22	1.060	.250	[2.69, 3.75]

	Contractor	45	3.53	1.079	.161	[3.21, 3.86]
	CM & Owner Representative	25	3.28	1.061	.212	[2.84, 3.72]
	Total	108	3.50	1.055	.101	[3.30, 3.70]
The equipment is expensive	Owner/Developer	20	3.45	.945	.211	[3.01, 3.89]
	Designer	18	3.28	1.320	.311	[2.62, 3.93]
	Contractor	45	3.60	.986	.147	[3.30, 3.90]
	CM & Owner Representative	25	3.44	.870	.174	[3.08, 3.80]
	Total	108	3.48	1.009	.097	[3.29, 3.67]
Cost of hiring employees with the required skills	Owner/Developer	20	3.60	.883	.197	[3.19, 4.01]
	Designer	17	3.35	1.320	.320	[2.67, 4.03]
	Contractor	44	3.48	1.023	.154	[3.17, 3.79]
	CM & Owner Representative	25	3.36	.810	.162	[3.03, 3.69]
	Total	106	3.45	.996	.097	[3.26, 3.64]
No time for training	Owner/Developer	19	3.11	.809	.186	[2.72, 3.50]
	Designer	18	3.39	1.378	.325	[2.70, 4.07]
	Contractor	44	3.48	1.023	.154	[3.17, 3.79]
	CM & Owner Representative	25	3.32	.748	.150	[3.01, 3.63]
	Total	106	3.36	.997	.097	[3.17, 3.55]
The related software is expensive	Owner/Developer	20	3.30	.657	.147	[2.99, 3.61]
	Designer	17	3.06	1.144	.277	[2.47, 3.65]
	Contractor	45	3.38	.886	.132	[3.11, 3.64]
	CM & Owner Representative	25	3.36	.810	.162	[3.03, 3.69]
	Total	107	3.31	.873	.084	[3.14, 3.48]
Cannot bill Reality Capture costs to my projects	Owner/Developer	20	3.05	1.191	.266	[2.49, 3.61]
	Designer	17	3.24	1.147	.278	[2.65, 3.83]
	Contractor	45	3.22	1.166	.174	[2.87, 3.57]
	CM & Owner Representative	25	3.32	1.215	.243	[2.82, 3.82]
	Total	107	3.21	1.166	.113	[2.99, 3.44]
Cannot justify the return on investment	Owner/Developer	20	3.10	1.071	.240	[2.60, 3.60]
	Designer	17	3.29	1.312	.318	[2.62, 3.97]
	Contractor	46	3.24	1.214	.179	[2.88, 3.60]
	CM & Owner Representative	24	3.17	.816	.167	[2.82, 3.51]
	Total	107	3.21	1.114	.108	[2.99, 3.42]
Lack of software interoperability	Owner/Developer	20	3.30	.733	.164	[2.96, 3.64]
	Designer	17	3.00	1.000	.243	[2.49, 3.51]
	Contractor	44	3.00	.964	.145	[2.71, 3.29]
	CM & Owner Representative	25	3.16	.800	.160	[2.83, 3.49]

	Total	106	3.09	.889	.086	[2.92, 3.27]
The related software is not user-friendly	Owner/Developer	20	3.15	.671	.150	[2.84, 3.46]
	Designer	16	3.06	1.237	.309	[2.40, 3.72]
	Contractor	45	3.02	.839	.125	[2.77, 3.27]
	CM & Owner Representative	25	3.20	.764	.153	[2.88, 3.52]
	Total	106	3.09	.857	.083	[2.93, 3.26]
Data processing is too time consuming	Owner/Developer	20	2.85	.988	.221	[2.39, 3.31]
	Designer	17	2.88	1.111	.270	[2.31, 3.45]
	Contractor	44	3.27	1.065	.160	[2.95, 3.60]
	CM & Owner Representative	25	3.00	.764	.153	[2.68, 3.32]
	Total	106	3.07	.998	.097	[2.87, 3.26]
Not important for the projects I work on	Owner/Developer	20	3.10	.968	.216	[2.65, 3.55]
	Designer	18	2.89	1.132	.267	[2.33, 3.45]
	Contractor	45	3.11	1.352	.202	[2.70, 3.52]
	CM & Owner Representative	25	2.68	1.069	.214	[2.24, 3.12]
	Total	108	2.97	1.188	.114	[2.75, 3.20]
The equipment is not user-friendly	Owner/Developer	19	3.16	.688	.158	[2.83, 3.49]
	Designer	17	3.12	1.219	.296	[2.49, 3.74]
	Contractor	45	2.78	.974	.145	[2.49, 3.07]
	CM & Owner Representative	25	2.92	.640	.128	[2.66, 3.18]
	Total	106	2.93	.908	.088	[2.76, 3.11]
Data collection is too time consuming	Owner/Developer	20	2.75	.967	.216	[2.30, 3.20]
	Designer	17	2.47	1.068	.259	[1.92, 3.02]
	Contractor	44	2.98	1.000	.151	[2.67, 3.28]
	CM & Owner Representative	25	3.20	.957	.191	[2.80, 3.60]
	Total	106	2.91	1.010	.098	[2.71, 3.10]
Risk/liability concerns	Owner/Developer	20	2.95	.887	.198	[2.53, 3.37]
	Designer	17	2.71	1.105	.268	[2.14, 3.27]
	Contractor	44	2.82	1.018	.153	[2.51, 3.13]
	CM & Owner Representative	25	2.84	.800	.160	[2.51, 3.17]
	Total	106	2.83	.951	.092	[2.65, 3.01]

Research subquestion 5.2 investigated difference in perceptions of the construction project stakeholders regarding the obstacles to wider adoption of RCT on commercial building projects. The following hypotheses were defined to address this research question:

- Null hypothesis (H_0): There is no statistically significant difference among perceptions of the four stakeholder groups regarding the obstacles preventing the adoption/or wider adoption of RCT on commercial building projects.
- Alternative hypothesis (H_A): There is a statistically significant difference among perceptions of the four stakeholder groups regarding the obstacles preventing the adoption/or wider adoption of RCT on commercial building projects.

ANOVA tests were used to compare the means of responses regarding RCT obstacles to address the research question. The assumptions of normality and homogeneity of variance were explored before conducting the ANOVA test. Visual inspection of the P-P Plot for the RCT obstacles indicated a good possibility that the data was approximately normally distributed (see APPENDIX J). Levene's test was conducted to check the assumption of homogeneity of variance for ANOVA. As shown in APPENDIX K, Levene's tests were not significant for any of the variables ($P > .05$). Thus, the assumption of homogeneity of variance is not violated. As shown in Table 24, ANOVA revealed no significant difference among perceptions of the four stakeholder groups for any of the RCT obstacles ($P < 0.05$). Thus, the null hypothesis could not be rejected. No evidence of statistically significant differences among perceptions of the owners/developers, designers, contractors, and CM and owner representatives regarding the obstacles to the adoption/or wider adoption of RCT on commercial building projects could be found. In other words, all four groups of stakeholders had approximately similar opinions about each obstacle to RCT adoption presented in the questionnaire. The RCT obstacles' ranking shown in Table 22 can be used as a reference that represents the general perceptions of all the US construction project stakeholders regarding obstacles preventing the adoption/or wider adoption of RCT on commercial building projects.

Table 24

ANOVA Test: Comparing the Means of Responses for RCT Obstacles

Variable (RCT Obstacles)		SS	df	MS	F	P
It is not a company priority	Between Groups	6.699	3	2.233	2.068	.109
	Within Groups	112.301	104	1.080		
	Total	119.000	107			
Not important for the projects I work on	Between Groups	3.454	3	1.151	.812	.490
	Within Groups	147.462	104	1.418		
	Total	150.917	107			
Lack of owner/client demand*	Between Groups	2.141	3	.714	.713	.547
	Within Groups	102.132	102	1.001		
	Total	104.274	105			
Lack of company budget	Between Groups	6.366	3	2.122	1.596	.195
	Within Groups	138.301	104	1.330		
	Total	144.667	107			
Lack of project-level budget	Between Groups	6.050	3	2.017	1.525	.212
	Within Groups	136.212	103	1.322		
	Total	142.262	106			
Cannot bill Reality Capture costs to my projects	Between Groups	.829	3	.276	.199	.897
	Within Groups	143.227	103	1.391		
	Total	144.056	106			
Cannot justify the return on investment	Between Groups	.444	3	.148	.116	.950
	Within Groups	131.032	103	1.272		
	Total	131.477	106			
The equipment is expensive	Between Groups	1.442	3	.481	.465	.707
	Within Groups	107.521	104	1.034		
	Total	108.963	107			
The equipment is not user-friendly	Between Groups	2.629	3	.876	1.065	.367
	Within Groups	83.909	102	.823		
	Total	86.538	105			
The related software is expensive	Between Groups	1.343	3	.448	.580	.629
	Within Groups	79.479	103	.772		
	Total	80.822	106			
The related software is not user-friendly	Between Groups	.591	3	.197	.263	.852
	Within Groups	76.465	102	.750		
	Total	77.057	105			
Lack of software interoperability	Between Groups	1.497	3	.499	.624	.601
	Within Groups	81.560	102	.800		
	Total	83.057	105			
Data collection is too time consuming	Between Groups	6.094	3	2.031	2.052	.111
	Within Groups	100.963	102	.990		
	Total	107.057	105			
	Between Groups	3.496	3	1.165	1.176	.323

Data processing is too time consuming	Within Groups	101.042	102	.991		
	Total	104.538	105			
of in-house expertise	Between Groups	.684	3	.228	.201	.896
	Within Groups	115.920	102	1.136		
	Total	116.604	105			
Cost of hiring employees with the required skills	Between Groups	.845	3	.282	.278	.841
	Within Groups	103.420	102	1.014		
	Total	104.264	105			
Lack of training	Between Groups	.508	3	.169	.184	.907
	Within Groups	93.653	102	.918		
	Total	94.160	105			
No time for training	Between Groups	1.893	3	.631	.628	.599
	Within Groups	102.485	102	1.005		
	Total	104.377	105			
Risk/liability concerns	Between Groups	.559	3	.186	.201	.895
	Within Groups	94.385	102	.925		
	Total	94.943	105			

*The Assumption of Normality for the Variable Was Not Satisfied.

Kruskal-Wallis non-parametric tests were employed to investigate if there are statistically significant differences among perceptions of the four stakeholder groups regarding the “lack of owner/client demand” obstacle. As shown in Table 25, the reduced number of site visits to collect data results were χ^2 (3, N = 105) = 1.103, p = 0.776. Thus, the Kruskal-Wallis test results confirmed the findings of ANOVA tests, indicating no difference among the perceptions of the owners/developers, designers, contractors, and CM and owner representatives regarding the “lack of owner/client demand” obstacle.

Table 25

Kruskal-Wallis Test: Comparing the Means of Responses for the Non-Normally Distributed RCT Obstacle

Test Statistics[a,b]	
	RCT Obstacle: Lack of Owner/Client demand
Kruskal-Wallis H	1.103
df	3
Asymp. Sig.	.776
a. Kruskal Wallis Test	
b. Grouping Variable: Role on a 'Typical' Construction/Development Project	

CHAPTER 5: CONCLUSION, LIMITATIONS, AND FUTURE RESEARCH

5.1 Conclusion

The purpose of this study was to investigate the use of RCT by US construction project stakeholders in the commercial building sector. Specifically, the study aimed to explore the opinions of US construction project stakeholders regarding the benefits and obstacles of using RCT throughout the project lifecycles. To achieve this goal, a cross-sectional survey instrument was developed and sent to members of professional organizations, including CMAA and IFMA across the US, as well as the author's industry connections on *LinkedIn*. The collected data was sub-aggregated into four major groups of stakeholders including: 1) designers, 2) contractors, 3) owner/developers, and 4) CMs and owner representatives. Further statistical analysis was then performed to answer the research questions.

Statistical analysis indicated that the majority of respondents were familiar with RCT. Over half of the owner/developers and contractors who had heard of RCT reported having personal experience with using RCT on their projects. Also, over half of the participants in each stakeholder group reported that their company used RCT. Additionally, the results revealed that the major commercial project types that RCT was most frequently used were on core and shell buildings, healthcare, and education projects. On the other hand, fewer respondents stated RCT experience on multi-family residential and retail projects. Furthermore, the majority of respondents with RCT experience reported that they use RCT on both new construction and addition, renovation, and/or interior fit-out projects.

Survey results showed that, on average, participants agreed that RCT benefits new construction projects and strongly agreed that RCT provides benefits on additions, renovations, or maintenance projects. The fact that participants more strongly agreed that RCT use was beneficial on addition, renovation, or maintenance projects than new construction projects was statistically significant. The analysis of RCT use by project type also revealed a significant difference between participants' opinions regarding RCT benefits on new construction versus renovations. Based on the literature, a lack of complete and accurate as-built documentation is one of the main challenges in renovation projects. The findings of this study are likely indicative of participants' perceptions that RCT can help address the need for accurate and complete as-built documentation in renovation projects.

CM and owner representatives, more than other stakeholders, agreed with the statement that RCT provides benefits during both the design/preconstruction phase and construction/fabrication phase of a project; while designers, more than other stakeholders, agreed most that RCT benefits O&M projects. Investigating the survey results by project phase revealed that, on average, construction project stakeholders agreed that RCT provides benefits during all phases of project lifecycles. Nevertheless, statistically significant differences were observed between the perceived benefits of using RCT in the O&M phase and design/preconstruction, as well as the O&M phase and construction/prefabrication phase. Mean comparison of the responses showed that, on average, participants perceived utilizing RCT is the least beneficial during the O&M phase of a project compared to other phases, though designers felt it was more important than other shareholder groups.

Results revealed that, on average, participants strongly agreed with the following RCT benefits: 1) increased accuracy of existing condition documentation, 2) reduced time required to document existing conditions, and 3) increased accuracy of the as-built documents. Also, on average, survey participants agreed with almost all of the other proposed benefits, including but not limited to: reduced number of site visits to collect data, reduced time required to generate 3D models, reduced project risk, increased speed of as-built document creation, increased accuracy of construction documents, increased accuracy of constructed system locations, and increased accuracy of surveying/layout. However, the average mean score of responses about reduced project duration indicated that participants neither agreed nor disagreed about this benefit of RCT. It should be noted that no statistically significant differences in participants' perceptions of the RCT benefits were observed when compared by stakeholder, which means the perceptions of designers, contractors, owner/developers, and CM and owner representatives did not significantly differ when considering the benefits of using RCT.

Finally, the results revealed no significant differences in participants' perceptions of RCT obstacles when compared by stakeholder group. According to the survey results, the major obstacles preventing the adoption/or wider adoption of RCT on projects were: lack of owner/client demand, lack of project-level budget, lack of in-house expertise, lack of training, lack of company budget, not being a company priority, the equipment is expensive, and cost of hiring employees with the required skills. However, on average, the participants neither agreed nor disagreed with the rest of the RCT obstacles proposed in the survey questionnaire.

This study represents an initial attempt to explore RCT use in the commercial building sector from US construction project stakeholders' points of view. The contribution of this study to the larger body of knowledge is to shed light on the perceptions and experiences of US construction project stakeholders regarding the benefits and obstacles of using RCT during different phases of projects. Also, this study provided a better understanding of the current status and extent of RCT use among construction project stakeholders across the US.

5.2 Limitations

The following limitations should be considered when interpreting the results of this study. Due to the lack of survey studies about RCT in the construction industry, the proposed RCT benefits and obstacles used in the questionnaire were derived from related studies such as BIM, 360 cameras, and laser scanning technologies. Therefore, the findings of this study cannot be compared to any previous survey studies, in part because none had previously existed on the topic. Secondly, responses from participants who stated that they had never heard of RCT were removed from the dataset. Also, participants from construction sectors other than commercial buildings were not included in the analysis phase of this study. Thirdly, it should be noted that the collected data from different construction professionals were sub-aggregated before conducting the statistical analysis. Responses from architects and engineers were aggregated into the designer group, and responses from the general contractors and subcontractors were considered under the contractor stakeholders. Also, those participants who chose "others" as their role, but their text entry indicated they were CMs or owner representatives, were aggregated in the fourth group of stakeholders (i.e., CM and owner representative). Lastly, the results of this study may not be generalizable to the whole US construction industry due to the relatively small sample compared to the population. Thus, findings herein should be interpreted given these limitations and readers should be cautious regarding generalization of the results beyond the study sample.

5.3 Future Research

Despite the large number of technical studies on RCT, including laser scanning and photogrammetry, reviewed literature revealed that research about the experiences and perceptions of construction project stakeholders regarding RCT benefits and obstacles on their projects is rare. Recent studies have seldom focused on the data processing stage or a specific application of RCT using the case study approach. Reviewing the literature revealed the need for further exploratory studies focusing on addressing the obstacles to implementing RCT on construction projects. Future studies are needed to investigate the use of RCT within different construction sectors, including heavy civil, facilities management, and single-family residential. Additionally, exploring the use of RCT in existing buildings would be a potential area for future studies due to the increasing trend in circular economy and sustainability.

REFERENCES

Akinci, B., Boukamp, F., Gordon, C., Huber, D., Lyons, C., & Park, K. (2006). A formalism for utilization of sensor systems and integrated project models for active construction quality control. *Automation in construction, 15*(2), 124-138.

Almukhtar, A., Saeed, Z. O., Abanda, H., & Tah, J. H. (2021). Reality Capture of Buildings Using 3D Laser Scanners. *CivilEng, 2*(1), 214-235.

USCB (U.S. Census Bureau). (2019). American housing survey. Retrieved August 18, 2021, from, https://www.census.gov/programs-surveys/ahs/data/interactive/ahstablecreator.html?s_areas=00000&s_year=2019&s_tablename=TABLE1&s_bygroup1=4&s_bygroup2=1&s_filtergroup1=1&s_filtergroup2=1

Autodesk, Inc. (2021), How Reality Capture is Changing the Design and Construction Industry. Retrieved Aug 16, 2021, from https://www.autodesk.com/campaigns/reality-capture

Azhar, S. (2011). Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry. *Leadership and management in engineering, 11*(3), 241-252.

Balado, J., Díaz-Vilariño, L., Arias, P., & Soilán, M. (2017). Automatic building accessibility diagnosis from point clouds. *Automation in construction, 82*, 103-111.

Barber, D., Mills, J., & Smith-Voysey, S. (2008). Geometric validation of a ground-based mobile laser scanning system. *ISPRS journal of photogrammetry and remote sensing, 63*(1), 128-141.

Becerik-Gerber, B., Jazizadeh, F., Kavulya, G., & Calis, G. (2011). Assessment of target types and layouts in 3D laser scanning for registration accuracy. *Automation in construction, 20*(5), 649-658.

Boavida, J., Oliveira, A., & Santos, B. (2012). Precise long tunnel survey using the Riegl VMX-250 mobile laser scanning system. Proceedings of the 2012 RIEGL International Airborne and Mobile User Conference, Orlando, FL, USA.

Bohn, J. S., & Teizer, J. (2010). Benefits and barriers of construction project monitoring using high-resolution automated cameras. *Journal of construction engineering and management*, *136*(6), 632-640.

Bosché, F., Ahmed, M., Turkan, Y., Haas, C. T., & Haas, R. (2015). The value of integrating Scan-to-BIM and Scan-vs-BIM techniques for construction monitoring using laser scanning and BIM: The case of cylindrical MEP components. *Automation in construction, 49*, 201-213.

Bosche, F., Haas, C. T., & Akinci, B. (2009). Automated recognition of 3D CAD objects in site laser scans for project 3D status visualization and performance control. *Journal of Computing in Civil Engineering, 23*(6), 311-318.

Boton, C., & Forgues, D. (2018). Practices and processes in BIM projects: an exploratory case study. *Advances in Civil Engineering, 2018*.

Brilakis, I., Lourakis, M., Sacks, R., Savarese, S., Christodoulou, S., Teizer, J., & Makhmalbaf, A. (2010). Toward automated generation of parametric BIMs based on hybrid video and laser scanning data. *Advanced Engineering Informatics, 24*(4), 456-465.

Buyukdemircioglu, M., Kocaman, S., & Isikdag, U. (2018). Semi-automatic 3D city model generation from large-format aerial images. *ISPRS International Journal of Geo-Information*, *7*(9), 339.

Cha, H., Kim, K., & Kim, C. (2012). Case study on selective demolition method for refurbishing deteriorated residential apartments. *Journal of construction engineering and management*.

Chen, C., Tang, L., Hancock, C. M., & Zhang, P. (2019). Development of low-cost mobile laser scanning for 3D construction indoor mapping by using inertial measurement unit, ultra-wide band and 2D laser scanner. *Engineering, Construction and Architectural Management*.

Chen, K., Lu, W., Xue, F., Tang, P., & Li, L. H. (2018). Automatic building information model reconstruction in high-density urban areas: Augmenting multi-source data with architectural knowledge. *Automation in Construction*, *93*, 22-34.

Cheng, L., Chen, S., Liu, X., Xu, H., Wu, Y., Li, M., & Chen, Y. (2018). Registration of laser scanning point clouds: A review. *Sensors*, *18*(5), 1641.

Cho, Y. K., Ham, Y., & Golpavar-Fard, M. (2015). 3D as-is building energy modeling and diagnostics: A review of the state-of-the-art. *Advanced Engineering Informatics, 29*(2), 184-195.

Coburn, J. Q., Freeman, I., & Salmon, J. L. (2017). A review of the capabilities of current low-cost virtual reality technology and its potential to enhance the design process. *Journal of computing and Information Science in Engineering*, *17*(3).

Colby, S., & Ortman, J. M. (2015). *Projections of the size and composition of the US population: 2014 to 2060* (pp. Report-No). Washington, DC: US Department of Commerce, Economics and Statistics Administration, US Census Bureau.

Colomina, I., & Molina, P. (2014). Unmanned aerial systems for photogrammetry and remote sensing: A review. *ISPRS Journal of photogrammetry and remote sensing, 92*, 79-97.

Coluzzi, R., Lanorte, A., & Lasaponara, R. (2010). On the LiDAR contribution for landscape archaeology and palaeoenvironmental studies: the case study of Bosco dell'Incoronata (Southern Italy). *Advances in Geosciences, 24*.

Cui, Y., Li, Q., Yang, B., Xiao, W., Chen, C., & Dong, Z. (2019). Automatic 3-D reconstruction of indoor environment with mobile laser scanning point clouds. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 12*(8), 3117-3130.

Dai, F., Rashidi, A., Brilakis, I., & Vela, P. (2013). Comparison of image-based and time-of-flight-based technologies for three-dimensional reconstruction of infrastructure. *Journal of construction engineering and management, 139*(1), 69-79.

Dick, A. R., Torr, P. H., & Cipolla, R. (2004). Modelling and interpretation of architecture from several images. *International Journal of Computer Vision, 60*(2), 111-134.

Deutsch, R. (2015). *Data-driven design and construction: 25 strategies for capturing, analyzing and applying building data*. John Wiley & Sons.

Dimitrov, A., & Golparvar-Fard, M. (2014). Vision-based material recognition for automated monitoring of construction progress and generating building information modeling from unordered site image collections. *Advanced Engineering Informatics, 28*(1), 37-49.

Dodge Data & Analytics. *Measuring the Impact of BIM on Complex Buildings: Smart Market Report*; Dodge Data & Analytics: Bedford, MA, USA, 2015.

Dong, B., Kennedy, C., & Pressnail, K. (2002). To retrofit or rebuild, that is the question: Using life-cycle energy performance for comparing construction options. Annual Conference of the Canadian Society for Civil Engineering,

Dore, C., & Murphy, M. (2014). Semi-automatic generation of as-built BIM façade geometry from laser and image data. *Journal of Information Technology in Construction (ITcon), 19*(2), 20-46.

Eastman, C. M., Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors*. John Wiley & Sons.

EPBD (2016). Proposal for a Directive of the Europian Parliament and of the Council Amending Directive 2012/27/EU on Energy Efficiency.

Fathi, H., Dai, F., & Lourakis, M. (2015). Automated as-built 3D reconstruction of civil infrastructure using computer vision: Achievements, opportunities, and challenges. *Advanced Engineering Informatics, 29*(2), 149-161.

Filgueira, A., González-Jorge, H., Lagüela, S., Díaz-Vilariño, L., & Arias, P. (2017). Quantifying the influence of rain in LiDAR performance. *Measurement, 95*, 143-148.

Frueh, C., & Zakhor, A. (2003). Constructing 3D city models by merging ground-based and airborne views. 2003 IEEE Computer Society Conference on Computer Vision and Pattern Recognition, 2003. Proceedings.,

Fryskowska, A., Walczykowski, P., Delis, P., & Wojtkowska, M. (2015). ALS and TLS data fusion in cultural heritage documentation and modeling. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 40*(5), 147.

Fuller, S. (2010). Life-cycle cost analysis (LCCA). *National Institute of Building Sciences, An Authoritative Source of Innovative Solutions for the Built Environment, 1090*.

Gerges, M., Austin, S., Mayouf, M., Ahiakwo, O., Jaeger, M., Saad, A., & El Gohary, T. (2017). An investigation into the implementation of Building Information Modeling in the Middle East. *Journal of Information Technology in Construction*, *22*, 1-15.

Golparvar-Fard, M., Bohn, J., Teizer, J., Savarese, S., & Peña-Mora, F. (2011). Evaluation of image-based modeling and laser scanning accuracy for emerging automated performance monitoring techniques. *Automation in construction, 20*(8), 1143-1155.

Golparvar-Fard, M., Peña-Mora, F., & Savarese, S. (2009). D4AR–a 4-dimensional augmented reality model for automating construction progress monitoring data collection, processing and communication. *Journal of information technology in construction, 14*(13), 129-153.

Gong, J., & Caldas, C. H. (2008). Data processing for real-time construction site spatial modeling. *Automation in construction, 17*(5), 526-535.

(GSA), G.S.A. GSA BIM Guide for 3D Imaging, 2009. Available from:<https:// www.gsa.gov/cdnstatic/GSA_BIM_Guide_Series_03.pdf>(cited 2021 10 January).

Guarnieri, A., Milan, N., & Vettore, A. (2013). Monitoring of complex structure for structural control using terrestrial laser scanning (TLS) and photogrammetry. *International Journal of Architectural Heritage, 7*(1), 54-67.

Haala, N., Peter, M., Kremer, J., & Hunter, G. (2008). Mobile LiDAR mapping for 3D point cloud collection in urban areas—A performance test. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci, 37*, 1119-1127.

Ham, Y., & Golparvar-Fard, M. (2015). Mapping actual thermal properties to building elements in gbXML-based BIM for reliable building energy performance modeling. *Automation in construction, 49*, 214-224.

Hasik, V., Escott, E., Bates, R., Carlisle, S., Faircloth, B., & Bilec, M. M. (2019). Comparative whole-building life cycle assessment of renovation and new construction. *Building and Environment, 161*, 106218.

Hatem, W. A., Abd, A. M., & Abbas, N. N. (2018). Barriers of adoption Building Information Modeling (BIM) in construction projects of Iraq. *Engineering Journal, 22*(2), 59-81.

Hebert, M., & Krotkov, E. (1992). 3D measurements from imaging laser radars: how good are they? *Image and vision computing, 10*(3), 170-178.

Holopainen, M., Kankare, V., Vastaranta, M., Liang, X., Lin, Y., Vaaja, M., Yu, X., Hyyppä, J., Hyyppä, H., & Kaartinen, H. (2013). Tree mapping using airborne, terrestrial and mobile laser scanning–A case study in a heterogeneous urban forest. *Urban forestry & urban greening, 12*(4), 546-553.

Ibp, I. (2015). *Brazil Energy Policy, Laws and Regulations Handbook Volume 1 Strategic Information and Basic Laws*. Int'l Business Publications.

Jagarajan, R., Asmoni, M. N. A. M., Mohammed, A. H., Jaafar, M. N., Mei, J. L. Y., & Baba, M. (2017). Green retrofitting–A review of current status, implementations and challenges. *Renewable and Sustainable Energy Reviews, 67*, 1360-1368.

Jaselskis, E. J., Gao, Z., Welch, A., & O'Brien, D. (2003). Pilot study on laser scanning technology for transportation projects. Mid-Continent Transportation Research Symposium,

Jung, J., Hong, S., Jeong, S., Kim, S., Cho, H., Hong, S., & Heo, J. (2014). Productive modeling for development of as-built BIM of existing indoor structures. *Automation in construction, 42*, 68-77.

Karsch, K., Golparvar-Fard, M., & Forsyth, D. (2014). ConstructAide: analyzing and visualizing construction sites through photographs and building models. *ACM Transactions on Graphics (TOG), 33*(6), 1-11.

Kashani, A. G., & Graettinger, A. J. (2015). Cluster-based roof covering damage detection in ground-based lidar data. *Automation in construction, 58*, 19-27.

Kedzierski, M., & Fryskowska, A. (2014). Terrestrial and aerial laser scanning data integration using wavelet analysis for the purpose of 3D building modeling. *Sensors, 14*(7), 12070-12092.

Khaddaj, M., & Srour, I. (2016). Using BIM to retrofit existing buildings. *Procedia Engineering, 145*, 1526-1533.

Kim, M.-K., Wang, Q., Park, J.-W., Cheng, J. C., Sohn, H., & Chang, C.-C. (2016). Automated dimensional quality assurance of full-scale precast concrete elements using laser scanning and BIM. *Automation in construction, 72*, 102-114.

Klein, L., Li, N., & Becerik-Gerber, B. (2011). Comparison of image-based and manual field survey methods for indoor as-built documentation assessment. In *Computing in Civil Engineering (2011)* (pp. 59-66).

Klein, L., Li, N., & Becerik-Gerber, B. (2012). Imaged-based verification of as-built documentation of operational buildings. *Automation in construction, 21*, 161-171.

Lagüela, S., Martínez, J., Armesto, J., & Arias, P. (2011). Energy efficiency studies through 3D laser scanning and thermographic technologies. *Energy and buildings, 43*(6), 1216-1221.

Lee, H., & Park, H. (2011). Gage-free stress estimation of a beam-like structure based on terrestrial laser scanning. *Computer-Aided Civil and Infrastructure Engineering, 26*(8), 647-658.

Lee, K. W., & Park, J. K. (2019). Comparison of UAV Image and UAV LiDAR for Construction of 3D Geospatial Information. *Sensors and Materials, 31*(10), 3327-3334.

Leica Geosystems AG. (2017). Reality Capture for Construction and Engineering Projects. Retrieved August 18, 2021, from https://blog.hexagongeosystems.com/wp-content/uploads/2019/09/Reality-Capture-for-Construction-and-Engineering.pdf

Li, S., Isele, J., & Bretthauer, G. (2008). Proposed methodology for generation of building information model with laserscanning. *Tsinghua Science and Technology, 13*(S1), 138-144.

Lowe, D. G. (1999). Object recognition from local scale-invariant features. Proceedings of the seventh IEEE international conference on computer vision,

Lu, Q., & Lee, S. (2017). Image-based technologies for constructing as-is building information models for existing buildings. *Journal of Computing in Civil Engineering, 31*(4), 04017005.

Ma, Z., Cooper, P., Daly, D., & Ledo, L. (2012). Existing building retrofits: Methodology and state-of-the-art. *Energy and buildings, 55*, 889-902.

Maalek, R., Lichti, D. D., & Ruwanpura, J. Y. (2019). Automatic recognition of common structural elements from point clouds for automated progress monitoring and dimensional quality control in reinforced concrete construction. *Remote Sensing, 11*(9), 1102.

Macher, H., Landes, T., & Grussenmeyer, P. (2017). From point clouds to building information models: 3D semi-automatic reconstruction of indoors of existing buildings. *Applied Sciences, 7*(10), 1030.

Marks, E. D., Cheng, T., & Teizer, J. (2013). Laser scanning for safe equipment design that increases operator visibility by measuring blind spots. *Journal of construction engineering and management, 139*(8), 1006-1014.

McCoy, A., & Yeganeh, A. (2021). An Overview of Emerging Construction Technologies. *NAIOP Research Foundation.*

McGraw-Hill Construction. (2014). *The business value of BIM for construction in major global markets: how contractors around the world are driving innovation with building information modeling* (Smart Market Report, Issue.

ME, M. K. S., Hemaraj, R., & Isha, S. (2019). Comparison on Measurement of a Building using Total Station, ArcGIS and Google Earth.

Moravec, H. P. (1981). Rover Visual Obstacle Avoidance. IJCAI,

Morris, T. (2004). *Computer vision and image processing*. Palgrave Macmillan.

Murphy, M., McGovern, E., & Pavia, S. (2013). Historic Building Information Modelling–Adding intelligence to laser and image based surveys of European classical architecture. *ISPRS journal of photogrammetry and remote sensing, 76*, 89-102.

Mutai, A. (2009). *Factors influencing the use of Building Information Modeling (BIM) within leading construction firms in the United States of America*. Indiana State University.

Nahangi, M., & Haas, C. T. (2014). Automated 3D compliance checking in pipe spool fabrication. *Advanced Engineering Informatics, 28*(4), 360-369.

Naoum, S. G. (2012). *Dissertation research and writing for construction students*. Routledge.

Nguyen, A., & Le, B. (2013). 3D point cloud segmentation: A survey. 2013 6th IEEE conference on robotics, automation and mechatronics (RAM),

Nowak, R., Orłowicz, R., & Rutkowski, R. (2020). Use of TLS (LiDAR) for building diagnostics with the example of a historic building in Karlino. *Buildings, 10*(2), 24.

Omar, T., & Nehdi, M. L. (2016). Data acquisition technologies for construction progress tracking. *Automation in construction, 70*, 143-155.

Pärn, E. A., Edwards, D. J., & Sing, M. C. (2017). The building information modelling trajectory in facilities management: A review. *Automation in construction*, *75*, 45-55.

Pătrăucean, V., Armeni, I., Nahangi, M., Yeung, J., Brilakis, I., & Haas, C. (2015). State of research in automatic as-built modelling. *Advanced Engineering Informatics, 29*(2), 162-171.

Peansupap, V., & Walker, D. H. (2005). Factors enabling information and communication technology diffusion and actual implementation in construction organisations. *J. Inf. Technol. Constr.*, *10*(14), 193-218.

Petzold, F., Bartels, H., & Donath, D. (2004). New techniques in building surveying.

Pollefeys, M., Van Gool, L., Vergauwen, M., Verbiest, F., Cornelis, K., Tops, J., & Koch, R. (2004). Visual modeling with a hand-held camera. *International Journal of Computer Vision, 59*(3), 207-232.

Pombo, O., Rivela, B., & Neila, J. (2016). The challenge of sustainable building renovation: assessment of current criteria and future outlook. *Journal of Cleaner production, 123*, 88-100.

Pradhananga, N. (2014). *Construction site safety analysis for human-equipment interaction using spatio-temporal data* (Doctoral dissertation, Georgia Institute of Technology).

Puri, N., Valero, E., Turkan, Y., & Bosché, F. (2018). Assessment of compliance of dimensional tolerances in concrete slabs using TLS data and the 2D continuous wavelet transform. *Automation in construction, 94*, 62-72.

Rabbani, T., Dijkman, S., van den Heuvel, F., & Vosselman, G. (2007). An integrated approach for modelling and global registration of point clouds. *ISPRS journal of photogrammetry and remote sensing, 61*(6), 355-370.

Rebolj, D., Babič, N. Č., Magdič, A., Podbreznik, P., & Pšunder, M. (2008). Automated construction activity monitoring system. *Advanced Engineering Informatics, 22*(4), 493-503.

Riveiro, B., DeJong, M., & Conde, B. (2016). Automated processing of large point clouds for structural health monitoring of masonry arch bridges. *Automation in construction, 72*, 258-268.

Riveiro, B., González-Jorge, H., Varela, M., & Jauregui, D. V. (2013). Validation of terrestrial laser scanning and photogrammetry techniques for the measurement of vertical underclearance and beam geometry in structural inspection of bridges. *Measurement, 46*(1), 784-794.

Rogers, E. M. (2010). *Diffusion of innovations*. Simon and Schuster.

Rottensteiner, F. (2003). Automatic generation of high-quality building models from lidar data. *IEEE Computer Graphics and Applications, 23*(6), 42-50.

Rubenstone, J. (2020, July 15). 5D Scheduling and Reality Capture May speed Payments. *Engineering News-Record.* Retrieved August 16, 2021, from, https://www.enr.com/articles/49710-d-scheduling-and-reality-capture-may-speed-payments

Sairam, N., Nagarajan, S., & Ornitz, S. (2016). Development of mobile mapping system for 3d road asset inventory. *Sensors, 16*(3), 367.

Schindler, G., Brown, M., & Szeliski, R. (2007). City-scale location recognition. 2007 IEEE Conference on Computer Vision and Pattern Recognition,

Schmid, C., & Mohr, R. (1997). Local grayvalue invariants for image retrieval. *IEEE transactions on pattern analysis and machine intelligence, 19*(5), 530-535.

Schofield, W., & Breach, M. (2007). *Engineering surveying*. CRC Press.

Sepasgozar, S. M., & Shirowzhan, S. (2016). Challenges and opportunities for implementation of laser scanners in building construction. In *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction* (Vol. 33, p. 1). IAARC Publications.

Shan, J., & Toth, C. K. (2018). *Topographic laser ranging and scanning: principles and processing*. CRC press.

Smith, P. (2014). BIM implementation–global strategies. *Procedia Engineering, 85*, 482-492.

Snavely, N., Seitz, S. M., & Szeliski, R. (2008). Modeling the world from internet photo collections. *International Journal of Computer Vision, 80*(2), 189-210.

Son, H., Kim, C., & Turkan, Y. (2015). Scan-to-BIM-an overview of the current state of the art and a look ahead. ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction,

Sun, C., Jiang, S., Skibniewski, M. J., Man, Q., & Shen, L. (2017). A literature review of the factors limiting the application of BIM in the construction industry. *Technological and Economic Development of Economy, 23*(5), 764-779.

Tang, P., Huber, D., Akinci, B., Lipman, R., & Lytle, A. (2010). Automatic reconstruction of as-built building information models from laser-scanned point clouds: A review of related techniques. *Automation in construction, 19*(7), 829-843.

Teller, S., Antone, M., Bodnar, Z., Bosse, M., Coorg, S., Jethwa, M., & Master, N. (2003). Calibrated, registered images of an extended urban area. *International Journal of Computer Vision, 53*(1), 93-107.

CIA, E. (2021). The World Factbook 2021. Retrieved Aug 18, 2021, from, https://www.cia.gov/the-world-factbook/field/population-growth-rate/

Thomson, C., Apostolopoulos, G., Backes, D., & Boehm, J. (2013). Mobile laser scanning for indoor modelling. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci, 5*(W2), 66.

Turkan, Y., Bosche, F., Haas, C. T., & Haas, R. (2012). Automated progress tracking using 4D schedule and 3D sensing technologies. *Automation in construction, 22*, 414-421.

Turkan, Y., Bosché, F., Haas, C. T., & Haas, R. (2013). Toward automated earned value tracking using 3D imaging tools. *Journal of construction engineering and management*, *139*(4), 423-433.

UNEP. (2018). Global Satus Report.united nations environmentprogramme(UNEP).. Accessed on October 2020 at: https://www.unep.org/news-and-stories/press-release/buildings-and-construction-sector-huge-untapped-potential-emission
USGBC. (2016). Benefits of green building. *US Green Building Council, 1*.

USGC. (2020). Lidar Based Specification Online. *NGP Standards and Specifications.*

Volk, R., Stengel, J., & Schultmann, F. (2014). Building Information Modeling (BIM) for existing buildings—Literature review and future needs. *Automation in construction, 38*, 109-127.

Vosselman, G., & Maas, H.-G. (2010). *Airborne and terrestrial laser scanning*. CRC press.

Wang, J., Sun, W., Shou, W., Wang, X., Wu, C., Chong, H.-Y., Liu, Y., & Sun, C. (2015a). Integrating BIM and LiDAR for real-time construction quality control. *Journal of Intelligent & Robotic Systems, 79*(3-4), 417-432.

Wang, J., Xu, K., Liu, L., Cao, J., Liu, S., Yu, Z., & Gu, X. D. (2013). Consolidation of low-quality point clouds from outdoor scenes. Computer Graphics Forum,

Wang, J., Zhang, S., & Teizer, J. (2015b). Geotechnical and safety protective equipment planning using range point cloud data and rule checking in building information modeling. *Automation in construction, 49*, 250-261.

Wang, Q., & Kim, M.-K. (2019). Applications of 3D point cloud data in the construction industry: A fifteen-year review from 2004 to 2018. *Advanced Engineering Informatics, 39*, 306-319.

Wang, Q., Kim, M.-K., Cheng, J. C., & Sohn, H. (2016). Automated quality assessment of precast concrete elements with geometry irregularities using terrestrial laser scanning. *Automation in construction, 68*, 170-182.

Wang, Q., Sohn, H., & Cheng, J. C. (2018). Automatic as-built BIM creation of precast concrete bridge deck panels using laser scan data. *J. Comput. Civ. Eng, 32*(3), 04018011.

Wang, Q., Tan, Y., & Mei, Z. (2020). Computational methods of acquisition and processing of 3D point cloud data for construction applications. *Archives of Computational Methods in Engineering, 27*(2), 479-499.

Wang, X., Truijens, M., Hou, L., Wang, Y., & Zhou, Y. (2014). Integrating Augmented Reality with Building Information Modeling: Onsite construction process controlling for liquefied natural gas industry. *Automation in construction, 40*, 96-105.

Wang, Y., Chen, Q., Zhu, Q., Liu, L., Li, C., & Zheng, D. (2019). A survey of mobile laser scanning applications and key techniques over urban areas. *Remote Sensing, 11*(13), 1540.

Wu, B., Wan, A., Yue, X., & Keutzer, K. (2018). Squeezeseg: Convolutional neural nets with recurrent crf for real-time road-object segmentation from 3d lidar point cloud. 2018 IEEE International Conference on Robotics and Automation (ICRA),

Xiang, B., Yao, J., Lu, X., Li, L., Xie, R., & Li, J. (2018). Segmentation-based classification for 3D point clouds in the road environment. *International Journal of Remote Sensing, 39*(19), 6182-6212.

Xiong, X., Adan, A., Akinci, B., & Huber, D. (2013). Automatic creation of semantically rich 3D building models from laser scanner data. *Automation in construction, 31*, 325-337.

Yan, W. Y., Shaker, A., & El-Ashmawy, N. (2015). Urban land cover classification using airborne LiDAR data: A review. *Remote Sensing of Environment, 158*, 295-310.

Yang, L., Cheng, J. C., & Wang, Q. (2020). Semi-automated generation of parametric BIM for steel structures based on terrestrial laser scanning data. *Automation in construction, 112*, 103037.

Yu, B., Liu, H., Wu, J., Hu, Y., & Zhang, L. (2010). Automated derivation of urban building density information using airborne LiDAR data and object-based method. *Landscape and Urban Planning, 98*(3-4), 210-219.

Zhang, K., Yan, J., & Chen, S.-C. (2006). Automatic construction of building footprints from airborne LIDAR data. *IEEE Transactions on Geoscience and Remote Sensing, 44*(9), 2523-2533.

Zhou, Z., Goh, Y. M., & Li, Q. (2015). Overview and analysis of safety management studies in the construction industry. *Safety science, 72*, 337-350.

APPENDIX A

eProtocol
Office of the Vice President for Research
321 General Services Building - Campus Delivery 2011 eprotocol
TEL: (970) 491-1553

DATE:	March 19, 2021
TO:	Olbina, Svetlana, 1584 Cnstr Mgmt
	Karbasiahvazi, Ali, 1584 Cnstr Mgmt, Haller, Kristin, 1584 Cnstr Mgmt, Goodrum, Paul, 1584 Cnstr Mgmt
FROM:	Chromiak, Angie, Compliance Review Assistant Administrator, CSU IRB Exempt
PROTOCOL TITLE:	REALITY CAPTURE TECHNOLOGIES USE IN THE US CONSTRUCTION INDUSTRY
FUNDING SOURCE	None
PROTOCOL NUMBER:	21-10677H
APPROVAL or DETERMINATION PERIOD:	March 19, 2021

NOTICE OF IRB REVIEW FOR HUMAN RESEARCH

Thank you for submitting your application for exempt review to Colorado State University IRB (CSU) (FWA0000647). We appreciate the work you have done on your proposal. The IRB has reviewed your submitted IRB application and all ancillary materials. Upon review, the IRB has determined that the above-entitled project meets the requirements for exemption under the federal regulations 45 CFR 46.101 that govern the protections of human subjects, specifically .

Exempt studies are subject to the ethical principles articulated in The Belmont Report, found at the OHRP Website www.hhs.gov/ohrp/humansubjects/guidance/belmont.html.

Your research must be conducted according to the proposal that was submitted to the IRB. If changes to the approved protocol occur, a revised protocol must be reviewed and approved by the IRB before implementation. For any proposed changes in your research protocol, please submit an amendment to the IRB. Exempt determinations are active for five (5) years. Please be aware that changes to your protocol may change this determination for exemption from 45 CFR 46.101 and may require submission of a new IRB application or other materials to the IRB.

A goal of the IRB is to prevent negative occurrences during any research study. However, despite the best intent, unforeseen circumstances or events may arise during the research. If an unexpected situation or adverse event happens during your investigation, please notify the IRB as soon as possible. We will ask for a complete written explanation of the event and your written response. Other actions also may be required depending on the nature of the event.

Please refer to the protocol number denoted above in all communication or correspondence related to your application and this approval. Should you have additional questions or require clarification of the contents of this letter, please contact the IRB Office. On behalf of the IRB, we wish you success in this scholarly pursuit.

Please direct any questions about the IRB's actions on this project to:

IRB Office - (970) 491-1553; RICRO_IRB@mail.Colostate.edu
Claire Chance, Senior IRB Coordinator - (970) 491-1381; Claire.Chance@Colostate.edu
Tammy Felton-Noyle, Senior IRB Coordinator - (970) 491-1655; Tammy.Felton-Noyle@Colostate.edu

Chromiak, Angie

Initial exempt determination has been granted on March 19, 2021 to recruit with the approved recruitment and consent procedures. The above-referenced research activity has been reviewed and determined to meet exempt review by the Institutional Review Board under exempt §46.104(d)(2)(i) of the 2018 Requirements. This study has no funding. Approved documents include: Methodology; Consent for Participation in Research; Consent for Participation in Research-Rev01; Follow-up Email; Questionnaire-Rev01; Invitation Email; Questionnaire.

APPENDIX B

Data Coding Instruction	
Variable	Assigned Value
Yes	1
No	2
Not Sure	3
Strongly disagree	1
Somewhat disagree	2
Neither agree nor disagree	3
Somewhat agree	4
Strongly agree	5
No Influence	1
Slight Influence	2
Moderate Influence	3
Strong Influence	4
Extremely Strong Influence	5
Owner/Developer	1
Architecture	2
Engineering	2
General Contracting	3
Subcontracting/Specialty Trade Contracting	3
CM & Owner Representative	4
Designer	2
Commercial Building (Mixed-Use, Multi-Family, Healthcare, Education, etc.)	1

APPENDIX C

Survey Instrument- through Qualtrics.com

Note: The author acknowledges Svetlana Olbina and Jonathan W Elliot as the authors of the questionnaire for this study.

Start of Block: ALL - INFORMED CONSENT

IC1
Dear Participant,

My name is Ali Karbasiahvazi and I am the Co-Principal Investigator on a research study in the Department of Construction Management at Colorado State University (CSU). We are conducting a research study exploring the "**Use of Reality Capture Technologies in the US Construction Industry**". This study investigates how Reality Capture technologies are being implemented, and how effective they are for tasks performed across the construction project lifecycle. In addition, we are seeking your experience and perspectives regarding what factors influence implementation, what benefits are realized, and what obstacles exist hindering the adoption of Reality Capture technologies on construction projects. The Principal Investigator in the research study is Dr. Svetlana Olbina.

If you are willing to do so, we would like you to take an anonymous online survey. Participation will take approximately 10-20 minutes. Your participation in this research is voluntary. If you decide to participate in the study, you may withdraw your consent and stop participation at any time without penalty. We will not collect your name or personal identifiers. When we report and share the data with others, we will combine the data from multiple participants and only publish results in an aggregated form. There are no known risks or direct benefits to you, but with your input, we hope to gain knowledge about the current applications of Reality Capture technologies in the construction industry.

Thank you for your time, we appreciate your participation.

Ali Karbasiahvazi
and
Dr. Svetlana Olbina

If you have any questions about this research, please contact Ali Karbasiahvazi (Ali.Karbasiahvazi@colostate.edu) or Dr. Svetlana Olbina (Svetlana.Olbina@colostate.edu)

If you have any questions about your rights as a volunteer in this research, please contact the CSU IRB at RICRO_IRB@mail.colostate.edu; 970-491-1553.

IC2 Do you consent to participate in this survey?

○ Yes (1)

○ No (2)

Skip To: End of Survey If Do you consent to participate in this survey? = No

End of Block: ALL - INFORMED CONSENT

Start of Block: ALL - DEFINITIONS

DEF1 **Definition of 'Reality Capture' for this study:**

For this study, Reality Capture is defined as the process of collecting surface data points to produce a digital 3D depiction of an existing object, building, structure or site using static, mobile or aerial laser scanning (LiDAR) and/or photogrammetry equipment. With either laser scanning (LiDAR) or photogrammetry methods, surfaces are measured and mapped to develop a textured, high-resolution, geometrically precise 3D representation of an object (Autodesk, 2021).

This study focuses specifically on the collection of spatial data (e.g., point clouds, photo meshes, etc.) for buildings, structures and/or the surrounding project sites for use during the project lifecycle.

End of Block: ALL - DEFINITIONS

Start of Block: ALL PARTICIPANT QUESTIONS

*

PAR1 Approximately how many years (round up to nearest whole year) have you worked in the Architecture, Engineering, Construction, and/or Operation and Maintenance industry?

____

PAR2 What is your current job title?

____

PAR3 In which state(s) do you work most often?

____

End of Block: ALL PARTICIPANT QUESTIONS

Start of Block: ALL - STAKEHOLDER AND SEGMENT

SEG1 Which of the choices below best describes your role on a 'typical' construction/development project?

- ◯ Owner/Developer (1)
- ◯ Architecture (2)
- ◯ Engineering (3)
- ◯ General Contracting (4)
- ◯ Subcontracting/Specialty Trade Contracting (5)
- ◯ Facilities Management (6)
- ◯ Modular Construction Manufacturing (7)
- ◯ Other (i.e., Other Design Consultant, Design Build, etc.) Please Specify: (8)

____

Skip To: End of Block If Which of the choices below best describes your role on a 'typical' construction/development project? = Facilities Management

Display This Question:

If Which of the choices below best describes your role on a 'typical' construction/development project? = Subcontracting/Specialty Trade Contracting

*

SEG1.1 What is your subcontracting company's trade or specialty?

____

Page Break

SEG2 Which of the following best describes your company's **PRIMARY** market sector?

○ Commercial Building (Mixed-Use, Multi-Family, Healthcare, Education, etc.) (1)

○ Infrastructure (Civil, Industrial, Utilities, Chemical Processing, etc.) (4)

○ Single Family Residential (5)

○ Other (Please Specify): (6) ____

Display This Question:

If Which of the following best describes your company's PRIMARY market sector? = Commercial Building (Mixed-Use, Multi-Family, Healthcare, Education, etc.)

SEG2.1 Have you/your company used reality capture technologies on the following projects types?'

	Yes (1)	No (2)
Core and Shell Buildings (1)	○	○
Multi-Family Residential (3)	○	○
Retail (5)	○	○
Mixed-Use (6)	○	○
Education (7)	○	○
Healthcare (9)	○	○
Interiors/Tenant Fit Out (10)	○	○
Other (Please Specify): (12)	○	○

Display This Question:

If Which of the following best describes your company's PRIMARY market sector? = Infrastructure (Civil, Industrial, Utilities, Chemical Processing, etc.)

Q115 Have you/your company used reality capture technologies on the following projects types?'

	Yes (1)	No (2)
Roads (1)	○	○
Bridges (3)	○	○
Utilities (6)	○	○
Renewable Energy (9)	○	○
Chemical/Petrochemical Processing (10)	○	○
Mining (11)	○	○
Oil and Gas Processing (12)	○	○
Other (Please Specify): (13)	○	○

Page Break

SEG3 What is your company's approximate total annual revenue?
Please enter a number WITHOUT a $ symbol, **i.e. 15,000,000**

____

End of Block: ALL - STAKEHOLDER AND SEGMENT

Start of Block: ALL - GEN PERCEPT & REALITY CAPTURE EXP

RCE1 Have you heard of Reality Capture technologies such as LiDAR/Laser Scanning and Photogrammetry?

○ Yes (1)

○ No (2)

Skip To: End of Survey If Have you heard of Reality Capture technologies such as LiDAR/Laser Scanning and Photogrammetry? = No

RCE2 Do you, personally, have work-related experience using Reality Capture technologies?

○ Yes (1)

○ No (2)

RCE3 Does your company have experience using Reality Capture technologies?

○ Yes (1)

○ No (2)

○ Not Sure (3)

Page Break

RCE0 Please provide your level of agreement with the following statements. Reality Capture technologies provide benefits during ____________________________.

	Strongly disagree (9)	Somewhat disagree (10)	Neither agree nor disagree (11)	Somewhat agree (12)	Strongly agree (13)
New construction projects (2)	o	o	o	o	o
Addition, renovation or maintenance projects (3)	o	o	o	o	o
The design/preconstruction phase of a project (14)	o	o	o	o	o
The construction/fabrication phase of a project (15)	o	o	o	o	o
The operation and maintenance phase of a project (16)	o	o	o	o	o

Page Break

End of Block: ALL - GEN PERCEPT & REALITY CAPTURE EXP

Start of Block: COM/HCE/SFR PERCEIVED BENEFITS

Page Break

CHSPB1 Please provide your level of agreement with the following statements. The use of Reality Capture technologies on a project could bring the following **benefits**:

	Strongly disagree (1)	Somewhat disagree (2)	Neither agree nor disagree (3)	Somewhat agree (4)	Strongly agree (5)
Reduced rework during design (1)	o	o	o	o	o
Reduced number of site visits to collect data (2)	o	o	o	o	o
Reduced time required to generate 3D models (3)	o	o	o	o	o
Reduced overall project cost (4)	o	o	o	o	o
Reduced project duration (5)	o	o	o	o	o
Reduced project risk (6)	o	o	o	o	o
Reduced time required for quality assurance processes (7)	o	o	o	o	o
Reduced time required for quality control processes (8)	o	o	o	o	o
Reduced time required to document existing conditions (9)	o	o	o	o	o
Reduced rework to correct errors in the field (10)	o	o	o	o	o

Increased accuracy of existing condition documentation (11)	○	○	○	○	○
Increased accuracy of construction documents (12)	○	○	○	○	○
Increased accuracy of installed work (13)	○	○	○	○	○
Increased accuracy of the as-built documents (14)	○	○	○	○	○
Increased speed of as-built document creation (15)	○	○	○	○	○
Increased accuracy of surveying/layout (16)	○	○	○	○	○
Increased speed of surveying/layout (17)	○	○	○	○	○
Increased accuracy of the constructed system locations (18)	○	○	○	○	○
Increased speed of installation of constructed elements (19)	○	○	○	○	○
Increased accuracy of prefabricated elements (20)	○	○	○	○	○

Increased construction quality (21)	○	○	○	○	○

CHSPB2 If there are **benefits** of using Reality Capture technologies on a project that you would like to add to the list above, please do so below:

____

____

____

____

____

End of Block: COM/HCE/SFR PERCEIVED BENEFITS

Start of Block: COM/HCE/SFR PERCEIVED OBSTACLES

CHSPO1 Please provide your level of agreement with the following statements.

The following **obstacles** prevent the adoption/or wider adoptions of Reality Capture technologies:

	Strongly disagree (21)	Somewhat disagree (22)	Neither agree nor disagree (23)	Somewhat agree (24)	Strongly agree (25)
It is not a company priority (1)	◯	◯	◯	◯	◯
Not important for the projects I work on (2)	◯	◯	◯	◯	◯
Lack of Owner/Client demand (3)	◯	◯	◯	◯	◯
Lack of company budget (4)	◯	◯	◯	◯	◯
Lack of project-level budget (5)	◯	◯	◯	◯	◯
Cannot bill Reality Capture costs to my projects (6)	◯	◯	◯	◯	◯
Cannot justify the return on investment (7)	◯	◯	◯	◯	◯
The equipment is expensive (8)	◯	◯	◯	◯	◯
The equipment is not user-friendly (9)	◯	◯	◯	◯	◯
The related software is expensive (10)	◯	◯	◯	◯	◯
The related software is not user-friendly (11)	◯	◯	◯	◯	◯

Lack of software interoperability (12)	○	○	○	○	○
Data collection is too time consuming (13)	○	○	○	○	○
Data processing is too time consuming (14)	○	○	○	○	○
Lack of in-house expertise (15)	○	○	○	○	○
Cost of hiring employees with the required skills (16)	○	○	○	○	○
Lack of training (17)	○	○	○	○	○
No time for training (18)	○	○	○	○	○
Risk/liability concerns (19)	○	○	○	○	○

CHSPO2 If there are **obstacles** to the adoption/or wider adoptions of Reality Capture technologies that you would like to add to the list above, please do so below:

____

____

____

____

____

End of Block: COM/HCE/SFR PERCEIVED OBSTACLES

Start of Block: FM - PERCIEVED BENEFITS

FMPB1
Do you believe that Reality Capture Technologies could be valuable for Facilities Management?

○ Yes (1)

○ No (2)

Skip To: End of Block If Do you believe that Reality Capture Technologies could be valuable for Facilities Management? = No

FMPB2 Please provide your level of agreement with the following statements.

The use of Reality Capture technologies could bring the following **benefits** to Facilities Management:

	Strongly disagree (1)	Somewhat disagree (2)	Neither agree nor disagree (3)	Somewhat agree (4)	Strongly agree (5)
Reduced time required to document building conditions (1)					
Reduced number of visits to collect information (2)					
Reduced measurement error in the field (6)					
Reduced time to document work completed (8)					
Reduced rework to correct errors in the field (10)					
Increased accuracy of building documentation (11)					
Increased accuracy of site documentation (12)					
Increased accuracy of the as-built documentation (14)					
Increased speed of as-built document creation (15)					

Increased accuracy of assets documentation (18)	○	○	○	○	○
Increased speed of assets documentation (24)	○	○	○	○	○

FMPB3 If there are benefits of **Reality Capture technologies in Facilities Management** that you would like to add to the list above, please do so below:

____

____

____

____

____

End of Block: FM - PERCIEVED BENEFITS

Start of Block: FM - PERCIEVED OBSTACLES

FMPO1 Please provide your level of agreement with the following statements.

The following **obstacles** prevent the adoption/or wider adoptions of **Reality Capture technologies in Facilities Management**:

	Strongly disagree (16)	Somewhat disagree (17)	Neither agree nor disagree (18)	Somewhat agree (19)	Strongly agree (20)
Minimal return on investment (1)	○	○	○	○	○
Line of site documentation does not help me (2)	○	○	○	○	○
Lack of budget (4)	○	○	○	○	○
The equipment is expensive (8)	○	○	○	○	○
The equipment is not user-friendly (9)	○	○	○	○	○
The related software is expensive (10)	○	○	○	○	○
The related software is not user-friendly (11)	○	○	○	○	○
Lack of software interoperability (12)	○	○	○	○	○
Data collection is too time consuming (13)	○	○	○	○	○
Data processing is too time consuming (14)	○	○	○	○	○
Lack of in-house expertise (15)	○	○	○	○	○

Cost of hiring employees with the required skills (16)	○	○	○	○	○
Lack of training (17)	○	○	○	○	○
No time for training (18)	○	○	○	○	○

FMPO2 If there are **obstacles** to the adoption/or wider adoptions of Reality Capture technologies in Facilities Management that you would like to add to the list above, please do so below:

____

____

____

____

____

End of Block: FM - PERCIEVED OBSTACLES

Start of Block: FM - FACTORS

FMFAC1 To what extent the following **factors influence** the decision to use Reality Capture technologies for Facilities Management?

	No Influence (1)	Slight Influence (2)	Moderate Influence (3)	Strong Influence (4)	Extremely Strong Influence (5)
Owner/client requested (1)	○	○	○	○	○
Provided as part of the construction documentation (2)	○	○	○	○	○
Budget for Facilities Management Tasks (3)	○	○	○	○	○
FM involvement in design/construction phase (4)	○	○	○	○	○
The Facilities Manager's skillset (9)	○	○	○	○	○
Preparing for an upcoming renovation (12)	○	○	○	○	○
Facility/Building Type (13)	○	○	○	○	○
Liability/risk exposure (17)	○	○	○	○	○
Existence of As-built documents (19)	○	○	○	○	○
Accuracy of As-built documents (23)	○	○	○	○	○

FMFAC2 If there are **factors** that **influence** your company's decision to use Reality Capture technologies for Facilities Management that you would like to add to the list above, please do so below:

____

____

____

____

____

End of Block: FM - FACTORS

Start of Block: FM - USE AND EFFECTIVENESS

Q105 Based on your/your firm's **Facilities Management experience** indicate how **effective** Reality Capture technologies are for the following tasks:

*If you HAVE NOT use Reality Capture for the tasks please check the "NOT USED FOR THIS TASK" box on the right side of the screen

	NOT EFFECTIVE AT ALL	**EXTREMELY EFFECTIVE**	Not used for this task
	0 10 20 30 40 50 60 70 80 90 100		
Documenting facility conditions ()			
Documenting fixed/permanent assets ()			
Documenting moveable assets ()			
Obtaining facility measurements/dimensions ()			
Verifying facility measurement/dimensions ()			
Facilitating 3D model creation ()			
Facilitating 2D documents creation ()			
Preparing for a facility renovation or addition ()			
Controlling/Mitigating Risk ()			

Q106 Are there other Facilities Management tasks that Reality Capture technologies are **effective** for that you would like to add? If so, list below:

End of Block: FM - USE AND EFFECTIVENESS

Start of Block: FM - REALIZED BENEFITS

FMRB1 Please provide your level of agreement with the following statements.

The below **benefits** of Reality Capture technologies were **realized** on my Facilities Management project(s):

	Strongly disagree (1)	Somewhat disagree (2)	Neither agree nor disagree (3)	Somewhat agree (4)	Strongly agree (5)
Reduced time required to document building conditions (1)	○	○	○	○	○
Reduced number of visits to collect information (2)	○	○	○	○	○
Reduced measurement error in the field (6)	○	○	○	○	○
Reduced time to document work completed (8)	○	○	○	○	○
Reduced rework to correct errors in the field (10)	○	○	○	○	○
Increased accuracy of building documentation (11)	○	○	○	○	○
Increased accuracy of site documentation (12)	○	○	○	○	○
Increased accuracy of the as-built documentation (14)	○	○	○	○	○
Increased speed of as-built document creation (15)	○	○	○	○	○

Increased accuracy of assets documentation (18)	○	○	○	○	○
Increased speed of assets documentation (24)	○	○	○	○	○

FMRB2 Were there other **realized benefits** of Reality Capture technologies in Facilities Management that you would like to add to the list above?

____

____

____

____

____

End of Block: FM - REALIZED BENEFITS

Start of Block: FM - REALIZED OBSTACLES

FMRO1
Please provide your level of agreement with the following statements.

The following **obstacles** prevented the adoption/or wider adoptions of Reality Capture technologies in Facilities Management:

	Strongly disagree (16)	Somewhat disagree (17)	Neither agree nor disagree (18)	Somewhat agree (19)	Strongly agree (20)
Minimal return on investment (1)	○	○	○	○	○
Line of site documentation does not help me (2)	○	○	○	○	○
Lack of budget (4)	○	○	○	○	○
The equipment is expensive (8)	○	○	○	○	○
The equipment is not user-friendly (9)	○	○	○	○	○
The related software is expensive (10)	○	○	○	○	○
The related software is not user-friendly (11)	○	○	○	○	○
Lack of software interoperability (12)	○	○	○	○	○
Data collection is too time consuming (13)	○	○	○	○	○
Data processing is too time consuming (14)	○	○	○	○	○
Lack of in-house expertise (15)	○	○	○	○	○

Cost of hiring employees with the required skills (16)	○	○	○	○	○
Lack of training (17)	○	○	○	○	○
No time for training (18)	○	○	○	○	○

RMRO2 If there are **obstacles** that prevented the adoption/or wider adoptions of Reality Capture technologies in Facilities Management that you would like to add to the list above, please do so below:

____

____

____

____

____

End of Block: FM - REALIZED OBSTACLES

Start of Block: HCE - FACTORS

HCEF1 To what extent do the following **factors influence** the decision to use Reality Capture technologies on a Infrastructure/Civil/Industrial P**roject**?

	No Influence (1)	Slight Influence (2)	Moderate Influence (3)	Strong Influence (4)	Extremely Strong influence (5)
Owner/client requested (1)	○	○	○	○	○
Project monetary value (2)	○	○	○	○	○
Project delivery method (3)	○	○	○	○	○
Early project phase involvement (4)	○	○	○	○	○
Project duration (5)	○	○	○	○	○
Project budget (6)	○	○	○	○	○
Amount of "verify in field" data required (7)	○	○	○	○	○
Amount of prefabricated components (8)	○	○	○	○	○
Employee/Project team skillset (9)	○	○	○	○	○
Demolition scope of work (10)	○	○	○	○	○
Renovation scope of work (11)	○	○	○	○	○
Addition to existing structure (12)	○	○	○	○	○
Project complexity (13)	○	○	○	○	○
Project site size (14)	○	○	○	○	○

Proximity to other structures (16)	○	○	○	○	○
Liability/risk exposure (17)	○	○	○	○	○
Rigorous quality standard/tight tolerances (18)	○	○	○	○	○
Level of data accuracy required (19)	○	○	○	○	○
Level of as-built data required (20)	○	○	○	○	○
Need for operation and maintenance data (21)	○	○	○	○	○

HCEF2 If there are factors that influence the decision to use Reality Capture technologies on a Infrastructure/Civil/Industrial Project that you would like to add to the list above, please do so below:

____

____

____

____

____

End of Block: HCE - FACTORS

Start of Block: HCE - REALIZED BENEFITS AND OBSTACLES

Q46 Based on your experience with Infrastructure/Civil/Industrial Project, rate your level of agreement with the following **realized benefits** of using Reality Capture technologies?

	Strongly disagree (1)	Somewhat disagree (2)	Neither agree nor disagree (3)	Somewhat agree (4)	Strongly agree (5)
Reduced rework during design (1)	○	○	○	○	○
Reduced the number of site visits to collect data (2)	○	○	○	○	○
Reduced time required to generate 3D models (3)	○	○	○	○	○
Reduced overall project cost (4)	○	○	○	○	○
Reduced project duration (5)	○	○	○	○	○
Reduced project risk (6)	○	○	○	○	○
Reduced time required for quality assurance processes (7)	○	○	○	○	○
Reduced time required for quality control processes (8)	○	○	○	○	○
Reduced time required to document existing conditions (9)	○	○	○	○	○
Reduced rework to correct errors in the field (10)	○	○	○	○	○

Increased accuracy of existing condition documentation (11)	○	○	○	○	○
Increased accuracy of construction documents (12)	○	○	○	○	○
Increased accuracy of installed work (13)	○	○	○	○	○
Increased accuracy of the as-built documents (14)	○	○	○	○	○
Increased speed of as-built document creation (15)	○	○	○	○	○
Increased accuracy of surveying/layout (16)	○	○	○	○	○
Increased speed of surveying/layout (17)	○	○	○	○	○
Increased accuracy of the constructed system locations (18)	○	○	○	○	○
Increased speed of installation of constructed elements (19)	○	○	○	○	○
Increased accuracy of prefabricated elements (20)	○	○	○	○	○

Increased construction quality (21)	○	○	○	○	○

Q81 If there are **benefits** of using Reality Capture technologies in Infrastructure/Civil/Industrial Project that you would like to add to the list above, please do so below:

____

Page Break

Q47 Based on your experience on Infrastructure/Civil/Industrial Project**,** rate your level of agreement with the following **obstacles** to the adoption/or wider adoptions of Reality Capture technologies:

	Strongly disagree (11)	Somewhat disagree (12)	Neither agree nor disagree (13)	Somewhat agree (14)	Strongly agree (15)
It is not a company priority (1)	○	○	○	○	○
Not important for the projects I work on (2)	○	○	○	○	○
Lack of Owner/Client demand (3)	○	○	○	○	○
Lack of company budget (4)	○	○	○	○	○
Lack of project-level budget (5)	○	○	○	○	○
Cannot bill Reality Capture costs to my projects (6)	○	○	○	○	○
Cannot justify the return on investment (7)	○	○	○	○	○
The equipment is expensive (8)	○	○	○	○	○
The equipment is not user-friendly (9)	○	○	○	○	○
The related software is expensive (10)	○	○	○	○	○
The related software is not user-friendly (11)	○	○	○	○	○

Lack of software interoperability (12)	○	○	○	○	○
Data collection is too time consuming (13)	○	○	○	○	○
Data processing is too time consuming (14)	○	○	○	○	○
Lack of in-house expertise (15)	○	○	○	○	○
Cost of hiring employees with the required skills (16)	○	○	○	○	○
Lack of training (17)	○	○	○	○	○
No time for training (18)	○	○	○	○	○
Risk/liability concerns (19)	○	○	○	○	○

Q83 If there are **obstacles** to the adoption/or wider adoptions of Reality Capture technologies in Infrastructure/Civil/Industrial Project that you would like to add to the list above, please do so below:

____

End of Block: HCE - REALIZED BENEFITS AND OBSTACLES

Start of Block: HCE NEW - USE/EFFECTIVENESS BY PHASE

Q39 Do you/your company use Reality Capture technologies on
New Infrastructure/Civil/Industrial Projects?

◯ Yes (1)

◯ No (2)

Page Break

Q40 Have you, or your company, used Reality Capture technologies during the **Design and/or Preconstruction** phase of a New Infrastructure/Civil/Industrial Project?

◯ Yes (1)

◯ No (2)

Skip To: Q42 If Have you, or your company, used Reality Capture technologies during the Design and/or Preconstruc... = No

Q41 Based on your/your firm's experience during the **Design and Preconstruction Phase** of a New Infrastructure/Civil/Industrial Project, indicate how **Effective** Reality Capture technologies are for the following tasks:

*If you HAVE NOT use Reality Capture for the tasks please check the "NOT USED FOR THIS TASK" box on the right side of the screen

	NOT EFFECTIVE AT ALL	EXTREMELY EFFECTIVE	Not used for this task
	0 10 20 30 40 50 60 70 80 90 100		
Documenting existing condition ()			
Obtaining field measurements ()			
Verifying field measurements ()			
Facilitating 3D model creation ()			
Facilitating 2D documents creation ()			
Facilitating virtual/mixed/augmented reality applications ()			
Quantifying materials ()			
Project visualization ()			
Understanding of the project scope ()			
Assuring Project Quality ()			
Controlling Project Quality ()			
Controlling Project Risk ()			
Mitigating Project Risk ()			
Other: (Please specify) ()			

Page Break

Q42 Have you, or your company, used Reality Capture technologies during the **Construction or Fabrication phase** of a New Infrastructure/Civil/Industrial Project?

○ Yes (1)

○ No (2)

Skip To: End of Block If Have you, or your company, used Reality Capture technologies during the Construction or Fabricati... = No

Page Break

Q43 Based on your/your firm's experience during the **Construction or Fabrication Phase** of a New Infrastructure/Civil/Industrial Project, indicate how **Effective** Reality Capture technologies are for the following tasks:

*If you HAVE NOT use Reality Capture for the tasks please check the "NOT USED FOR THIS TASK" box on the right side of the screen

	NOT EFFECTIVE AT ALL	EXTREMELY EFFECTIVE	Not used for this task
	0 10 20 30 40 50 60 70 80 90 100		
Obtaining measurements for prefabrication/off-site fabrication ()			
Obtaining measurements for field use during construction ()			
Increasing efficiency of surveying and field layout ()			
Establishing the location of constructed systems ()			
Establishing the location of prefabricated elements ()			
Establishing the location of utility components and systems ()			
Documenting work-in-place/as-built conditions ()			
Documenting project progress ()			
Documenting work before it is not visible (e.g. reinforcing before pour) ()			
Documenting materials stored on site ()			
Comparing completed work to design requirements ()			
Verification of Construction Quality ()			
Completing Construction inspections ()			
Other: (Please specify) ()			

End of Block: HCE NEW - USE/EFFECTIVENESS BY PHASE

Start of Block: HCE MAT - USE /EFFECTIVENESS BY PHASE

Q110 Do you/your company use Reality Capture technologies on Infrastructure/Civil/Industrial **Maintenance** Projects?

○ Yes (1)

○ No (2)

Skip To: End of Block If Do you/your company use Reality Capture technologies on Infrastructure/Civil/Industrial Maintenan... = No

Q112 Based on your/your firm's experience during Infrastructure/Civil/Industrial Maintenance Project, indicate how **effective** Reality Capture technologies are for the following **tasks**:

*If you HAVE NOT use Reality Capture for the tasks please check the "NOT USED FOR THIS TASK" box on the right side of the screen

	NOT EFFECTIVE AT ALL	EXTREMELY EFFECTIVE	Not used for this task
	0 10 20 30 40 50 60 70 80 90 100		
Documenting existing condition ()			
Obtaining field measurements ()			
Verifying field measurements ()			
Obtaining measurements for prefabrication/off-site fabrication ()			
Facilitating 3D model creation ()			
Facilitating 2D documents creation ()			
Facilitating virtual/mixed/augmented reality applications ()			
Quantifying materials ()			
Project visualization ()			
Understanding of the project scope ()			
Assuring Project Quality ()			
Controlling Project Quality ()			
Controlling Project Risk ()			
Mitigating Project Risk ()			
Other: (Please specify) ()			

End of Block: HCE MAT - USE /EFFECTIVENESS BY PHASE

Start of Block: COM/SFR - FACTORS

Q11 To what extent the following **factors influence** the decision to use Reality Capture technologies on a project?

	No Influence (1)	Slight Influence (2)	Moderate Influence (3)	Strong Influence (4)	Extremely Strong influence (5)
Owner/client requested (1)	○	○	○	○	○
Project monetary value (2)	○	○	○	○	○
Project delivery method (3)	○	○	○	○	○
Early project phase involvement (4)	○	○	○	○	○
Project duration (5)	○	○	○	○	○
Project budget (6)	○	○	○	○	○
Amount of "verify in field" data required (7)	○	○	○	○	○
Amount of prefabricated components (8)	○	○	○	○	○
Employee/Project team skillset (9)	○	○	○	○	○
Demolition scope of work (10)	○	○	○	○	○
Renovation scope of work (11)	○	○	○	○	○
Addition to existing structure (12)	○	○	○	○	○
Project complexity (13)	○	○	○	○	○
Project site size (14)	○	○	○	○	○

Proximity to other structures (16)	○	○	○	○	○
Liability/risk exposure (17)	○	○	○	○	○
Rigorous quality standard/tight tolerances (18)	○	○	○	○	○
Level of as-built data required (20)	○	○	○	○	○
Need for operation and maintenance data (21)	○	○	○	○	○

Q95 If there are factors that influence the decision to use Reality Capture technologies on a project that you would like to add to the list above, please do so below:

____

____

____

____

____

End of Block: COM/SFR - FACTORS

Start of Block: COM - REALIZED BENEFITS/OBSTACLES

Q29 Based on your **commercial building construction experience**, rate your level of agreement with the following **realized benefits** of using Reality Capture technologies?

	Strongly disagree (1)	Somewhat disagree (2)	Neither agree nor disagree (3)	Somewhat agree (4)	Strongly agree (5)
Reduced rework during design (1)	○	○	○	○	○
Reduced number of site visits to collect data (2)	○	○	○	○	○
Reduced time required to generate 3D models (3)	○	○	○	○	○
Reduced overall project cost (4)	○	○	○	○	○
Reduced project duration (5)	○	○	○	○	○
Reduced project risk (6)	○	○	○	○	○
Reduced time required for quality assurance processes (7)	○	○	○	○	○
Reduced time required for quality control processes (8)	○	○	○	○	○
Reduced time required to document existing conditions (9)	○	○	○	○	○
Reduced rework to correct errors in the field (10)	○	○	○	○	○

Increased accuracy of existing condition documentation (11)	○	○	○	○	○
Increased accuracy of construction documents (12)	○	○	○	○	○
Increased accuracy of installed work (13)	○	○	○	○	○
Increased accuracy of the as-built documents (14)	○	○	○	○	○
Increased speed of as-built document creation (15)	○	○	○	○	○
Increased accuracy of surveying/layout (16)	○	○	○	○	○
Increased speed of surveying/layout (17)	○	○	○	○	○
Increased accuracy of the constructed system locations (18)	○	○	○	○	○
Increased speed of installation of constructed elements (19)	○	○	○	○	○
Increased accuracy of prefabricated elements (20)	○	○	○	○	○

Increased construction quality (21)	○	○	○	○	○

Q87 If there are **benefits** of using Reality Capture technologies in **Commercial Projects** that you would like to add to the list above, please do so below:

____

Page Break

Q33 Based on your commercial building construction experience**,** rate your level of agreement with the following **obstacles** to the adoption/or wider adoptions of Reality Capture technologies:

	Strongly disagree (11)	Somewhat disagree (12)	Neither agree nor disagree (13)	Somewhat agree (14)	Strongly agree (15)
It is not a company priority (1)					
Not important for the projects I work on (2)					
Lack of Owner/Client demand (3)					
Lack of company budget (4)					
Lack of project-level budget (5)					
Cannot bill Reality Capture costs to my projects (6)					
Cannot justify the return on investment (7)					
The equipment is expensive (8)					
The equipment is not user-friendly (9)					
The related software is expensive (10)					
The related software is not user-friendly (11)					

Lack of software interoperability (12)	○	○	○	○	○
Data collection is too time consuming (13)	○	○	○	○	○
Data processing is too time consuming (14)	○	○	○	○	○
Lack of in-house expertise (15)	○	○	○	○	○
Cost of hiring employees with the required skills (16)	○	○	○	○	○
Lack of training (17)	○	○	○	○	○
No time for training (18)	○	○	○	○	○
Risk/liability concerns (19)	○	○	○	○	○

Q88 If there are **obstacles** to the adoption/or wider adoptions of Reality Capture technologies in **Construction Projects** that you would like to add to the list above, lease do so below:

____

End of Block: COM - REALIZED BENEFITS/OBSTACLES

Start of Block: COM NEW - USE/EFFECTIVENESS BY PHASE

Q20 Do you/your company use Reality Capture technologies on **New Construction Projects**?

◯ Yes (1)

◯ No (2)

Skip To: End of Block If Do you/your company use Reality Capture technologies on New Construction Projects? = No

Page Break

Q21 Have you, or your company, used Reality Capture technologies during the **Design and/or Preconstruction** phase of a New Construction Project?

◯ Yes (1)

◯ No (2)

Skip To: Q23 If Have you, or your company, used Reality Capture technologies during the Design and/or Preconstruc... = No

Page Break

Q22 Based on your/your firm's experience during the **Design and/or Preconstruction Phase of a New Construction Project**, indicate how **effective** Reality Capture technologies are for the following tasks:

*If you HAVE NOT use Reality Capture for the tasks please check the "NOT USED FOR THIS TASK" box on the right side of the screen

	NOT EFFECTIVE AT ALL	**EXTREMELY EFFECTIVE**	Not used for this task
	0 10 20 30 40 50 60 70 80 90 100		
Documenting existing condition ()			
Obtaining field measurements ()			
Verifying field measurements ()			
Obtaining measurements for prefabrication/off-site fabrication ()			
Facilitating 3D model creation ()			
Facilitating 2D documents creation ()			
Facilitating virtual/mixed/augmented reality applications ()			
Quantifying materials ()			
Project visualization ()			
Understanding of the project scope ()			
Assuring Project Quality ()			
Controlling Project Quality ()			
Controlling/Mitigating Project Risk ()			
Other: (Please specify) ()			

Page Break

Q23 Have you, or your company, used Reality Capture technologies during the **Construction and/or Fabrication** phase of a **New Construction Project**?

○ Yes (1)

○ No (2)

Skip To: End of Block If Have you, or your company, used Reality Capture technologies during the Construction and/or Fabri... = No

Page Break

Q25 Based on your/your firm's experience during the **Construction and/or Fabrication Phase of a New Construction Project**, indicate how **effective** Reality Capture technologies are for the following tasks:

*If you HAVE NOT use Reality Capture for the tasks please check the "NOT USED FOR THIS TASK" box on the right side of the screen

	NOT EFFECTIVE AT ALL	**EXTREMELY EFFECTIVE**	NOT USED FOR THIS TASK
	0 10 20 30 40 50 60 70 80 90 100		
Obtaining measurements for prefabrication/off-site fabrication ()			
Obtaining measurements for field use during construction ()			
Increasing efficiency of surveying and field layout ()			
Establishing the location of constructed systems ()			
Establishing the location of prefabricated elements ()			
Establishing the location of mechanical, electrical, and/or plumbing systems ()			
Documenting work-in-place/as-built conditions ()			
Documenting project progress ()			
Documenting work before it is not visible (e.g. reinforcing before pour) ()			
Documenting materials stored on site ()			
Comparing completed work to design requirements ()			
Verification of Construction Quality ()			
Completing Construction inspections ()			
Other: (Please specify) ()			

End of Block: COM NEW - USE/EFFECTIVENESS BY PHASE

Start of Block: COM RENO - USE/EFFECTIVENESS BY PHASE

Q31 Do you/your company use Reality Capture technologies on **Addition, Renovation and/or Interior Fit-Out Projects**?

- Yes (1)
- No (2)

Skip To: End of Block If Do you/your company use Reality Capture technologies on Addition, Renovation and/or Interior Fit-... = No

Page Break

Q32 Have you, or your company, used Reality Capture technologies during the **Design and/or Preconstruction** phase of **A**ddition, Renovation and/or Interior Fit-Out Project?

- Yes (1)
- No (2)

Skip To: Q34 If Have you, or your company, used Reality Capture technologies during the Design and/or Preconstruc... = No

Page Break

Q33 Based on your/your firm's experience during the **Design and/or Preconstruction Phase of Addition, Renovation and/or Interior Fit-Out Project**, indicate how **effective** Reality Capture technologies are for the following tasks:

*If you HAVE NOT use Reality Capture for the tasks please check the "NOT USED FOR THIS TASK" box on the right side of the screen

	NOT EFFECTIVE AT ALL	EXTREMELY EFFECTIVE	Not used for this task
	0 10 20 30 40 50 60 70 80 90 100		
Documenting existing condition ()			
Obtaining field measurements ()			
Verifying field measurements ()			
Obtaining measurements for prefabrication/off-site fabrication ()			
Facilitating 3D model creation ()			
Facilitating 2D documents creation ()			
Facilitating virtual/mixed/augmented reality applications ()			
Quantifying materials ()			
Project visualization ()			
Understanding of the project scope ()			
Assuring Project Quality ()			
Controlling Project Quality ()			
Controlling/Mitigating Project Risk ()			
Other: (Please specify) ()			

Page Break

Q34 Have you, or your company, used Reality Capture technologies during the **Construction and/or Fabrication** phase of Addition, Renovation and/or Interior Fit-Out Project?

- ○ Yes (1)
- ○ No (2)

Skip To: End of Block If Have you, or your company, used Reality Capture technologies during the Construction and/or Fabri... = No

Page Break

Q35 Based on your/your firm's experience during the Construction and/or Fabrication Phase of **Addition, Renovation and/or Interior Fit-Out** Project, indicate how **effective** Reality Capture technologies are for the following tasks:

*If you HAVE NOT use Reality Capture for the tasks please check the "NOT USED FOR THIS TASK" box on the right side of the screen

	NOT EFFECTIVE AT ALL	EXTREMELY EFFECTIVE	Not used for this task
	0 10 20 30 40 50 60 70 80 90 100		
Obtaining measurements for prefabrication/off-site fabrication ()			
Obtaining measurements for field use during construction ()			
Increasing efficiency of surveying and field layout ()			
Establishing the location of constructed systems ()			
Establishing the location of prefabricated elements ()			
Establishing the location of mechanical, electrical, and/or plumbing systems ()			
Documenting work-in-place/as-built conditions ()			
Documenting project progress ()			
Documenting work before it is not visible (e.g. reinforcing before pour) ()			
Documenting materials stored on site ()			
Comparing completed work to design requirements ()			
Verification of Construction Quality ()			
Completing Construction inspections ()			
Other: (Please specify) ()			

End of Block: COM RENO - USE/EFFECTIVENESS BY PHASE

Start of Block: SFR - REALIZED BENEFITS/OBSTACLES

Q54 Based on your **Single Family Residential Project experience**, rate your level of agreement with the following **realized benefits** of using Reality Capture technologies?

	Strongly disagree (1)	Somewhat disagree (2)	Neither agree nor disagree (3)	Somewhat agree (4)	Strongly agree (5)
Reduced rework during design (1)					
Reduced number of site visits to collect data (2)					
Reduced time required to generate 3D models (3)					
Reduced overall project cost (4)					
Reduced project duration (5)					
Reduced project risk (6)					
Reduced time required for quality assurance processes (7)					
Reduced time required for quality control processes (8)					
Reduced time required to document existing conditions (9)					
Reduced rework to correct errors in the field (10)					

Increased accuracy of existing condition documentation (11)					
Increased accuracy of construction documents (12)					
Increased accuracy of installed work (13)					
Increased accuracy of the as-built documents (14)					
Increased speed of as-built document creation (15)					
Increased accuracy of surveying/layout (16)					
Increased speed of surveying/layout (17)					
Increased accuracy of the constructed system locations (18)					
Increased speed of installation of constructed elements (19)					
Increased construction quality (21)					

Q91 If there are **benefits** of using Reality Capture technologies in Single Family Residential Projects that you would like to add to the list above, please do so below:

____

Page Break

Q55 Based on your Single Family Residential Project experience**,** rate your level of agreement with the following **obstacles** to the adoption/or wider adoptions of Reality Capture technologies.

	Strongly disagree (11)	Somewhat disagree (12)	Neither agree nor disagree (13)	Somewhat agree (14)	Strongly agree (15)
It is not a company priority (1)	○	○	○	○	○
Not important for the projects I work on (2)	○	○	○	○	○
Lack of Owner/Client demand (3)	○	○	○	○	○
Lack of company budget (4)	○	○	○	○	○
Lack of project-level budget (5)	○	○	○	○	○
Cannot bill Reality Capture costs to my projects (6)	○	○	○	○	○
Cannot justify the return on investment (7)	○	○	○	○	○
The equipment is expensive (8)	○	○	○	○	○
The equipment is not user-friendly (9)	○	○	○	○	○
The related software is expensive (10)	○	○	○	○	○
The related software is not user-friendly (11)	○	○	○	○	○

Lack of software interoperability (12)	○	○	○	○	○
Data collection is too time consuming (13)	○	○	○	○	○
Data processing is too time consuming (14)	○	○	○	○	○
Lack of in-house expertise (15)	○	○	○	○	○
Cost of hiring employees with the required skills (16)	○	○	○	○	○
Lack of training (17)	○	○	○	○	○
No time for training (18)	○	○	○	○	○
Risk/liability concerns (19)	○	○	○	○	○

Q92 If there are **obstacles** to the adoption/or wider adoptions of Reality Capture technologies in Single Family Residential Projects that you would like to add to the list above, please do so below:

____

End of Block: SFR - REALIZED BENEFITS/OBSTACLES

Start of Block: SFR NEW - USE AND EFFECTIVENESS BY PHASE

Q49 Do you/your company use Reality Capture technologies on **New Single Family Residential Projects**?

◯ Yes (1)

◯ No (2)

Skip To: End of Block If Do you/your company use Reality Capture technologies on New Single Family Residential Projects? = No

Page Break

Q50 Have you, or your company, used Reality Capture technologies during the **Design and/or Preconstruction** phase of New Single Family Residential Projects?

◯ Yes (1)

◯ No (2)

Skip To: Q52 If Have you, or your company, used Reality Capture technologies during the Design and/or Preconstruc... = No

Page Break

Q51 Based on your/your firm's experience during the **Design and/or Preconstruction Phase** of a **New Single Family Residential Project**, indicate how **effective** Reality Capture technologies are for the following tasks:

*If you HAVE NOT use Reality Capture for the tasks please check the "NOT USED FOR THIS TASK" box on the right side of the screen

	NOT EFFECTIVE AT ALL	EXTREMELY EFFECTIVE	Not used for this task
	0 10 20 30 40 50 60 70 80 90 100		
Documenting existing condition ()			
Obtaining field measurements ()			
Verifying field measurements ()			
Facilitating 3D model creation ()			
Facilitating 2D documents creation ()			
Facilitating virtual/mixed/augmented reality applications ()			
Quantifying materials ()			
Project visualization ()			
Understanding of the project scope ()			
Assuring Project Quality ()			
Controlling Project Quality ()			
Controlling Project Risk ()			
Mitigating Project Risk ()			
Other: (Please specify) ()			

Page Break

Q52 Have you, or your company, used Reality Capture technologies during the **Construction** phase of New Single Family Residential Projects?

○ Yes (1)

○ No (2)

Skip To: End of Block If Have you, or your company, used Reality Capture technologies during the Construction phase of Ne... = No

Page Break

Q53 Based on your/your firm's experience during the **Construction Phase of a New Single Family Residential Project**, indicate how **effective** Reality Capture technologies are for the following tasks:

*If you HAVE NOT use Reality Capture for the tasks please check the "NOT USED FOR THIS TASK" box on the right side of the screen

	NOT EFFECTIVE AT ALL	EXTREMELY EFFECTIVE	Not used for this task
	0 10 20 30 40 50	60 70 80 90 100	
Obtaining measurements for field use during construction ()			
Increasing efficiency of surveying and field layout ()			
Establishing the location of constructed systems ()			
Establishing the location of mechanical, electrical, and/or plumbing systems ()			
Documenting work-in-place/as-built conditions ()			
Documenting project progress ()			
Documenting work before it is not visible (e.g. reinforcing before pour) ()			
Documenting materials stored on site ()			
Comparing completed work to design requirements ()			
Verification of Construction Quality ()			
Completing Construction inspections ()			
Other: (Please specify) ()			

End of Block: SFR NEW - USE AND EFFECTIVENESS BY PHASE

Start of Block: SFR RENO - USE AND EFFECTIVENESS BY PHASE

Q56 Do you/your company use Reality Capture technologies on **Addition or Renovation Single Family Residential Projects**?

- ○ Yes (1)
- ○ No (2)

Skip To: End of Block If Do you/your company use Reality Capture technologies on Addition or Renovation Single Family Resi... = No

Page Break

Q57 Have you, or your company, used Reality Capture technologies during the **Design and/or Preconstruction** phase of **Addition or Renovation Single Family Residential Projects**?

○ Yes (1)

○ No (2)

Skip To: Q59 If Have you, or your company, used Reality Capture technologies during the Design and/or Preconstruc... = No

Page Break

Q58 Based on your/your firm's experience during the **Design and/or Preconstruction Phase of a Addition or Renovation Single Family Residential Project**, indicate how **effective** Reality Capture technologies are for the following tasks:

*If you HAVE NOT use Reality Capture for the tasks please check the "NOT USED FOR THIS TASK" box on the right side of the screen

	NOT EFFECTIVE AT ALL	EXTREMELY EFFECTIVE	Not used for this task
	0 10 20 30 40 50 60 70 80 90 100		
Documenting existing condition ()			
Obtaining field measurements ()			
Verifying field measurements ()			
Facilitating 3D model creation ()			
Facilitating 2D documents creation ()			
Facilitating virtual/mixed/augmented reality applications ()			
Quantifying materials ()			
Project visualization ()			
Understanding of the project scope ()			
Assuring Project Quality ()			
Controlling Project Quality ()			
Controlling Project Risk ()			
Mitigating Project Risk ()			
Other: (Please specify) ()			

Page Break

Q59 Have you, or your company, used Reality Capture technologies during the **Construction** phase of **Addition or Renovation Single Family Residential Projects**?

- Yes (1)
- No (2)

Skip To: End of Block If Have you, or your company, used Reality Capture technologies during the Construction phase of Add... = No

Page Break

Q60 Based on your/your firm's experience during the Construction Phase of a **Addition or Renovation Single Family Residential** Project, indicate how **effective** Reality Capture technologies are for the following tasks:

*If you HAVE NOT use Reality Capture for the tasks please check the "NOT USED FOR THIS TASK" box on the right side of the screen

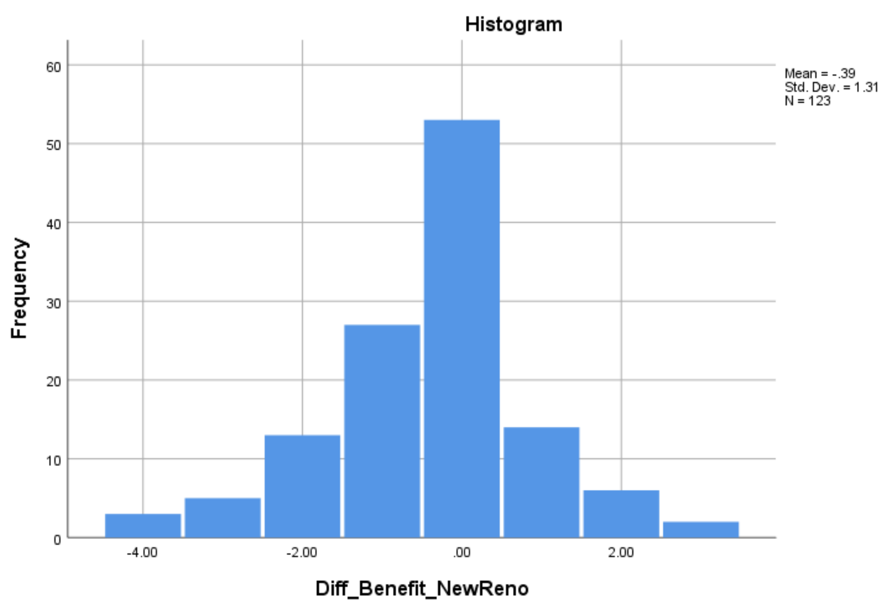
	NOT EFFECTIVE AT ALL / EXTREMELY EFFECTIVE 0 10 20 30 40 50 60 70 80 90 100	Not used for this task
Obtaining measurements for field use during construction ()		
Increasing efficiency of surveying and field layout ()		
Establishing the location of constructed systems ()		
Establishing the location of mechanical, electrical, and/or plumbing systems ()		
Documenting work-in-place/as-built conditions ()		
Documenting project progress ()		
Documenting work before it is not visible (e.g. reinforcing before pour) ()		
Documenting materials stored on site ()		
Comparing completed work to design requirements ()		
Verification of Construction Quality ()		
Completing Construction inspections ()		
Other: (Please specify) ()		

End of Block: SFR RENO - USE AND EFFECTIVENESS BY PHASE

APPENDIX D

Test of Normality (RQ2.3)

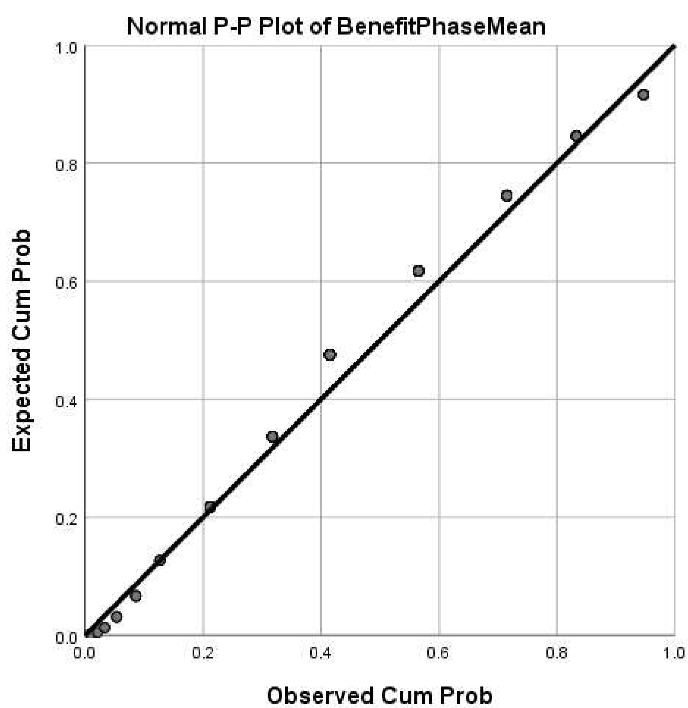
Descriptives				
			Statistic	Std. Error
Diff_Benefit_NewReno	Mean		-.3902	.11809
	95% Confidence Interval for Mean	Lower Bound	-.6240	
		Upper Bound	-.1565	
	5% Trimmed Mean		-.3690	
	Median		.0000	
	Variance		1.715	
	Std. Deviation		1.30970	
	Minimum		-4.00	
	Maximum		3.00	
	Range		7.00	
	Interquartile Range		1.00	
	Skewness		-.333	.218
	Kurtosis		.863	.433



APPENDIX E

Test of Normality – RQ3.4

Descriptive Statistics							
	N	Mean	Std. Deviation	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
RCT Provides Benefits During the design/preconstruction phase of a project	122	3.84	1.174	-.953	.219	.157	.435
RCT Provides Benefits During the construction/fabrication phase of a project	123	3.86	1.196	-.867	.218	-.158	.433
RCT Provides Benefits During the operation and maintenance phase of a project	123	3.48	1.133	-.550	.218	-.181	.433
Valid N (listwise)	122						



APPENDIX F

Research Question 3.4 - Tests of Homogeneity of Variances					
		Levene Statistic	df1	df2	Sig.
RCT Provides Benefits During the design/preconstruction phase of a project	Based on Mean	1.299	3	118	.278
	Based on Median	.844	3	118	.473
	Based on Median and with adjusted df	.844	3	108.471	.473
	Based on trimmed mean	.964	3	118	.412
RCT Provides Benefits During the construction/fabrication phase of a project	Based on Mean	.675	3	119	.569
	Based on Median	.670	3	119	.572
	Based on Median and with adjusted df	.670	3	115.358	.572
	Based on trimmed mean	.626	3	119	.599
RCT Provides Benefits During the operation and maintenance phase of a project	Based on Mean	1.664	3	119	.179
	Based on Median	1.444	3	119	.233
	Based on Median and with adjusted df	1.444	3	114.406	.234
	Based on trimmed mean	1.626	3	119	.187

APPENDIX G

Research Question 3.4 - Multiple Comparisons (Post Hoc Test)							
Tukey HSD							
Dependent Variable	(I) Role on a 'Typical' Construction/ Development Project	(J) Role on a 'Typical' Construction/ Development Project	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
RCT Provides Benefits During the design/preconstruction phase of a project	Owner/Developer	Designer	.002	.363	1.000	-.94	.95
		Contractor	.022	.292	1.000	-.74	.78
		CM & Owner Representative	-.245	.332	.881	-1.11	.62
	Designer	Owner/Developer	-.002	.363	1.000	-.95	.94
		Contractor	.020	.317	1.000	-.81	.85
		CM & Owner Representative	-.248	.354	.897	-1.17	.68
	Contractor	Owner/Developer	-.022	.292	1.000	-.78	.74
		Designer	-.020	.317	1.000	-.85	.81
		CM & Owner Representative	-.268	.281	.776	-1.00	.46
	CM & Owner Representative	Owner/Developer	.245	.332	.881	-.62	1.11
		Designer	.248	.354	.897	-.68	1.17
		Contractor	.268	.281	.776	-.46	1.00
RCT Provides Benefits During the construction/fabrication phase of a project	Owner/Developer	Designer	-.117	.363	.988	-1.06	.83
		Contractor	-.397	.296	.537	-1.17	.37
		CM & Owner Representative	-.417	.336	.603	-1.29	.46
	Designer	Owner/Developer	.117	.363	.988	-.83	1.06
		Contractor	-.281	.315	.810	-1.10	.54

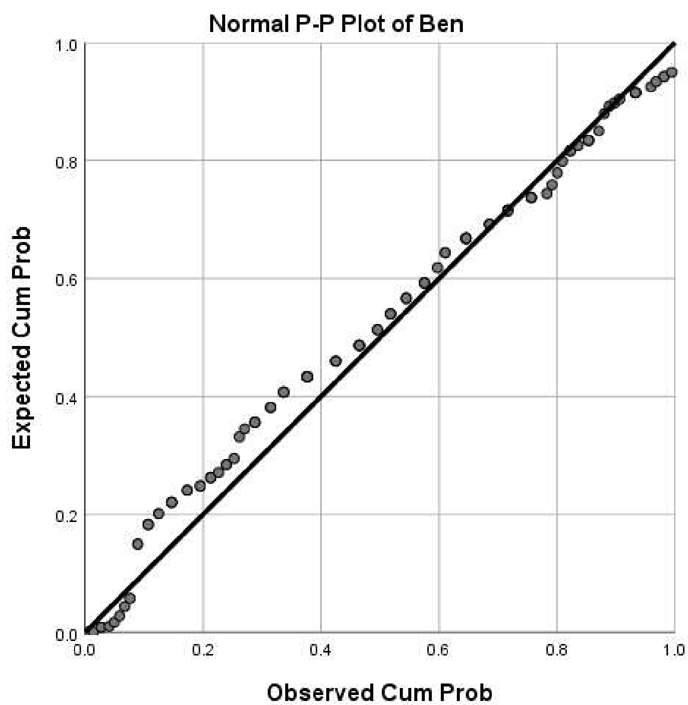
		CM & Owner Representative	-.300	.354	.831	-1.22	.62
	Contractor	Owner/Developer	.397	.296	.537	-.37	1.17
		Designer	.281	.315	.810	-.54	1.10
		CM & Owner Representative	-.019	.284	1.000	-.76	.72
	CM & Owner Representative	Owner/Developer	.417	.336	.603	-.46	1.29
		Designer	.300	.354	.831	-.62	1.22
		Contractor	.019	.284	1.000	-.72	.76
RCT Provides Benefits During the operation and maintenance phase of a project	Owner/Developer	Designer	-.950*	.336	.028	-1.82	-.08
		Contractor	-.558	.274	.180	-1.27	.16
		CM & Owner Representative	-.407	.311	.559	-1.22	.40
	Designer	Owner/Developer	.950*	.336	.028	.08	1.82
		Contractor	.392	.292	.536	-.37	1.15
		CM & Owner Representative	.543	.327	.350	-.31	1.39
	Contractor	Owner/Developer	.558	.274	.180	-.16	1.27
		Designer	-.392	.292	.536	-1.15	.37
		CM & Owner Representative	.150	.263	.940	-.54	.84
	CM & Owner Representative	Owner/Developer	.407	.311	.559	-.40	1.22
		Designer	-.543	.327	.350	-1.39	.31
		Contractor	-.150	.263	.940	-.84	.54
*. The mean difference is significant at the 0.05 level.							

APPENDIX H

Test of Normality of RCT Benefits Based on the Absolute Skewness Value (RQ4.2)

Descriptive Statistics								
RCT Benefits	N	Mean	Std. Deviation	Variance	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
Reduced rework during design	113	3.80	1.079	1.164	-.930	.227	.493	.451
Reduced number of site visits to collect data	113	4.10	1.000	.999	-1.181	.227	1.117	.451
Reduced time required to generate 3D models	113	3.99	1.073	1.152	-.909	.227	.274	.451
Reduced overall project cost	113	3.41	1.015	1.029	-.317	.227	-.383	.451
Reduced project duration	113	3.30	.981	.962	-.292	.227	-.406	.451
Reduced project risk	113	3.94	.938	.880	-.932	.227	1.050	.451
Reduced time required for quality assurance processes	112	3.63	1.004	1.009	-.674	.228	.148	.453
Reduced time required for quality control processes	112	3.56	1.055	1.113	-.730	.228	.075	.453
Reduced time required to document existing conditions	112	4.29	.999	.999	-1.706	.228	2.763	.453
Reduced rework to correct errors in the field	112	3.77	1.040	1.081	-.792	.228	.213	.453
Increased accuracy of existing condition documentation	111	4.36	.861	.742	-1.730	.229	3.595	.455
Increased accuracy of construction documents	112	3.93	.984	.968	-.838	.228	.286	.453
Increased accuracy of installed work	111	3.81	.968	.937	-.896	.229	.925	.455
Increased accuracy of the as-built documents	111	4.22	.928	.862	-1.488	.229	2.556	.455
Increased speed of as-built document creation	110	3.94	1.052	1.106	-.787	.230	.031	.457

Increased accuracy of surveying/layout	108	3.90	1.023	1.046	-.541	.233	-.615	.461
Increased speed of surveying/layout	109	3.83	1.032	1.065	-.434	.231	-.758	.459
Increased accuracy of the constructed system locations	112	3.91	1.000	1.001	-.643	.22	-.144	.453
Increased speed of installation of constructed elements	112	3.54	1.048	1.098	-.120	.228	-.785	.453
Increased accuracy of prefabricated elements	111	3.77	1.044	1.090	-.491	.229	-.323	.455
Increased construction quality	111	3.77	.963	.926	-.57	.229	.257	.455
Valid N (listwise)	103							



APPENDIX I

Tests of Homogeneity of Variance (RQ4.2)

RCT Benefit		Levene Statistic	df1	df2	Sig.
Reduced rework during design	Based on Mean	1.200	3	109	.313
	Based on Median	.352	3	109	.788
	Based on Median and with adjusted df	.352	3	100.279	.788
	Based on trimmed mean	.744	3	109	.528
Reduced number of site visits to collect data	Based on Mean	.270	3	109	.847
	Based on Median	.341	3	109	.796
	Based on Median and with adjusted df	.341	3	96.520	.796
	Based on trimmed mean	.342	3	109	.795
Reduced time required to generate 3D models	Based on Mean	1.283	3	109	.284
	Based on Median	.982	3	109	.404
	Based on Median and with adjusted df	.982	3	92.034	.405
	Based on trimmed mean	1.009	3	109	.392
Reduced overall project cost	Based on Mean	1.365	3	109	.257
	Based on Median	1.038	3	109	.379
	Based on Median and with adjusted df	1.038	3	95.603	.380
	Based on trimmed mean	1.399	3	109	.247
Reduced project duration	Based on Mean	.263	3	109	.852
	Based on Median	.316	3	109	.813
	Based on Median and with adjusted df	.316	3	105.877	.813
	Based on trimmed mean	.293	3	109	.830
Reduced project risk	Based on Mean	.586	3	109	.626
	Based on Median	.586	3	109	.625
	Based on Median and with adjusted df	.586	3	105.181	.625
	Based on trimmed mean	.547	3	109	.651
Reduced time required for quality assurance processes	Based on Mean	1.389	3	108	.250
	Based on Median	1.263	3	108	.291
	Based on Median and with adjusted df	1.263	3	104.291	.291
	Based on trimmed mean	1.626	3	108	.188
	Based on Mean	2.513	3	108	.062
	Based on Median	2.836	3	108	.042

Reduced time required for quality control processes	Based on Median and with adjusted df	2.836	3	101.099	.042
	Based on trimmed mean	2.953	3	108	.036
Reduced time required to document existing conditions	Based on Mean	1.876	3	108	.138
	Based on Median	1.645	3	108	.183
	Based on Median and with adjusted df	1.645	3	107.939	.183
	Based on trimmed mean	1.790	3	108	.153
Reduced rework to correct errors in the field	Based on Mean	.033	3	108	.992
	Based on Median	.115	3	108	.951
	Based on Median and with adjusted df	.115	3	104.794	.951
	Based on trimmed mean	.026	3	108	.994
Increased accuracy of existing condition documentation	Based on Mean	1.362	3	107	.258
	Based on Median	.667	3	107	.574
	Based on Median and with adjusted df	.667	3	90.839	.574
	Based on trimmed mean	1.331	3	107	.268
Increased accuracy of construction documents	Based on Mean	1.368	3	108	.256
	Based on Median	.945	3	108	.421
	Based on Median and with adjusted df	.945	3	106.607	.421
	Based on trimmed mean	1.025	3	108	.385
Increased accuracy of installed work	Based on Mean	.572	3	107	.634
	Based on Median	.273	3	107	.844
	Based on Median and with adjusted df	.273	3	104.516	.844
	Based on trimmed mean	.702	3	107	.553
Increased accuracy of the as-built documents	Based on Mean	.230	3	107	.876
	Based on Median	.273	3	107	.844
	Based on Median and with adjusted df	.273	3	104.258	.844
	Based on trimmed mean	.337	3	107	.799
Increased speed of as-built document creation	Based on Mean	.466	3	106	.707
	Based on Median	.357	3	106	.784
	Based on Median and with adjusted df	.357	3	100.133	.784
	Based on trimmed mean	.473	3	106	.701
Increased accuracy of surveying/layout	Based on Mean	.601	3	104	.616
	Based on Median	.468	3	104	.705
	Based on Median and with adjusted df	.468	3	97.992	.705
	Based on trimmed mean	.501	3	104	.682
Increased speed of surveying/layout	Based on Mean	.775	3	105	.511
	Based on Median	.444	3	105	.722

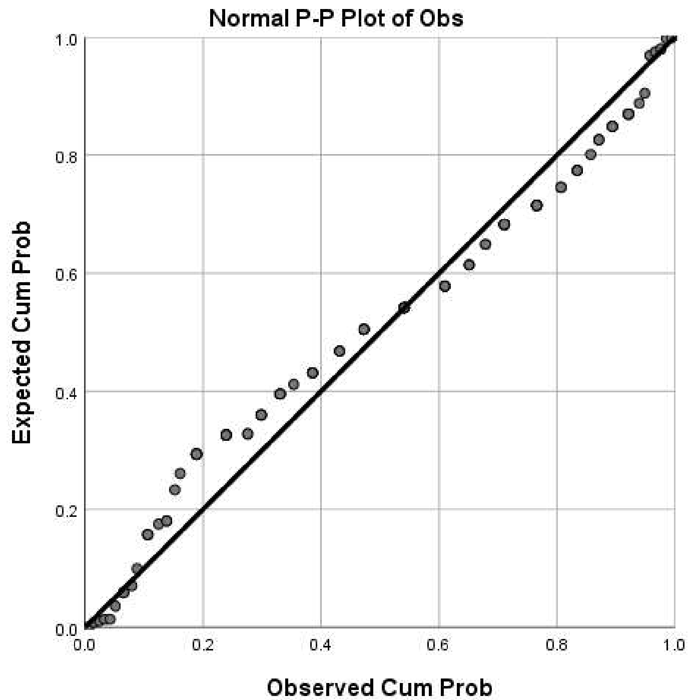
	Based on Median and with adjusted df	.444	3	99.766	.722
	Based on trimmed mean	.678	3	105	.567
Increased accuracy of the constructed system locations	Based on Mean	.787	3	108	.503
	Based on Median	.600	3	108	.616
	Based on Median and with adjusted df	.600	3	104.357	.616
	Based on trimmed mean	.718	3	108	.543
Increased speed of installation of constructed elements	Based on Mean	.292	3	108	.831
	Based on Median	.346	3	108	.792
	Based on Median and with adjusted df	.346	3	104.216	.792
	Based on trimmed mean	.319	3	108	.812
Increased accuracy of prefabricated elements	Based on Mean	.348	3	107	.791
	Based on Median	.444	3	107	.722
	Based on Median and with adjusted df	.444	3	96.933	.722
	Based on trimmed mean	.453	3	107	.715
Increased construction quality	Based on Mean	2.493	3	107	.064
	Based on Median	1.755	3	107	.160
	Based on Median and with adjusted df	1.755	3	97.672	.161
	Based on trimmed mean	2.495	3	107	.064

APPENDIX J

Test of Normality of RCT Obstacles Based on the Absolute Skewness Value (RQ5.2)

Descriptive Statistics								
RCT Obstacles	N	Mean	Std. Deviation	Variance	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
RCT Obstacle: It is not a company priority	108	3.50	1.055	1.112	-.390	.233	-.427	.461
RCT Obstacle: Not important for the projects I work on	108	2.97	1.188	1.410	-.014	.233	-.790	.461
RCT Obstacle: Lack of Owner/Client demand	106	3.84	.997	.993	-1.142	.235	1.372	.465
RCT Obstacle: Lack of company budget	108	3.56	1.163	1.352	-.591	.233	-.443	.461
RCT Obstacle: Lack of project-level budget	107	3.81	1.158	1.342	-.999	.234	.412	.463
RCT Obstacle: Cannot bill Reality Capture costs to my projects	107	3.21	1.166	1.359	-.321	.234	-.631	.463
RCT Obstacle: Cannot justify the return on investment	107	3.21	1.114	1.240	-.209	.234	-.626	.463
RCT Obstacle: The equipment is expensive	108	3.48	1.009	1.018	-.532	.233	.262	.461
RCT Obstacle: The equipment is not user-friendly	106	2.93	.908	.824	-.102	.235	.455	.465
RCT Obstacle: The related software is expensive	107	3.31	.873	.762	-.129	.234	.741	.463

RCT Obstacle: The related software is not user-friendly	106	3.09	.857	.734	.002	.235	.991	.465
RCT Obstacle: Lack of software interoperability	106	3.09	.889	.791	.061	.235	.682	.465
RCT Obstacle: Data collection is too time consuming	106	2.91	1.010	1.020	.249	.235	-.253	.465
RCT Obstacle: Data processing is too time consuming	106	3.07	.998	.996	-.193	.235	-.163	.465
RCT Obstacle: Lack of in-house expertise	106	3.74	1.054	1.111	-.395	.235	-.632	.465
RCT Obstacle: Cost of hiring employees with the required skills	106	3.45	.996	.993	-.250	.235	-.353	.465
RCT Obstacle: Lack of training	106	3.56	.947	.897	-.234	.235	-.236	.465
RCT Obstacle: No time for training	106	3.36	.997	.994	-.011	.235	-.379	.465
RCT Obstacle: Risk/liability concerns	106	2.83	.951	.904	-.261	.235	-.056	.465
Valid N (listwise)	100							


Normal P-P Plot of Obs
Expected Cum Prob
Observed Cum Prob
0.0
0.2
0.4
0.6
0.8
1.0

APPENDIX K

Tests of Homogeneity of Variance (RQ5.2)

RCT Obstacle		Levene Statistic	df1	df2	Sig.
It is not a company priority	Based on Mean	1.369	3	104	.256
	Based on Median	.907	3	104	.441
	Based on Median and with adjusted df	.907	3	102.457	.441
	Based on trimmed mean	1.595	3	104	.195
Not important for the projects I work on	Based on Mean	2.357	3	104	.076
	Based on Median	2.294	3	104	.082
	Based on Median and with adjusted df	2.294	3	102.354	.082
	Based on trimmed mean	2.352	3	104	.077
RCT Obstacle: Lack of Owner/Client demand	Based on Mean	4.785	3	102	.004
	Based on Median	2.375	3	102	.074
	Based on Median and with adjusted df	2.375	3	92.423	.075
	Based on trimmed mean	3.588	3	102	.016
Lack of company budget	Based on Mean	1.868	3	104	.140
	Based on Median	.662	3	104	.577
	Based on Median and with adjusted df	.662	3	96.138	.577
	Based on trimmed mean	1.610	3	104	.192
Lack of project-level budget	Based on Mean	2.868	3	103	.040
	Based on Median	1.799	3	103	.152
	Based on Median and with adjusted df	1.799	3	90.452	.153
	Based on trimmed mean	2.487	3	103	.065
Cannot bill Reality Capture costs to my projects	Based on Mean	.185	3	103	.907
	Based on Median	.100	3	103	.960
	Based on Median and with adjusted df	.100	3	93.748	.960
	Based on trimmed mean	.168	3	103	.918
Cannot justify the return on investment	Based on Mean	1.766	3	103	.158
	Based on Median	1.272	3	103	.288

	Based on Median and with adjusted df	1.272	3	92.920	.288
	Based on trimmed mean	1.812	3	103	.150
The equipment is expensive	Based on Mean	1.437	3	104	.236
	Based on Median	1.026	3	104	.384
	Based on Median and with adjusted df	1.026	3	103.278	.384
	Based on trimmed mean	1.413	3	104	.243
The equipment is not user-friendly	Based on Mean	3.846	3	102	.012
	Based on Median	3.087	3	102	.031
	Based on Median and with adjusted df	3.087	3	92.109	.031
	Based on trimmed mean	4.222	3	102	.007
The related software is expensive	Based on Mean	.971	3	103	.409
	Based on Median	.980	3	103	.405
	Based on Median and with adjusted df	.980	3	99.403	.405
	Based on trimmed mean	1.049	3	103	.374
The related software is not user-friendly	Based on Mean	1.439	3	102	.236
	Based on Median	1.870	3	102	.139
	Based on Median and with adjusted df	1.870	3	91.664	.140
	Based on trimmed mean	1.588	3	102	.197
Lack of software interoperability	Based on Mean	.449	3	102	.719
	Based on Median	1.180	3	102	.321
	Based on Median and with adjusted df	1.180	3	101.804	.321
	Based on trimmed mean	.450	3	102	.718
Data collection is too time consuming	Based on Mean	.145	3	102	.933
	Based on Median	.238	3	102	.869
	Based on Median and with adjusted df	.238	3	99.254	.869
	Based on trimmed mean	.134	3	102	.940
Data processing is too time consuming	Based on Mean	1.978	3	102	.122
	Based on Median	1.453	3	102	.232
	Based on Median and with adjusted df	1.453	3	99.256	.232

	Based on trimmed mean	1.814	3	102	.149
Lack of in-house expertise	Based on Mean	1.232	3	102	.302
	Based on Median	.721	3	102	.542
	Based on Median and with adjusted df	.721	3	96.492	.542
	Based on trimmed mean	1.139	3	102	.337
Cost of hiring employees with the required skills	Based on Mean	2.105	3	102	.104
	Based on Median	1.185	3	102	.319
	Based on Median and with adjusted df	1.185	3	95.765	.320
	Based on trimmed mean	2.144	3	102	.099
Lack of training	Based on Mean	1.131	3	102	.340
	Based on Median	.599	3	102	.617
	Based on Median and with adjusted df	.599	3	96.559	.617
	Based on trimmed mean	1.095	3	102	.355
No time for training	Based on Mean	5.668	3	102	.001
	Based on Median	4.501	3	102	.005
	Based on Median and with adjusted df	4.501	3	98.949	.005
	Based on trimmed mean	5.963	3	102	.001
Risk/liability concerns	Based on Mean	1.321	3	102	.272
	Based on Median	.899	3	102	.444
	Based on Median and with adjusted df	.899	3	99.376	.444
	Based on trimmed mean	1.436	3	102	.237