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Benefits and Obstacles to the Adoption of Reality Capture Technologies in the U.S. Commercial and Infrastructure Construction Sectors

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Abstract: Most previous Reality Capture Technology (RCT) research in construction focuses on the technical aspects of data collection, processing, and post-processing, while fewer studies have explored stakeholder perceptions about adopting and implementing RCT. This research investigated the perceptions of various construction project stakeholders in the commercial and infrastructure sectors regarding the benefits of, and obstacles hindering, the adoption of RCTs. A survey was distributed to the membership of U.S.-based professional organizations. Exploratory Factor Analysis was implemented to investigate and confirm logical and consistent empirical groupings of the benefits and obstacles listed in the survey. In general, mean comparisons revealed consistency across stakeholder perceptions of the benefits and obstacles of RCTs. However, significantly different perceptions about the increased accuracy of prefabricated elements, RCTs not being a company priority, lack of company budget, and data collection being too time consuming were observed between stakeholder groups. The study identified several benefits to RCT adoption (including, but not limited to, reduced project risk, increased accuracy of prefabricated elements and installed work as well as increased speed of as-built document creation) that were not noted in previous studies. Several obstacles to RCT (including, but not limited to, RCT not being a company priority, lack of Owner/Client demand, inability to bill RCT costs to the project, and cost of hiring employees with the required skills) were not observed in previous studies.

Keywords: project stakeholders; perceptions; exploratory factor analysis; laser scanning; photogrammetry



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1. Introduction

Construction has been characterized as a low productivity industry due to poor management and the use of outdated methods [1–3]. The collection of existing site conditions is one area where outdated equipment and methods are prevalent [4–7]. Traditional surveying techniques used to create as-built documentation and conduct structure inspections are typically expensive, labor-intensive, prone to errors, and able to provide only single point location measurements [3,8]. Additionally, data reliability and consistency can be a challenge in the case of manually collected data [9]. Regardless of the problems associated with traditional existing condition data collection, reality capture technologies (RCTs) are used less frequently than traditional methods [2,3]. Previous studies indicate that construction stakeholders are reluctant to adopt RCTs due to limited knowledge of the applications and the lack of an existing framework for acquiring and processing point cloud data specific to construction applications and across the project life cycle [1–3]. Therefore, given the documented benefits of RCTs, it is prudent to raise awareness among construction project stakeholders regarding the benefits, as well as provide information concerning the barriers they may encounter when implementing these technologies [2].

2. Literature Review

The construction industry has traditionally been slow in adopting emerging technologies [10]. According to Alomari et al. [11], 62% of construction firms used laser scanning applications, but the minority of owners were aware of the technology. However, there has been growing demand for 3D point cloud data documenting buildings and infrastructure [12], which creates an opportunity for the more extensive adoption of RCTs [13]. In addition, more construction professionals should become knowledgeable about technologies [11]. Therefore, it is important to explore reasons for slow technology adoption and to develop strategies for its implementation [10]. On the contrary, Almukhtar et al. [1] posit that, more recently, RCT implementation is on the rise in the construction industry due, in part, to the increasing use of 3D models.

2.1. Defining Reality Capture Technologies in Construction

When broadly defined, reality capture hardware can include project site webcams, ground penetrating radar, robotic total stations, and GPS rovers [13]. While these technologies do collect ‘existing condition data’, it is important to note that in this study RCTs were defined for the survey respondents as the “use of hardware including laser scanners, cameras mounted on Unmanned Aerial Vehicles (UAVs) and high definition 360-degree photography 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” [1,14,15]. Therefore, in this study, RCTs were delimited to laser scanning, photogrammetry, and the integration of these technologies.

2.2. Project Stakeholder Perceptions about the Benefits of Using RCT

2.2.1. RCT Benefits to Designers

The implementation of RCT data helps designers and surveyors deliver projects more efficiently and improves client satisfaction [4,14]. Reality capture-based models enable quick and clear communications of the project revisions and progress to all project stakeholders [4]. Detailed existing condition reality capture data collection enables designers to quickly obtain realistic 3D representations of their projects and ensure that design models are spatially precise and closely mimic, or match, real-world conditions [4,14]. This approach minimizes the number of change orders and the associated rework, which contributes to a positive return on investment (ROI) [14]. Moreover, in the project design stage, the use of RCTs provides more accurate existing condition data, particularly on projects where as-built documentation is not available or is outdated or inaccurate. For addition and renovation projects, RCTs can reduce design time and rework, minimize the number of return site visits to remeasure and verify conditions, reduce the time and manual work required to capture existing condition data, and reduce the labor costs for surveying and documentation [4,14]. Engineers benefit from using RCTs for construction inspection, as-built documentation, and mapping existing infrastructure for planning and design [13], which better prepares them to solve any potential problems in the early project phases [14]. Improvement in project quality, the ability to track project progress and minimize the impact of errors on site, as well as improved safety were the top project benefits of utilizing RCTs indicated by engineers [13].

2.2.2. RCT Benefits to Contractors

Repeated RCT-based data collection and analysis can promote continual process improvement on construction projects [13]. Contractors utilize RCTs to manage projects more efficiently through early issue identification and tracking. These practices minimize potential delays and costly rework, which promotes the completion of projects on-time and within budget [4]. BIM models produced based on point clouds enhance collaboration throughout the project duration and improve construction progress communication among all project stakeholders [4]. RCT data, when used in conjunction with software applications,

can automate earthwork calculations, streamline site management, improve safety, improve tracking through progress documentation, and improve project verification and quality control (QC) [13,14]. Contractors rated the improved ability to track project progress, manage project schedules and project budgets, and quality and safety as the top project benefits of using RCT [13,16]. Construction management personnel most frequently cited producing 3D models, resolving problems before errors occur, the improved comparison of planned and as-built facilities, and information sharing among stakeholders as the benefits of laser scanning use [11]. RCTs provide very accurate visual information about on-site construction processes and help with the discovering of discrepancies during construction by comparing as-built to as-designed documentation [4,14].

Highway construction stakeholders indicated the following benefits of quality management technologies, including laser scanning: improved construction worker safety, improved schedule performance, increased productivity, and reduced personnel time [2]. Reality capture data are useful for discovering and resolving deviations in roadway flatness and ensuring that the installed work is in accordance with the design, resulting in high quality project deliverables [4]. In bridge construction, reality capture data are used for the dimensional quality control of pillars and supports before bridge assembly, for ensuring that bridge elements are constructed in accordance with the design, and for daily bridge construction monitoring and progress [4].

2.2.3. RCT Benefits to Owners

Similar to contractors, the owners stated that an improved ability to track project progress, improved project quality, and improved safety were the top project benefits resulting from the use of RCTs [13]. Since the reality capture scans are very accurate and detailed, the owners are able to better visualize their projects [14] and understand the cost and cash flow of the project, especially in the case of complex projects [16]. Owners can experience several benefits of using RCT data during the maintenance phase of infrastructure projects such as roads, bridges and tunnels. The needed maintenance work for roads and bridges is quickly identified with RCTs, which ensures their structural safety. RCTs help maintenance checks of tunnels to ensure that they are in good working order [4].

2.3. Benefits of Using RCT in Commercial and Infrastructure Construction

Research suggests that the implementation of RCTs improves project quality, jobsite safety, the ability to track work progress, the ability to manage project schedules and project budgets, and minimizes the impact of errors on site [1,10,12,13]. Alomari et al. [11] posit that producing 3D models was the most important benefit of laser scanning use. The use of terrestrial laser scanning (TLS) for construction quality assurance (QA)/quality control (QC) was more cost-effective because it reduced data collection time by 80% as compared to conventional approaches [17]. The use of TLS for structural safety diagnosis helped reduce the project duration by four months and project costs by 50% compared to the traditional approach [18]. The cost benefits of using robotics and automation technology (RAT), including laser scanners, are achieved from savings on labor, resources, time, and rework reduction [1,10,19]. Tang et al. [17] and Wu et al. [20] suggest that the use of TLS equipment would be even more beneficial for larger and more complex projects.

TLS equipment is capable of fast and accurate acquisition of large amounts of data at lower cost, thus, increasing productivity [1,10,12,20]. Accurate point cloud data helps decision making and improves efficiency during the project construction phase (e.g., progress tracking) as well as during the operation and maintenance phase [12]. The integration of TLS and BIM is beneficial for improving as-built documentation, construction quality control, and progress control [21]. In addition, laser scanning improves the ability to compare as-built and as-designed models and information sharing among stakeholders [11]. Since TLS equipment can collect data at range, these methods minimize the disruption of construction processes as compared to traditional spatial data collection practices [20].

Since data collection is highly automated, operating TLS equipment requires minimal employee training or technical skills [20].

In the infrastructure construction sector, the use of technologies for QA/QC resulted in improved performance on road construction projects when compared to the use of conventional data collection equipment and procedures [2]. Highway construction professionals perceived improved construction worker safety, improved schedule performance, increased productivity, reduced personnel time working on tasks, and accurate soil compaction values as the top five benefits of using quality management technologies [2]. The use of laser scanners for automated pavement condition assessment provides more efficient, faster and safer data collection, and more accurate and consistent data than manual surveying techniques [9]. In addition, laser scanning can help obtain multi-year 3D pavement condition data that can be used to create the predictive models [9]. RCTs are an effective method for collecting as-built bridge data, which can be used for assessing damage due to accidents or natural disasters. Having as-built point cloud data of utility conduits, drainage pipes, pavement subgrade and pavement thickness eliminates the need for using ground-penetrating radar for surveying utilities [22].

2.4. Project Stakeholder Perceptions of Obstacles to RCT Adoption

Participants in the Dodge Data and Analytics [13] survey stated that the following issues need to be addressed to increase the usefulness of RCTs: establishing better and faster methods to share data with remote and field teams, reducing data file size, and increasing the ability to incorporate data into BIM models. Respondents also noted having more user-friendly software to reduce training needs, and increasing the ability to incorporate point cloud data into scheduling and project management software applications would increase RCT adoption [13].

A low level of knowledge about laser-based technologies, lack of experience, lack of trust in laser scanning technology and cultural resistance were the most frequently mentioned barriers by construction management personnel. The most commonly noted shortcomings of laser scanning were the perceived high cost of equipment, high maintenance costs, large file sizes, and the low quality of outputs [11]. Highway construction stakeholders perceived device accuracy concerns, cost of technology, lack of compatibility with existing practice, limited information on effectiveness, and implementation complexity as the major barriers to the adoption of quality management technologies including laser scanning [2]. Project owners indicated that the usefulness of RCTs could be increased through the creation of more user-friendly software applications, establishing better and faster ways to share data with remote and field teams, and creating better analysis software for reality capture data [13].

2.5. Obstacles to RCT Adoption in Commercial and Infrastructure Construction

The perceived high cost of RCT software, hardware and associated maintenance was a prevalent obstacle to more extensive RCT adoption by the construction industry [1,10,11,17,20]. In addition, the majority of previous studies found that personnel-related obstacles such as lack of experience and skills, resistance to change, and need for training prevented RCT utilization [1,10,11,19]. Other studies pointed out obstacles that related to data processing, including the need to improve data processing efficiency, effectiveness and automation of algorithms, the fusion of information obtained from multiple resources, and difficulty with obtaining real-time information [19,20]. Low quality of output data, large file size, and insufficient computational power of processing machines are additional technology-related obstacles to RCT implementation [1,11,20].

The main obstacles to using quality management technologies in road construction projects were device accuracy concerns, the cost of technology, the incompatibility of technology with existing practice, limited information on effectiveness, implementation complexity, and the need for extensive employee training [2,3,22,23]. DOTs reported data processing-related obstacles including challenges in matching historical pavement data

with new data obtained by laser scanning, registration and the alignment of multiple-timestamped 3D point clouds to monitor pavement areas over time, and the inability of vendors to deliver required data causing transportation agencies to process the collected 3D pavement data in order to obtain the needed information [9].

3. Study Purpose

Almukhtar et al. [1] posit that, compared to other disciplines that utilize RCTs, there is a need for more research investigating the use of these technologies within the construction industry. The majority of studies that include RCTs in construction address these specific tools as part of broader investigations of all ‘technology’ adoption in construction. Laser scanning and photogrammetry-specific research typically explores the technical aspects of data collection, processing and post-processing, and fewer studies explore stakeholder perceptions, acceptance, and the adoption or evaluation of such technologies in construction [19]. Fewer still are studies that compare the perceived benefits and barriers to RCT adoption between industry segments by stakeholder, and rarely do studies specifically report the survey respondent’s level of RCT-related experience. Those studies that surveyed perceptions of RCTs (e.g., [2,10,11]) differ from the current investigation in focus and methodology, timeframe, sample size and diversity, as well as the type and robustness of the data analysis.

Therefore, the purpose of this research was to further previous studies by exploring and comparing these perceptions between construction project stakeholders and between the commercial and infrastructure industry segments. Following an analysis of the survey respondent demographics as well as RCT awareness and experience, the following research questions (RQs) were explored to achieve the study purpose:

- RQ1: How do construction stakeholders rate the perceived benefits of, and obstacles preventing, the adoption of RCTs?
- RQ2: Are significant differences in mean perceptions of the benefits of, and obstacles preventing, the adoption of RCTs observed when compared by construction stakeholders?
- RQ3: Are significant differences in mean perceptions of the benefits of, and obstacles preventing, the adoption of RCTs observed when compared by construction industry sector?
- RQ4: Do the perceived benefits of, and obstacles preventing, the adoption of RCTs group in a logical factor structure resultant Exploratory Factor Analysis?
 - RQ4a: Are significant differences in the emergent factor means for the ‘RCT benefits’ observed when compared by construction stakeholders?
 - RQ4b: Are significant differences in the emergent factor means for the ‘RCT benefits’ observed when compared by construction industry sector?
 - RQ4c: Are significant differences in the emergent factor means for the ‘RCT Obstacles’ observed when compared by construction stakeholders?
 - RQ4d: Are significant differences in the emergent factor means for the ‘RCT Obstacles’ observed when compared by construction industry sector?

4. Methodology

4.1. Survey Development and Distribution

The instrument administered in this study was developed based on the literature review. As noted previously, survey-based research that explored construction stakeholder perceptions of RCTs is limited. Therefore, related studies exploring information technology, such as BIM, 2D and single-point digital existing condition documentation were also reviewed during the creation of the survey instrument [24–27]. Survey items for analysis comprised respondent demographics, the awareness and experience with RCTs, their perceptions of the benefits of implementing RCTs, and the perceived obstacles that prevent the utilization of RCTs on construction projects.

The authors noted that the term ‘reality capture’ could comprise a broad and nuanced collection of tools and applications, and that RCT can be broadly defined to include numerous technologies that document ‘existing condition data’ [13]. It is important to note that RCT was defined for the survey respondents in this study using Autodesk’s [14] definition as follows: “Reality capture is 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”.

Survey participants were asked to rate their level of agreement with the 21 benefits of using RCT (Table 1) and the 19 obstacles to the adoption of RCT (Table 2). Levels of agreement were reported on a 5-point scale (1 = Strongly Disagree to 5 = Strongly Agree).

Table 1. Benefits of Using RTC.

Benefit Number	Benefit
1	Reduced rework during design
2	Reduced number of site visits to collect data
3	Reduced time required to generate 3D models
4	Reduced overall project cost
5	Reduced project duration
6	Reduced project risk
7	Reduced time required for quality assurance processes
8	Reduced time required for quality control processes
9	Reduced time required to document existing conditions
10	Reduced rework to correct errors in the field
11	Increased accuracy of existing condition documentation
12	Increased accuracy of construction documents
13	Increased accuracy of installed work
14	Increased accuracy of the as-built documents
15	Increased speed of as-built document creation
16	Increased accuracy of surveying/layout
17	Increased speed of surveying/layout
18	Increased accuracy of the constructed system locations
19	Increased speed of installation of constructed elements
20	Increased accuracy of prefabricated elements
21	Increased construction quality

Table 2. Obstacles that Prevent the Adoption of RTC.

Obstacle Number	Obstacle
1	RCT is not a company priority
2	RCT is not important for the projects I work on
3	Lack of owner/client demand
4	Lack of company budget
5	Lack of project-level budget
6	Not able to bill RCT costs to my projects
7	Not able to justify the return on investment
8	High cost of the equipment
9	Lack of user-friendliness of the equipment
10	High cost of the related software
11	Lack of user-friendliness of the related software
12	Lack of software interoperability
13	Data collection too time consuming
14	Data processing too time consuming
15	Lack of in-house expertise
16	Cost of hiring employees with the required skills
17	Lack of training
18	Lack of time for training
19	Risk/liability concerns

The online survey was approved by the Institutional Review Board (IRB) of Colorado State University, and the link was distributed to professionals working in the U.S. who were members of the Construction Management Association of America (CMAA) and the International Facility Management Association (IFMA). In addition, the authors asked their U.S. construction-industry based LinkedIn connections to complete the survey. Responses were collected during a four-week period.

4.2. Statistical Analysis

The statistical analysis in this study comprised two phases of quantitative investigation. Phase one (RQ 1) comprised an exploration of mean rankings for the 21 perceived benefits of, and the 19 perceived obstacles to, RCT adoption by the four stakeholder types. Next, mean differences were explored between groups using Analysis of Variance (ANOVA, RQ 2) for multi-level comparisons by stakeholder type and student *t*-tests (RQ 3) to explore mean differences on the two-level (commercial vs. infrastructure) analyses.

Phase two of the research study comprised exploratory factor analysis (EFA). As previously noted, the authors reviewed numerous research studies and industry websites to gather a list of perceived benefits and obstacles to construction technology as well as RCT-specific adoption. Exploration of the groupings of the benefits and obstacles in the survey instrument (e.g., factor structure) was conducted to investigate evidence of the face validity of these perceptions. That is, EFA was conducted to investigate whether benefits and obstacles selected from previous studies empirically loaded in accordance with the literature review and reported industry practices from technology companies.

According to Pett et al. [28], “The decision as to the number of factors to be retained [in EFA] should be based on an artful combination of the outcomes obtained from statistical indicators, the factors’ theoretical coherence, a desire for simplicity, and the original goals of the factor analysis project”. Therefore, the RCT benefits and obstacles in the survey were treated as distinct and separate lists, and the emergent factor structure was evaluated independently. An unrotated factor solution rarely provides meaningful and understandable item clusters, and often indicates a general factor which may be a statistical artifact [28]. Therefore, Principal Component Analysis was employed and a Varimax rotated factor solution was used to identify the emergent factor structure. Eigenvalues ≥ 0.40 were the initial criterion for survey item investigation. Items with a factor loading ≥ 0.40 on multiple factors were evaluated and assigned to groups based on their theoretical coherence as suggested by Pett et al. [28].

Finally, in phase two, post EFA factor means were calculated for the four groupings for RCT benefits and obstacles. Following these calculations, mean comparisons were explored between RCT benefit and obstacle groupings using ANOVA (RQ 4a and 4c) for multi-level comparisons by stakeholder type and student *t*-tests (RQ 4b and 4d) to explore mean differences on the two-level (commercial vs. infrastructure) analyses.

5. Results

5.1. Sample and Data Screening

In total, 540 respondents consented to complete the survey. The data were screened using a multi-step process to ensure that the sample comprised industry members who had some familiarity with RCTs. After defining RCTs for the participants as described in Section 4, the researchers solicited a dichotomous (e.g., yes or no) response from participants regarding whether they had ‘heard of RCT’. Survey respondents ($n = 83$) who identified that they had not heard of RCT were directed to the end of the survey. Missing responses for this item, e.g., participants ($n = 111$) who did not respond to the item asking if they had heard of RCT, were culled from the sample.

The 346 remaining respondents who had heard of RCT indicated their ‘primary role’ in the construction industry. The ‘primary role’ item was utilized to eliminate groups with minimal representation and establish five construction stakeholder categories; (1) Owners/Developers; (2) Designers (Architecture, Engineering); (3) Contractors (General

and Subcontractors); (4) Construction Managers/Owner Representatives; and (5) Design Build. It should be noted that only 20 of the consenting survey respondents identified ‘Facilities Management (FM)’ as their primary role. Due to the limited representation of FM stakeholders, as well as unequal sample sizes compared to other stakeholder groups, the authors chose a conservative approach and eliminated the FM group from the analysis, and plan to pursue a larger sample of FM stakeholders in future studies.

The survey included an ‘other’ selection option where participants could provide their ‘primary role’ as a text entry. The text entries were reviewed by the researchers and evaluated. Some respondents selected ‘Other’ and then listed one of the specified categories as the text entry. For example, an ‘other’ selection and text response of ‘A/E Design’ was regrouped in the ‘Designers’ category. However, an ‘other’ selection and text response such as ‘Project Management’, ‘Insurance Claims Adjuster’ or ‘Educator’ were culled, removing 28 responses from the sample, since it was unclear what stakeholder these respondents would best represent. The researchers noted that 11 respondents indicated ‘Design Build’ as their primary role via the text entry. Given that these participants were involved in both design and construction, they were grouped as a separate stakeholder category and included in the general analysis of RCTs Benefits and Obstacles to adoption. However, these respondents were excluded from analysis comparing mean responses by specific stakeholder groups (i.e., the comparison between Designer and Contractor stakeholders). Given this conservative data screening approach, it should be noted that sample sizes noted in the results table vary slightly between research questions.

Finally, the respondents were queried regarding their ‘primary industry sector’. The ‘primary sector’ item was utilized to eliminate groups with minimal representation and establish five construction stakeholder categories; (1) Commercial/Buildings (2) Civil/Infrastructure; (3) Military/Government; (4) Multiple Sectors. It was noted that only 7 participants indicated ‘single family residential’; these responses were culled due to the small sample size. Similar to the ‘primary role’ survey item, the instrument included an ‘other’ selection option where participants could provide their ‘primary role’ as a text entry. In total, 27 respondents selected ‘other’ as the ‘primary sector’ and provided responses such as ‘Government’ ‘Local Government’, and ‘Military’ without indicating vertical or horizontal construction. These respondents were grouped in the ‘Military/Government’ category. Six respondents indicated working in multiple sectors by selecting ‘other’ and providing text responses such as ‘infrastructure and buildings’ or ‘both commercial and infrastructure’. Given that these participants were involved in multiple construction sectors, they were grouped as a separate category and included in the general analysis of RCTs Benefits and Obstacles to adoption. However, these respondents were excluded from the analysis comparing mean responses by stakeholder-specific group (i.e., the comparison between designer and contractor stakeholders). Table 3 depicts the sample groupings by Stakeholder and Segment. Table 4 provides the level of awareness and personal experience with RCT by stakeholder.

Table 3. Sample Participants by Primary Role and Sector ($n = 278$).

Stakeholder	<i>n</i>	%	Industry Segment (<i>n</i>)			
			Commercial	Infrastructure	Government	Multiple
Owner/Developer	60	21.3	23	26	10	1
Designer	90	32.6	19	67	4	0
Contractor	45	16.3	33	9	2	1
CM/Owner Rep.	73	25.9	25	36	10	2
Design Build	10	3.9	4	3	1	2

Table 4. Sample Participants RCT Awareness and Experience with RCT ($n = 278$).

Stakeholder	n	%	Awareness and Experience *	
			Heard of RCT	Personal Exp. w/RCT
Owner/Developer	60	21.3	60	29 (48.3%)
Designer	90	32.6	90	42 (46.7%)
Contractor	45	16.3	45	27 (60.0%)
CM/Owner Rep.	73	25.9	73	23 (32.5%)
Design Build	10	3.9	10	6 (60.0%)

* Frequency of “Yes” responses.

5.2. Addressing the Research Questions (RQs)

As noted in the survey development section, all survey respondents reported their levels of agreement with benefits and obstacle statements in the survey based on a 5-point scale where 1 = Strongly Disagree and 5 = Strongly Agree. The following section revisits and presents the results for each RQ.

5.2.1. Phase 1—Data Analysis

RQ1 explored the mean rankings of the perceived benefits of, and obstacles preventing, the adoption of RCTs by construction stakeholders. For benefits, the mean rankings were above 3.24 for all stakeholders, indicating a slight level of agreement on average across all benefits listed in the survey instrument. Tables 5 and 6, respectively, provide the ‘top 5’ and ‘bottom 5’ ranked benefit means and standard deviations by stakeholder. Means in the 4–5 range equate to levels of agreement between “agree” and “strongly agree”.

Table 5. RCT Top 5 Ranked Benefits by Stakeholder ($n = 262$).

Owners/Developers ($n = 59$)	Mean	SD
Increased accuracy of existing condition documentation	4.41	0.619
Reduced time required to document existing conditions	4.36	0.866
Reduced number of site visits to collect data	4.27	0.868
Reduced time required to generate 3D models	4.19	0.937
Increased accuracy of the as-built documents	4.10	0.845
Arch/Engineer ($n = 90$)	Mean	SD
Increased accuracy of existing condition documentation	4.34	0.81
Reduced number of site visits to collect data	4.27	0.919
Reduced time required to document existing conditions	4.24	0.891
Increased accuracy of the as-built documents	4.22	0.731
Reduced time required to generate 3D models	4.20	0.974
Contractor ($n = 42$)	Mean	SD
Increased accuracy of existing condition documentation	4.29	0.995
Reduced time required to document existing conditions	4.29	0.97
Reduced time required to generate 3D models	4.12	0.916
Reduced number of site visits to collect data	4.07	1.113
Increased accuracy of the as-built documents	4.01	1.082
CM/Owners Rep. ($n = 71$)	Mean	SD
Increased accuracy of existing condition documentation	4.45	0.858
Increased accuracy of the as-built documents	4.27	0.916
Reduced time required to document existing conditions	4.26	0.943
Increased accuracy of construction documents	4.16	0.828
Increased speed of as-built document creation	4.16	0.895

Table 6. RCT Bottom Five Ranked Benefits by Stakeholder ($n = 262$).

Owners/Developers ($n = 59$)	Mean	SD
Reduced time required for quality assurance processes	3.58	0.986
Increased accuracy of prefabricated elements	3.51	0.989
Increased speed of installation of constructed elements	3.44	0.987
Reduced project duration	3.42	0.855
Reduced time required for quality control processes	3.42	0.986
Arch/Engineer ($n = 90$)	Mean	SD
Reduced overall project cost	3.57	0.912
Reduced time required for quality assurance processes	3.56	0.961
Increased accuracy of prefabricated elements	3.55	0.965
Reduced time required for quality control processes	3.5	0.963
Reduced project duration	3.4	0.872
Contractor ($n = 42$)	Mean	SD
Increased speed of installation of constructed elements	3.6	0.989
Reduced time required for quality control processes	3.59	0.999
Reduced time required for quality assurance processes	3.57	0.991
Reduced overall project cost	3.43	1.129
Reduced project duration	3.24	1.008
CM/Owners Rep. ($n = 71$)	Mean	SD
Reduced overall project cost	3.49	0.954
Reduced time required for quality assurance processes	3.48	0.908
Increased speed of installation of constructed elements	3.46	0.939
Reduced time required for quality control processes	3.35	1.001
Reduced project duration	3.31	0.767

For obstacles, the mean rankings were above 2.5 to 3.96 for all stakeholders, indicating a wider spread of average rankings from “disagree” to “agree”. The means and standard deviations by stakeholder for both the ‘top 5’ and ‘bottom 5’ obstacles to RCT adoption are provided in Tables 7 and 8, respectively. Means in the 3–4 range equate to levels of agreement between “neither agree or disagree” and “agree”, whereas means in the 2–3 range represent levels of agreement between “disagree” and “neither agree or disagree”.

Table 7. RCT Top 5 Obstacles by Stakeholder ($n = 248$).

Owner/Developer ($n = 58$)	Mean	SD
Lack of in-house expertise	3.79	0.987
Lack of project-level budget	3.59	1.069
Lack of training	3.58	0.951
Lack of Owner/Client demand	3.51	0.954
Cost of hiring employees with the required skills	3.44	0.915
Designer ($n = 86$)	Mean	SD
Lack of owner/client demand	3.61	1.082
Lack of project-level budget	3.61	1.139
Lack of in-house expertise	3.37	1.284
Lack of training	3.36	1.147
High cost of the equipment	3.35	0.983
Contractor ($n = 38$)	Mean	SD
Lack of Owner/Client demand	3.63	1.125
Lack of project-level budget	3.50	1.247
High cost of the equipment	3.49	0.885
Lack of in-house expertise	3.46	1.189
RCT is not a company priority	3.36	1.112
CM/Owners Rep. ($n = 68$)	Mean	SD
Lack of Owner/Client demand	3.96	0.888
Lack of project-level budget	3.94	0.844
Lack of in-house expertise	3.75	1.07
Lack of company budget	3.68	1.071
Lack of training	3.63	0.913

Table 8. RCT Bottom Five Obstacles by Stakeholder ($n = 248$).

Owner/Developer ($n = 59$)	Mean	SD
RCT is not important for the projects I work on	2.86	1.008
Not able to justify the return on investment	2.86	1.025
Not able to bill RCT costs to my projects	2.78	0.948
Data collection too time consuming	2.73	0.868
Risk/liability concerns	2.59	0.931
Designer ($n = 88$)	Mean	SD
Not being able to justify the return on investment	2.89	1.146
Risk/liability concerns	2.88	1.111
Data processing too time consuming	2.86	1.047
RCT is not important for the projects I work on	2.76	1.114
Data collection too time consuming	2.50	0.967
Contractor ($n = 39$)	Mean	SD
Lack of user-friendliness of the related software	3.03	0.778
RCT is not important for the projects I work on	2.95	1.297
Data collection too time consuming	2.87	0.978
Lack of user-friendliness of the equipment	2.87	0.864
Risk/liability concerns	2.67	0.898
CM/Owners Rep. ($n = 68$)	Mean	SD
Lack of user-friendliness of the equipment	2.99	0.743
Data processing too time consuming	2.97	0.81
Data collection too time consuming	2.94	0.879
Risk/liability concerns	2.94	0.896
RCT is not important for the projects I work on	2.87	1.05

RQ2 explored the differences in mean level of agreement in perceived benefits of, and obstacles to, the adoption of RCTs. ANOVA results revealed no significant difference in mean perceptions of the benefits of, and obstacles to, the adoption of RCTs construction stakeholder type at the $p < 0.05$ level.

RQ3 investigated differences in mean level of agreement in perceived benefits of, and obstacles to, the adoption of RCTs. For Benefits, t -test results revealed a significant difference ($t = 2.13$, $p = 0.03$) in means by industry sector on the ‘Increased accuracy of prefabricated elements’ being an RCT adoption benefit. Specifically, while both sectors indicated a slight level of agreement, on average, commercial industry stakeholders agreed more strongly ($M = 3.75$, $SD = 1.03$) that ‘increased accuracy of prefabricated elements’ was a benefit of RCT adoption than did their Infrastructure sector counterparts’ ($M = 3.47$, $SD = 0.92$).

For obstacles to RCT adoption, t -test results revealed significant differences in means by industry segment on ‘RCT is not a company priority’, ‘Lack of company budget’, and ‘Data collection is too time consuming’ at the $p < 0.05$ level. In all cases, significantly higher mean levels of agreement on the obstacles to RCT adoption were observed for commercial sector stakeholders when compared to the means of their Infrastructure sector counterparts. The results of the t -tests are provided in Table 9.

Table 9. Obstacles to RCT Adoption by Commercial and Infrastructure Sectors.

Obstacles	n	M	SD	t	df	p
RCT is not a company priority				2.154	228	0.032
Commercial Sector	98	3.46	1.037			
Infrastructure Sector	132	3.14	1.14			
Lack of company budget				2.054	229	0.041
Commercial Sector	98	3.58	1.13			
Infrastructure Sector	133	3.27	1.142			
Data collection is too time consuming				2.487	225	0.014
Commercial Sector	96	2.9	0.989			
Infrastructure Sector	131	2.58	0.911			

5.2.2. Phase 2—Exploratory Factor Analysis

Phase two of the research study comprised exploratory factor analysis (EFA). As previously noted, the authors reviewed numerous research studies and industry websites to gather a list of perceived benefits and obstacles to technology and RCT adoption. In addition, the purpose of the EFA was to separately investigate the empirical loadings of RCT benefit and obstacle survey items for comparison to previous research and reported industry practices.

5.2.3. Sampling Adequacy for EFA and Internal Consistency Reliability

The Kaiser-Meyer-Olkin (KMO) test was performed to ensure adequate sample size ($n = 278$) for the EFA. The KMO test yielded a score of 0.91 for RCT Benefits and 0.88 for RCT Obstacles. According to Field [29], a KMO value between 0.80 and 0.90 is considered ‘great’ evidence for sample adequacy when performing EFA. Internal consistency reliability statistics (α) of 0.94 and 0.92 were observed for RCT Benefits and RCT Obstacles, respectively.

For RCT Benefits, four factors emerged in the rotated factor solution using total eigenvalue > 1.00 as a threshold for initial factor identification [28]. Investigation of the RCT Benefits factor structure indicated six items loaded on a ‘Reduced Project Risk’ factor (grouping 1), six items loaded on a ‘Increased Quality’ factor (grouping 2), five items loaded on an ‘Accuracy of Existing and Constructed Work’ factor (grouping 3) and four items loaded on a ‘Speed of Documentation’ factor (grouping 4). Eigenvalue loadings and the emergent four-factor structure (e.g., factor groupings) for RCT Benefits is provided in Table 10.

Table 10. Exploratory Factor Analysis—Perceived RCT Benefits.

Rotated Component Matrix	Factor Grouping			
	1	2	3	4
Reduced overall project cost	0.596			
Reduced project duration	0.669			
Reduced project risk	0.570			
Reduced time required for quality assurance processes	0.768			
Reduced time required for quality control processes	0.771			
Reduced rework to correct errors in the field	0.589			
Increased construction quality		0.554		
Increased accuracy of installed work		0.637		
Increased accuracy of surveying/layout		0.497		
Increased accuracy of the constructed system locations		0.613		
Increased speed of installation of constructed elements		0.735		
Increased accuracy of prefabricated elements		0.771		
Increased accuracy of the as-built documents			0.512	
Reduced rework during design			0.727	
Reduced number of site visits to collect data			0.599	
Increased accuracy of existing condition documentation			0.772	
Increased accuracy of construction documents			0.680	
Reduced time required to generate 3D models				0.756
Reduced time required to document existing conditions				0.518
Increased speed of as-built document creation				0.583
Increased speed of surveying/layout				0.640

For RCT Obstacles, four factors emerged in the rotated factor solution using a total eigenvalue > 1.00 as a threshold for initial factor identification [28]. One RCT Obstacle item (Risk/Liability Concerns) failed to load above the >0.50 benchmark and was therefore removed from the item list. The EFA was conducted with the remaining 18 RCT Obstacle items. Investigation of the RCT Obstacles factor structure indicated that seven items loaded on a ‘Lack of Demand/Budget’ factor (grouping 1), five items loaded on a ‘Hardware/Software Issues’ factor (grouping 2), four items loaded on a ‘Workforce and Training’ factor (grouping 3) and two items loaded on a ‘Data Collection/Processing’

factor (grouping 4). Eigenvalue loadings and the emergent two-factor structure (e.g., factor groupings) for RCT Obstacles is provided in Table 11.

Table 11. Exploratory Factor Analysis—Perceived RCT Obstacles.

Rotated Component Matrix	Factor Grouping			
	1	2	3	4
RCT is not a company priority	0.608			
RCT is not important for the projects I work on	0.697			
Lack of Owner/Client demand	0.687			
Lack of company budget	0.754			
Lack of project-level budget	0.745			
Not being able to bill RCT costs to my projects	0.633			
Not being able to justify the return on investment	0.739			
High cost of the equipment		0.693		
Lack of user-friendliness of the equipment		0.721		
High cost of the related software		0.799		
Lack of user-friendliness of the related software		0.789		
Lack of software interoperability		0.711		
Lack of in-house expertise			0.841	
Cost of hiring employees with the required skills			0.811	
Lack of training			0.86	
Lack of time for training			0.764	
Data collection too time consuming				0.804
Data processing too time consuming				0.789

RQ4a explored mean differences in the emergent factor groupings for ‘RCT Benefits’, (1) ‘Reduced Project Risk’, (2) ‘Increased Quality’, (3) ‘Accuracy of Existing and Constructed Work’, and (4) ‘Speed of Documentation’, by stakeholder type. ANOVA results revealed no significant difference in mean RCT benefit groupings by construction stakeholder type at the $p < 0.05$ level.

For RQ4b, a *t*-test exploring mean differences in the emergent factor groupings for ‘RCT Benefits’ between Commercial and Infrastructure revealed no significant findings at the $p < 0.05$ level.

RQ4c explored differences in the emergent factor groupings for ‘RCT Obstacles’; (1) ‘Lack of Demand/Budget’, (2) ‘Hardware/Software Issues’, (3) ‘Workforce and Training’, and (4) ‘Data Collection/Processing’ by stakeholder type. ANOVA results revealed a significant difference in mean perceptions on the ‘Lack of Demand/Budget’ RCT obstacle grouping ($F = 2.404$, $df = 4$, $p = 0.047$). Post-hoc plan comparisons reveal that the significant difference ($t = 2.49$, $p = 0.013$) in mean level perception of ‘Lack of Demand/Budget’ was observed between ‘Designers’ ($n = 81$, $M = 3.20$, $SD = 0.72$) and ‘CM/Owners Representatives’ ($n = 67$, $M = 3.52$, $SD = 0.76$).

For RQ4d, *t*-test results revealed significant differences in means by industry segment on RCT obstacle groupings for ‘Lack of Demand/Budget’ and ‘Data collection/processing’ at the $p < 0.05$ level. In all cases, significantly higher mean levels of agreement on the obstacles to RCT adoption were observed for Commercial sector stakeholders when compared to the means of their Infrastructure sector counterparts. The results of the *t*-tests are provided in Table 12.

Table 12. Obstacle Grouping RCT by Commercial and Infrastructure Sectors.

Obstacles Grouping	<i>n</i>	M	SD	<i>t</i>	df	<i>p</i>
‘Lack if Demand/Budget’				2.439	223	0.016
Commercial Sector	93	3.47	0.74			
Infrastructure Sector	132	3.21	0.85			
‘Data Collection/Processing’				2.257	225	0.025
Commercial Sector	96	2.98	0.91			
Infrastructure Sector	131	2.71	0.87			

6. Discussion

6.1. RQ1: How Do Construction Stakeholders Perceive and Rank the Benefits of, and Obstacles Preventing, the Adoption of RCTs?

6.1.1. Stakeholder Perceptions of the Benefits of the Adoption of RCTs

In general, all stakeholders agreed with 19 out of 21 benefits offered in the survey and neither disagreed nor agreed that RCTs were beneficial for reducing the time required for quality control processes or reducing project duration. An analysis of the top five benefits revealed that the means of responses were between 4.0 and 4.45 for all four stakeholder groups, indicating their agreement with these benefits of RCTs. Specifically, increased accuracy of existing condition documentation, reduced time required to document existing conditions, and increased accuracy of the as-built documents were among the top five benefits for all four groups of respondents. Documenting existing conditions and creating as-builts are some of the major applications of the RCTs with which the study respondents might be more familiar and, therefore, they expressed their higher level of agreement with benefits of fast and accurate data collection with RCTs compared to more traditional approaches. These findings align with those of the previous studies that consistently indicated the accuracy of collected data [4,14,22] and quick data collection [1,10,12,20] as the major benefits of using RCTs.

A reduced number of site visits to collect data and the reduced time required to generate 3D models were among the top five benefits indicated by the Owners/Developers, Designers, and Contractors. These stakeholders are the direct users of the point cloud data in the planning, design and construction phases of a project and, thus, had an opportunity to experience these benefits. Since highly accurate and comprehensive data are collected only once, there is no need to return to the site for additional measurements. The process for point cloud data output, registration and integration into BIM applications is becoming more user-friendly, resulting in less time required for 3D modeling. These findings support the statement of RCT suppliers such as Autodesk [14] and Leica [4] that revealed the same two RCT benefits for Designers and Contractors. Interestingly, these two benefits do not appear among the top five benefits of the CM/Owner Representative group; instead, they indicated the increased accuracy of construction documents and the increased speed of as-built document creation as their fourth and fifth top benefits. This perception could be a result of the more significant involvement of CM/Owner Representatives in using construction documents and creating as-builts and, based on that experience, they perceived these two applications of RCTs as most beneficial. This finding is a contribution of our study since it was not identified by previous research.

Regarding the bottom ranked benefits with which stakeholders ‘neither agreed nor disagreed’ or ‘agreed’ (means of responses ranging from 3.24 to 3.60), reduced time required for QA and QC processes, and reduced project duration were indicated by all four groups of stakeholders. This was not an expected finding since reality capture is a quick method for recording installed work conditions and evaluating work quality. In addition, recording installed work throughout the construction phase of the project and creating as-builts is faster with the use of RCTs compared to traditional methods and, therefore, should contribute to the shorter overall duration of a project. The finding about project duration contradicts those of Leica [4], Dodge Data and Analytics [13] and Ogunrinde et al. [2] that found that RCT implementation benefits contractors by decreasing project duration.

Similarly, Autodesk [14] and Leica [4] posit that RCT helps Contractor and CM/Owner Representatives with improving QC, which is in contrast with our findings.

Owners, Contractors, and CM/Owner Representatives perceived increased speed of installation of constructed elements to be among the bottom five benefits, with the means of responses being close to the border line between the 'neither agree nor disagree' and 'agree' ratings. This may indicate that respondents have not utilized RCTs extensively during installation of the constructed elements and perceived this approach to be less beneficial. Increased accuracy of prefabricated elements due to the use of RCTs was among the bottom five benefits according to Owners and Designers. This perception might result from these two respondent groups not working on prefabricated or modular construction projects, or the 'prefabrication' may occur post-design among contractors (i.e., mechanical, electrical and plumbing trades) to promote efficient project execution. These findings represent one research contribution which might be due to the recent proliferation of prefabrication in construction that was not evident in previous studies.

One interesting finding is that reduced overall project cost was among the bottom five benefits for Designers, Contractors and CM/Owner's Representatives; however, means of responses were still in the 'neither agree nor disagree/agree' range. Since RCTs provide very accurate point cloud data and increase the ability to visualize and discover errors in project data early on, the number of change orders and rework are minimized. Thus, our expectation was that respondents would report a strong perception that RCT implementation lowered the overall cost of projects. It would be useful to explore this finding further by specifically asking respondents if they track ROI and evaluate the cost effectiveness of RCTs compared to the overall project cost. This finding was notably lower than that of Dodge Data and Analytics [13], which indicated that an important contractor benefit from RCT was reduced project cost.

6.1.2. Stakeholder Perceptions of the Obstacles Preventing the Adoption of RCTs

According to all four groups of respondents, lack of in-house expertise, lack of Owner/Client demand, and lack of project-level budget were among the top five obstacles that prevented RCT adoption. Our findings confirm that of Alomari et al. [11], who also indicated that lack of in-house expertise was an obstacle to RCT adoption by contractors. However, no other studies revealed that project stakeholders perceived the lack of Owner/Client demand and lack of project-level budget as obstacles to RCT adoption; therefore, these findings represent a study contribution. Companies that are interested in the adoption of RCT should aim to educate Owners/Clients about the benefits of utilizing RCTs on projects. Specifically, these include the benefits of obtaining higher-quality project deliverables and promoting owner understanding of the project design and construction progress. Consequently, the lack of a project-level budget could potentially be alleviated if owners had a better understanding of the benefits of RCT which could increase their willingness to pay for these services. Since the use of RCTs can require specialized skills, it is important that the company's top management provides support for developing in-house expertise by training current employees or hiring new employees that possess adequate RCT knowledge.

Lack of training was also identified as one of the top five obstacles by all stakeholder groups except Contractors. Contractors most likely utilize RCTs more than other stakeholders and, due to that practical experience with RCT, they neither agreed nor disagreed that lack of training is an obstacle to adoption. This finding is in contrast with the Dodge Data and Analytics [13] study which reported that contractors indicated that the lack of training was a barrier to RCT adoption. Similarly, Contractors and Designers indicated that the high cost of the RCT equipment was one of the top five barriers. This finding aligns to those of Alomari et al. [11] and Ogurinede et al. [2], who also found that high equipment cost was perceived as an obstacle by Contractors. Designers and Contractors are direct users of point cloud data for documenting existing conditions for use in design, or as-built data captured during the construction phase of a project. Therefore, they would benefit from

in-house RCT services. However, that would require purchasing or renting RCT equipment, and while prices have decreased over time, they may still not be affordable, especially for smaller companies.

Only the Owners stakeholder group reported the cost of hiring employees with the required skills as being among the top five obstacles. This is an encouraging finding indicating that Designers, Contractors, and CM/Owner Representatives did not perceive this cost as a major obstacle to the adoption of RCTs. That is, stakeholders that typically hire professionals with the RCT skills didn't perceive this as a top-5 barrier, whereas Owners' perceptions may be indirect and based on their projects as opposed to the direct hiring of RCT professionals.

A lack of company budget was among the top five obstacles only for CM/Owner Representatives. This is an important finding because it indicates that all respondents besides CM/Owner Representatives may be able to allocate budgets for RCT implementation. However, this finding also indicated that CM/Owner Representatives may be unable to compensate other stakeholders within the project budget for these services. This provides further evidence that Contractors and Designers may need to justify RCT cost through project-level cost savings captured through practices that save money, resulting in increased efficiency, reduced rework, etc.

We also analyzed the bottom five obstacles to adoption of RCTs by the four stakeholder groups. The means of responses for the bottom ranked obstacles ranged from 2.5 to 3.03. Responses under 3.0 trended toward slight disagreement and those closer to 3.0 indicate neither agreement nor disagreement that a given obstacle prevented RCT adoption. For example, RCT not being important for the projects they work on, data collection being too time consuming, and risk/liability concerns were among the bottom five obstacles for all four stakeholders. This is an encouraging finding, since it shows that the respondents perceived that RCT was important for their projects, that data collection was not too time consuming, and that risk/liability concerns did not negatively affect decisions about RCT use.

Another promising result is that, according to Owners and Designers, not being able to justify RCT-related ROI was among the bottom five obstacles. This indicates that these stakeholders recognize the value of RCTs with respect to upfront costs. For designers, the expenses they may need to justify via ROI include direct investment into RCT equipment, software, and personnel training. This is particularly important in the case of Owners, since they pay, directly or indirectly, for project-level RCT services. According to Owners, not being able to bill RCT costs to their projects was among the bottom five obstacles. This is an important finding demonstrating Owner willingness to pay for RCT services. It is also a new finding discovered by our study and one not found by previous research.

With the exception of Contractors, who reported a slight agreement that time consuming data processing was an obstacle to RCT adoption, all stakeholders reported slight disagreement that the time-consuming nature of RCT data processing prevents adoption. This finding is interesting because, in the recent past, significant time investment was required for post-processing to produce 'usable' point cloud data. Notably, all stakeholders reported slight disagreement that the time-consuming nature of RCT data collection prevents adoption. These findings provided support for the advertised advancements from RCT hardware and software producers [4,14]. One potential explanation why the time-consuming data processing was an obstacle to RCT adoption for Contractors might be that field decision making often happens much more quickly than initial design development. That is, the need for 'real-time' data may be a more challenging obstacle to RCT adoption for Contractors than other stakeholders.

Lack of user-friendliness of the equipment was among the bottom five obstacles according to Contractors and CM/Owner Representatives. These two stakeholder groups might perceive that either the RCT equipment was user-friendly or that, even if the RCT equipment was not user-friendly, it did not prevent them from using it. In either case, this finding is promising since it shows that for stakeholders, who are directly involved in the construction phase, lack of equipment user-friendliness is not a significant barrier to RCT

use. This finding confirms those of previous studies. Similarly, lack of user-friendliness of the related software was among the bottom five obstacles for Contractors, indicating their perception of the software being simple to use and, thus, not preventing them from adopting RCT during the construction phase. However, according to the study by [13], contractors stated that the improved user-friendliness of RCT software would help RCT adoption, which is in contrast with our findings.

6.2. RQ2: Are Significant Differences in Perceptions of the Benefits of, and Obstacles Preventing, the Adoption of RCTs Observed When Compared by Construction Stakeholders?

ANOVA comparisons of the mean responses of the four stakeholder groups revealed no significant differences (at the $p < 0.05$ level) between perceptions of the benefits of, and obstacles preventing, the adoption of RCTs. This is an important finding because it shows consistent perceptions and agreements among the Owners/Developers, Designers, Contractors and CM/Owner Representatives. The following findings differed from our expected hypothesis, shedding new light on the perceived benefits of, and obstacles preventing, RCT adoption. For example, we anticipated that Designers might agree more strongly that reduced rework during design and increased accuracy of construction documents were RCT benefits compared to the other stakeholders since they are directly involved in the project design process. However, this hypothesis was not confirmed in the current study. Similarly, it seemed logical that Contractors would perceive increased accuracy of the constructed system locations, increased accuracy of prefabricated elements and increased construction quality to be significantly more beneficial as compared to the other stakeholders. Again, this result was not empirically reflected in our analysis. Regarding obstacles, we anticipated that there might be significant differences in perceptions between Owners, Designers and Contractors. For example, it seemed logical that the Owners might report significantly higher mean perception than other stakeholders that the lack of Owner/Client demand and inability to justify the return on investment were major obstacles to RCT adoption. Similarly, we expected that Designers and Contractors would report significantly higher levels of agreement than Owners that the lack of project-level budget, not being able to bill RCT costs to their projects, data collection and data processing being too time consuming, as well as the cost of hiring employees with the required skills were significant obstacles to RCT adoption. Again, these hypotheses were rejected in the current study.

In general, it is unique and valuable to discover that all four stakeholder groups reported similar perceptions and expressed similar levels of agreement regarding the RCT benefits and obstacles included in the survey. That is, in practical terms, we could not empirically identify (at the $p < 0.05$ level) the probable stakeholder type of a given respondent based solely on the reported mean perception of a given RCT benefit or obstacle. While previous studies investigated some of these aspects for one stakeholder group or for multiple technologies in general [2,10,11], no previous studies comparing perceptions between different stakeholders specific to the benefits of, and obstacles to, RCT adoption in construction were found. Therefore, this finding is an important contribution to the research in the area of RCT implementation in construction.

6.3. RQ3: Are Significant Differences in Perceptions of the Benefits of, and Obstacles Preventing, the Adoption of RCTs Observed When Compared by Construction Industry Sector?

t-Test comparisons of the mean responses of the stakeholders from commercial and infrastructure sectors indicated significant differences in the perceived level of agreement that increased accuracy of prefabricated elements was a benefit of RCT implementation. Specifically, respondents from the commercial building sector reported significantly higher levels of agreement than did respondents from the infrastructure sector. This was an interesting finding, since prefabricated construction is utilized in commercial building and infrastructure projects and presumably both sectors could benefit from accurate reality capture during the manufacturing and installation of prefabricated components. One explanation for this finding might be that the respondents from the commercial sector may be ‘fitting’ prefabricated components within other, and sometimes existing, structures,

whereas prefabricated items such as steel or precast bridge components make up a large portion of the infrastructure scope of work and have been created without RCT for many years, reducing the perceived benefit of RCT for that industry segment. Overall, for the remaining benefits, similar to RQ2, it was useful to find that the respondents consistently agreed with the benefits that RCTs bring, regardless of the sector they belong to or the type of projects they work on.

t-Test comparisons revealed that the respondents from the commercial sector reported significantly higher levels of agreement than did respondents from the infrastructure sector that ‘RCT not being a company priority’, ‘lack of company budget’, and ‘data collection being too time consuming’ are obstacles to adoption. This may indicate that respondents in the infrastructure sector might be giving higher priority to RCT adoption. However, while mean differences were significant ($p < 0.05$), it should be noted that mean responses for both sectors were in the same range, that is, respondents reported only slight levels of agreement that these obstacles hindered RCT adoption. Regarding company budget availability for RCT adoption, our findings showed that the lack of company budget is a larger obstacle for the commercial sector than for the infrastructure sector. Commercial sector respondents reported levels of agreement with this obstacle in the ‘agree’ category, while the respondents from the infrastructure sector neither agreed nor disagreed with this obstacle. The reason for this might be that our respondents were employed by larger infrastructure/civil companies that have higher business volume and, therefore, more resources to invest in RCT adoption. Respondents from both sectors neither agreed nor disagreed that ‘data collection being too time consuming’ is an obstacle to RCT adoption. However, the reason for a significant difference in the perceptions of the respondents from the two sectors may be that the respondents from the commercial sector were involved in projects that require more scans, and hence more time for obtaining reality capture data. That is, commercial buildings may include many rooms that require scanning, whereas highway projects may allow for fewer long-distance scans to collect comprehensive data. These findings are valuable since there were no previous studies that compared perceptions about the benefits of, and obstacles to, the adoption of RCT by the construction industry sector.

Previous research explored some of these aspects for either one construction sector only or in some cases for the entire construction industry, or investigated multiple technologies in general [2,9–11]. However, the authors found no previous studies comparing perceptions between different construction industry stakeholders or sectors specific to the benefits of, and obstacles to, RCT adoption in construction. Therefore, these findings represent a novel contribution to the research on RCT implementation in construction.

6.4. RQ4: Do the Perceived Benefits of, and Obstacles Preventing, the Adoption of RCTs Group in a Logical Factor Structure Resultant Exploratory Factor Analysis?

EFA demonstrated that the following six RCT benefit items loaded together in a ‘reduced project risk’ benefit grouping: (1) reduced overall project cost, (2) reduced project duration, (3) reduced project risk, (4) reduced time for QA, (5) reduced time for QC, and (6) reduced rework to correct errors in the field. These six items loaded in a logical order, suggesting their interdependence. For example, reduced rework to correct errors will result in both reduced project cost and project duration. Similarly, reduced project risk may lead to reduced project cost, while less time spent on QA and QC may also decrease overall project duration. Our findings about reduced project cost align with those of Leica [4], Dodge Data and Analytics [13], Bademosi and Issa [10], Almukhtar et al. [1], Wang and Kim [12], Ham and Lee [18], and Tang et al. [17]. We found that RCT use results in reduced project duration, confirming the findings of Dodge Data and Analytics [13], Bademosi and Issa [10], Almukhtar et al. [1], Wang and Kim [12], Ham and Lee [18], Sepasgozaar et al. [19], Ogunrinde et al. [2] and Yen et al. [22]. Similar to our study, Ogunrinde et al. [2], Tang et al. [17], and Aryan et al. [21] found that RCT use improves QA/QC, while the findings of Dodge Data and Analytics [13], Bademosi and Issa [10], Almukhtar et al. [1],

Wang and Kim [12], Sepasgozaar et al. [19], and Yen et al. [22] revealed the same result as our study, that is, that RCT is beneficial since it reduces rework.

The following six RCT benefit items loaded together in an ‘increased quality’ benefit grouping: (1) increased construction quality, (2) increased accuracy of installed work, (3) increased accuracy of surveying/layout, (4) increased accuracy of the constructed system locations, (5) increased speed of installation of constructed elements, and (6) increased accuracy of prefabricated elements. All of these RCT benefits are interconnected in that they address ‘accuracy and speed of construction’. For instance, increased accuracy of surveying/layout results in increased accuracy of the constructed system locations, increases the accuracy of installed work, and increased the speed of installation of constructed elements with the achievement of increased construction quality as the ultimate benefit. The increased accuracy of prefabricated elements also has a positive impact on construction quality. Our findings correspond to those of the previous studies. For example, Tang et al. [17] also found that RCT increases construction quality, while Wu et al. [20], Bademosi and Issa [10], Almukhtar et al. [1], Wang and Kim [12], Psomas et al. [3], Yen et al. [22], and Salameh and Tsai [9] identified the increased accuracy of surveying/layout, and these two RCT benefits mirror our study finding. The remaining four benefits in this grouping were identified by this research only, which represents another contribution to the body of knowledge.

EFA demonstrated that the following five RCT benefit items loaded together in an ‘accuracy of existing and constructed work’ benefit grouping: (1) increased accuracy of the as-built documents, (2) reduced rework during design, (3) reduced number of site visits to collect data, (4) increased accuracy of existing condition documentation, and (5) increased accuracy of construction documents. Given the accuracy of reality capture data obtained by RCTs, fewer site visits to collect data are required, and less rework is needed during the design phase. Since RCTs provide accurate existing condition data, the accuracy of construction documents and as-built documents also increased. These findings align to those of the previous studies, e.g., Aryan et al. [21] and Yen et al. [22] also found that increased accuracy of the as-built documents is a benefit of using RCT. Similar to our study, Bademosi and Issa [10], Almukhtar et al. [1], and Sepasgozaar et al. [19] identified reduced rework during design as a direct benefit of RTCs, Yen et al. [22] pointed out that RTCs were beneficial for increasing accuracy of existing condition documentation, and Alomari et al. [11] also stated that RCT utilizations increase the accuracy of construction documents.

The following four RCT benefit items loaded together in a ‘speed of documentation’ benefit grouping: (1) reduced time required to generate 3D models, (2) reduced time required to document existing conditions, (3) increased speed of as-built document creation, and (4) increased speed of surveying/layout. Use of RCTs promoted faster site surveying and site layout, faster documentation of existing conditions with the use of reality capture data, faster generation of 3D models because of the availability of the accurate 3D reality capture data, and faster creation of as-built documents due to fast and accurate reality capture. Our findings are similar to those of the previous studies, for example, Alomari et al. [11] found that RCTs help reduce the time required to generate 3D models, Wu et al. [20], Bademosi and Issa [10], Almukhtar et al. [1], Wang and Kim [12], and Yen et al. [22] indicated that RCT use reduces time required to document existing conditions, and Salameh and Tsai [9] found that the speed of as-built document creation increases with the use of RCTs.

EFA demonstrated that the following seven RCT obstacle items loaded together in a ‘lack of demand/budget’ obstacle grouping: (1) RCT is not a company priority, (2) RCT is not important for the projects they work on, (3) lack of Owner/Client demand, (4) lack of company budget, (5) lack of project-level budget, (6) inability to bill RCT costs to their projects, and (7) inability to justify the return on investment. These seven items loaded in a logical grouping, suggesting their interdependence. For example, if the Owner/Client do not require RCT use on their projects, RCT adoption is not a priority of a company, or

RCT use is not important for projects, it is likely that the adoption of RCTs will be slow. Similar to the demand-related obstacles, if the budget is insufficient at the company or project level, the RCTs cost cannot be billed to a project, and return on investment into RCTs cannot be justified, therefore the RCT adoption will be slow or non-existent. Similar to Bademosi and Issa's [10] research, our study found that not being able to justify the return on investment is an obstacle that prevents RCT adoption. The six obstacles in this EFA grouping were discovered by our research, and therefore represent a contribution to the body of knowledge.

The following five RCT obstacle items loaded together in a 'hardware/software issue' grouping, (1) high cost of the equipment, (2) lack of user-friendliness of the equipment, (3) high cost of the related software, (4) lack of user-friendliness of the related software, and (5) lack of software interoperability. The loading of these five items in a logical order indicates their interdependence. The perceived high cost of both RCT equipment and related software prevents the adoption of RCTs. In addition, the lack of user-friendliness of equipment and software and the lack of software interoperability are interrelated barriers to RCT adoption. These findings align to those of the previous studies. For example, Yen et al. [22], Ogunrinde et al. [2], Psomas et al. [3], Fathi et al. [23], Tang et al. [17], Bademosi and Issa [10], Wu et al. [20], Alomari et al. [11], and Almkhtar et al. [1] also found that expensive RCT equipment and expensive related software prevents RCT adoption. Similarly, our findings about lack of user-friendliness of the equipment as a barrier to RCT adoption confirm those of Wu et al. [20], Alomari et al. [11], Almkhtar et al. [1], and Bademosi and Issa [10]. Additionally, the results related to lack of user-friendliness of the related software and lack of software interoperability are aligned with the findings of Bademosi and Issa [10] and Almkhtar et al. [1].

EFA demonstrated that the following four RCT obstacle items loaded together in a 'workforce and training' obstacle grouping: (1) lack of in-house expertise, (2) cost of hiring employees with the required skills, (3) lack of training, and (4) lack of time for training. All four items are strongly related; for example, lack of in-house expertise would require either hiring employees with the necessary experience or training current employees to obtain RCT skills. Either approach requires investment, as there is an associated cost for hiring new employees as well as the cost and time that are needed to train current employees. Each of these four items is individually an important obstacle, but combined they could have even larger, compounding negative effects on RCT adoption. Our study confirms that the lack of RCT skills is an obstacle to the adoption of RCTs, similar to the findings of Sepasgozaar et al. [19], Bademosi and Issa [10], Alomari et al. [11], and Almkhtar et al. [1]. Additionally, we confirmed the findings of several authors: Sepasgozaar et al. [19], Bademosi and Issa [10], Alomari et al. [11], Almkhtar et al. [1], Yen et al. [22], Ogunrinde et al. [2], Psomas et al. [3], and Fathi et al. (2015), who identified that the lack of training is an obstacle. However, this finding contradicts that of Wu et al. [20], whose study showed that operating RCT requires minimal employee training and technical skills. Lack of time for training is another barrier discovered by our study, which is similar to the findings of Yen et al. [22], Ogunrinde et al. [2], Psomas et al. [3], and Fathi et al. [23].

In a 'data collection and processing' obstacle grouping, the following two RCT obstacles loaded together: (1) data collection is too time consuming, and (2) data processing is too time consuming. These two items loaded in a logical order, indicating a strong relationship between the perceived time investment required for both data collection using RCTs and then the processing of the collected data. These findings align to those of the previous studies of those such as Salameh and Tsai [9], who also found that data collection is too time consuming, and Wu et al. [20], Sepasgozaar et al. [19] and Salameh and Tsai [9], who indicated that data processing is too time consuming.

6.5. RQ4a: Are Significant Differences in the Emergent Factors of ‘RCT Benefits’ Observed When Compared by Construction Stakeholders?

Regarding differences in perceptions of the RCT benefit groupings when compared by construction stakeholders (RQ4a), an ANOVA showed that there were no significant differences among respondent perceptions about ‘reduced project risk’, ‘increased quality’, ‘accuracy of existing and constructed work’, or the ‘speed of documentation’ groupings of the RCT benefits items given the construction stakeholder (i.e., Owner/Developer, Designer, Contractor, CM/Owner Representative). This is a useful and expected finding, since all four stakeholder groups can benefit from reduced project risk, accurate work, increased project quality, and faster documentation. Additionally, since there was no previous EFA-based research that explored if there were significant differences between perceptions of construction stakeholders about RCT benefits, these findings are a contribution of our study.

6.6. RQ4b: Are Significant Differences in the Emergent Factors of ‘RCT Benefits’ Observed When Compared by Construction Industry Sector?

Similar to RQ4a, the *t*-test comparison of RCT benefit groupings revealed no significant differences between respondent perceptions regarding the ‘reduced project risk’, ‘increased quality’, ‘accuracy of existing and constructed work’, or ‘speed of documentation’ groupings of the RCT benefits given the construction industry sectors (i.e., commercial and infrastructure). However, the perceptions of the two respondent groups were all positive and strong, with mean responses ranging from 3.60–4.16, indicating their agreement with the RCT benefit groupings. This finding suggests that RCTs benefit construction regardless of whether they are implemented on a commercial building or infrastructure project. Similar to RQ4a, the literature review did not find previous studies that investigated if there were significant differences between perceptions of RCT benefits between stakeholders from different construction industry sectors, and, therefore, our findings represent a contribution to the body of knowledge.

6.7. RQ4c: Are Significant Differences in the Emergent Factors of ‘RCT Obstacles’ Observed When Compared by Construction Stakeholders?

Regarding differences in perceptions of the RCT obstacle groupings when compared by construction stakeholders, an ANOVA showed significant differences in respondent perceptions regarding the ‘lack of demand/budget’ obstacles grouping. Post-hoc analysis revealed that a significant difference was observed between Designers and CM/Owner Representatives. Specifically, CM/Owner Representatives reported higher levels of agreement that lack of demand/budget was an obstacle to RCT adoption. As with some of the previous comparisons, this may be due to Designer’s directly applying RCTs when creating designs/3D models which could lead to easier justification of RCT adoption from a ROI perspective. Regarding the three other obstacle groupings (‘a hardware/software issue’, ‘workforce and training’, and ‘data collection and processing’), an ANOVA showed that there were no significant differences among respondent perceptions when compared by construction stakeholders. This is an interesting but unexpected finding. The authors would expect, for example, that the Owner/Developer respondent group might not find these three obstacle categories as important as other stakeholder groups, such as Designer, Contractor and CM/Owner Representative, that are typically directly affected by these three categories of issues and barriers. In addition, there were no previous studies that investigated if there were significant differences between perceptions of construction stakeholders regarding RCT obstacles; therefore, these findings represent an additional study contribution.

6.8. RC4d: Are Significant Differences in the Emergent Factors of ‘RCT Obstacles’ Observed When Compared by Construction Industry Sector?

For differences in perceptions of RCT obstacle groupings when compared by construction industry sector, a *t*-test showed significant differences between respondent perceptions regarding ‘lack of demand/budget’, and ‘data collection and processing’. The means of responses were in the ‘neither agree nor disagree’ range for both obstacle groupings.

Respondents from the commercial sector reported significantly higher levels of agreement that the items in these two obstacle groupings prevented RCT adoption compared to the respondents from the infrastructure sector. The reason for this perception might be because commercial building projects may require more frequent data collection and processing than infrastructure projects and, therefore, require more time and financial investment into RCTs and RCT services. This finding is in line with Tang et al. [17] and Wu et al. [20], who posit that the use of RCT would be even more beneficial for larger and more complex projects. For the remaining two groupings of obstacles, 'hardware and software issues', and 'workforce and training issues', a *t*-test revealed no significant difference between respondent perceptions. In other words, perceptions of 'hardware/software issues', and 'training/workforce issues' were similar regardless of whether the project was a commercial building or an infrastructure project. Since our literature review did not find research that studied if there were significant differences between perceptions of RCT obstacles among stakeholders from different construction industry sectors, our research findings contribute to the body of knowledge.

7. Conclusions

This research explored the perceptions of construction project stakeholders, that is, Owners/Developers, Designers, Contractors, and CM/Owner Representatives about the benefits of, and obstacles to, the adoption of RCTs in the United States. A quantitative survey was distributed to stakeholders in the commercial and infrastructure industry segments. Survey responses were analyzed using descriptive statistics, ANOVA, *t*-test and EFA.

All four stakeholder groups agreed with the majority of RCT benefits listed in the survey and identified increased accuracy of existing condition documentation and as-built documents, as well as the reduced time required to document existing conditions as the top benefits of RCT use. Reduced time required for QA/QC, and reduced project duration were among the bottom ranked RCT benefits. All four groups of respondents agreed that lack of in-house expertise, lack of Owner/Client demand, and lack of project-level budget were among the top five obstacles that prevented RCT adoption, while RCT not being important for the projects they work on, data collection being too time consuming, and risk/liability concerns were among the bottom five obstacles.

The ANOVA indicated no significant differences among the four stakeholder groups' perceptions about the benefits of, and obstacles preventing the adoption of RCT. In other words, Owners/Developers, Designers, Contractors, and CM/Owner Representatives reported similar levels of agreement with RCT benefits and obstacles to its adoption. The *t*-test revealed no significant differences between perceptions of stakeholders from commercial and infrastructure industry segments regarding the benefits of and obstacles preventing the adoption of RCT except for RCT helping increase the accuracy of prefabricated elements. Stakeholders from the commercial segment reported a significantly higher level of agreement with this benefit compared to the respondents from the infrastructure segment. Regarding obstacles, the respondents from the commercial segment reported significantly higher levels of agreement that 'RCT not being a company priority', 'lack of company budget', and 'data collection being too time consuming' were obstacles to RCT adoption compared to the respondents from the infrastructure segment.

EFA revealed that the twenty-one individual RCT benefits were empirically grouped in a logical factor structure. The four RCT benefit groupings (e.g., factors) included a 'reduced project risk' category that was comprised of reduced 'overall project cost', 'project duration', 'time for QA/QC' and 'rework to correct errors in the field'. RCT benefit grouping two 'increase quality of construction' comprised the following benefits: increased accuracy of 'surveying/layout', 'installed work', 'prefabricated elements' and 'constructed system locations' and 'increasing the speed of installation of constructed elements'. RCT benefit grouping three 'increased accuracy of existing and constructed work' comprised the following benefits: 'increasing accuracy of construction documents', 'as-built documents', 'existing condition documentation', 'reducing rework during design', and 'reduced number

of site visits to collect data'. The final RCT grouping (e.g., four) indicated that the EFA was 'speed of documentation', which included the following benefits: reducing time required to 'document existing conditions', 'generate 3D models', and 'increased speed of surveying/layout' and 'increase speed of as-built document creation'.

Regarding the obstacles to RCT adoption, EFA revealed that the 19 individual obstacles grouped in a logical factor structure. Of the four RCT obstacle groupings, the first was a 'lack of demand/budget', which was comprised of 'lack of Owner/Client demand', 'RCT is not a company priority', 'RCT not being important for the projects they work on', 'lack of company budget', 'lack of project-level budget', 'inability to bill RCT costs to their projects', and 'not being able to justify the ROI'. The second obstacle grouping was 'hardware/software issues' preventing RCT adoption; this grouping comprised 'high cost of the equipment', 'high cost of software', 'lack of user-friendliness of the equipment', 'lack of user-friendliness of the software, and 'lack of software interoperability'. Workforce and training-related obstacles grouped as well, specifically the following individual obstacles grouped in this factor: 'lack of in-house expertise', 'lack of training', 'lack of time for training', and 'cost of hiring employees with the required skills'. The final RCT obstacle group (e.g., four) was 'Data/Collection and Processing': this factor included the two obstacles of 'data collection is too time consuming' and 'data processing is too time consuming'.

ANOVA comparisons of RCT benefit groupings by stakeholder (i.e., Owner/Developer, Designer, Contractor, CM/Owner Representative) revealed no significant differences on the four benefit groupings: reduced project risk, increased quality, accuracy of existing and constructed work, and the speed of documentation. *t*-test comparisons of RCT benefit groupings by construction industry segments (i.e., commercial and infrastructure) also indicated that there was no significant difference in benefit groups between industry sectors. Regarding obstacle groupings, the ANOVA showed a significant mean difference on the 'lack of demand/budget' grouping only. *t*-tests revealed significant differences between respondent perceptions about the 'lack of demand/budget', and the 'data collection and processing' obstacle categories given the construction industry segment. Specifically, respondents from the commercial sector reported significantly higher levels of agreement that these two obstacle groupings were barriers to RCT adoption than did their infrastructure sector counterparts.

This research contributes to the body of knowledge by filling the gap of limited or non-existent studies that compared construction project stakeholder perceptions about RCT benefits and obstacles, that is, differences of perceptions among Owner/Developer, Designer, Contractor, and CM/Owner Representative stakeholders. There were no previous studies that compared perceptions about the RCT benefits and obstacles by the construction industry sector, that is, commercial vs. infrastructure. Additionally, previous studies that did survey perceptions of RCTs had different scopes, utilized different methodology and data analysis, explored smaller and less diverse samples, and were conducted between 2–6 years ago. One of the major contributions of the current study is a discovery of the following new benefits of implementing RCT: reduced project risk, reduced number of site visits to collect data, increased accuracy of prefabricated elements, installed work, and the constructed system locations, as well as the increased speed of as-built document creation and the installation of constructed elements. Additionally, this study identified several obstacles that prevented RCT adoption that were not mentioned in the previous research, specifically RCT not being a company priority, RCT not being important for the projects they work on, lack of Owner/Client demand, lack of company budget and project-level budget, not being able to bill RCT costs to their projects, and the cost of hiring employees with the required skills.

Limitations and Future Research

This study had several limitations which should be considered when interpreting the results. The study was limited to construction project stakeholders who identified commercial buildings and infrastructure as their primary market sector. The survey was

sent to CMMA and IFMA members that worked in the United States only. The survey instrument defined and delimited RCTs for respondents for the purpose of focusing on perceptions of Laser Scanning and Photogrammetry applications. Therefore, this paper presents participant stakeholder perceptions regarding the benefits of, and obstacles to, laser scanning and photogrammetry adoption. Caution should be exercised in generalizing the results of this study to other technologies, samples, or populations. Future studies could benefit from larger samples, focusing particularly on Facility Managers that may benefit from utilizing RCTs. Additionally, the survey could be sent to several other professional organizations whose members comprise larger samples of architects and contractors as well as organizations that focus on other construction sectors, such as residential. A future study could explore factors that influence stakeholder decisions to use the technologies on projects as well as explore the effectiveness of using RCTs during different project phases. A next logical step in this line of research would also be to complete in-depth studies exploring aspects of the challenges and benefits of RCT adoption.

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