IOWA STATE UNIVERSITY
Digital Repository

2016

Civil integrated management and the implementation of CIM-related technologies in the transportation industry

Fangyu Guo
Iowa State University

Follow this and additional works at: https://lib.dr.iastate.edu/etd

Part of the Civil Engineering Commons

Civil integrated management and the implementation of CIM-related technologies in the transportation industry

by

Fangyu Guo

A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Civil Engineering (Construction engineering and management)

Program of Study Committee:
Charles Jahren, Co-Major Professor
Yelda Turkan, Co-Major Professor
David Jeong
Jing Dong
Ellen Fairchild

Iowa State University

Ames, Iowa

2016

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

ABSTRACT

As advanced technologies are adopted in the transportation industry, it is important to investigate how they can be integrated and better utilized to facilitate the success of public transportation agencies. It is also important to devise efficient ways to address the considerable amount of digital data created as these technologies are used. A newly introduced concept – Civil Integrated Management (CIM) – has potential for addressing these issues, because it involves collection, organization, and managed accessibility of accurate data and information throughout the transportation asset lifecycle. CIM is also expected to facilitate the use of various advanced technologies, so the purpose of this dissertation is to further explore the concept of CIM and investigate how it can be implemented to assist with transportation projects and programs.

After initial preparation (i.e., conducting literature reviews, consulting with experts, developing questionnaires, and identifying target agencies), two weeks of on-site visits were conducted with seven state transportation agencies to document their insights and practices associated with the CIM concept. Coding strategies were used to analyze the field notes collected from the presentations provided by host agencies and discussions throughout the visits. To further investigate one of the CIM enabling technologies – light detection and ranging (LiDAR), a web-based survey was disseminated to 28 LiDAR professionals; it produced 15 responses. Five phone interviews were also conducted using the Delphi method to develop a LiDAR data utilization workflow for 3D modeling. To investigate another CIM enabling technology – an electronic document management (EDM) system, important data related to EDM practices were extracted from field notes obtained from the CIM on-site visits. Meanwhile, follow-up interviews were conducted with the four transportation agencies identified as leading agencies with respect

to EDM, and a video interview was conducted with one additional construction company involved with enterprise-level EDM implementation.

As pioneering research on CIM, the results of this dissertation provide transportation agencies and other researchers with an essential roadmap for implementing and refining the CIM concept. The findings and recommendations listed in this dissertation are also expected to assist transportation agencies in better utilizing and integrating various CIM-related technologies into their transportation projects and programs.

CHAPTER 1 INTRODUCTION

Background

Over the past few decades, various advanced technologies have been adopted in the transportation industry to improve accuracy and efficiency in design and construction; examples include LiDAR, information modeling, global positioning systems (GPS), and automatic machine guidance (AMG) (Jaselskis et al. 2005, Williams et al. 2013, Walters et al. 2008, Hartmann et al. 2008, Peyret 2000, and Heikkilä and Jaakkola 2009). Transportation design and construction processes have been gradually improved through the emergence of these technologies. LiDAR technology has been used to collect accurate 3D measurements of existing on-site features, and the resulting data can then be used to create 3D design models (Heikkilä and Jaakkola 2009). Investigations have also been conducted into using LiDAR for detecting and visualizing actual construction progress (Turkan et al. 2012, Kim et al. 2013). The impact of 3D information modeling (also called 3D engineered models by FHWA and hereafter in this document) is also substantial for highway design and construction. Because the benefits of building information modeling (BIM) have been observed in the vertical (commercial and institutional) design and construction industries, an increasing number of professionals have begun to apply 3D engineered models within the horizontal (infrastructure and/or transportation) design and construction industry (McGraw-Hill 2012, O'Brien et al. 2012, and Dadi et al. 2014). Many public transportation agencies and their contractors and consultants in the U.S. have been using 3D engineered models for various applications, most often in project planning, design and construction phases. 3D Engineered models are especially beneficial for interdisciplinary coordination, clash detection, earthwork quantity calculations, and AMG (Du et al. 2006, O'Brien et al. 2012, and Cylwik and Dwyer 2012). By combining 3D engineered models with

GPS assisted machine control (often referred to as AMG in the industry and hereafter in this document), productivity in earthwork operations can be increased by up to 50% while reducing surveying costs by up to 75% (FHWA 2016). Another example of a commonly adopted advanced information technology is Geographic Information System (GIS), a digital database specifically designed to store and analyze spatially-organized, object-oriented data (Foote and Lynch 1995). GIS is typically used for spatial analysis and for developing maps that help project teams prepare effective project plans (Esri 2014, Cheng and Yang 2001, Bansal and Pal 2009). Research studies have been conducted to investigate the use of GIS for various planning purposes (Cheng and Chang 2001, Salim et al. 2002). In a case study performed in Iowa, a GIS-based snow removal system helped increase the efficiency of snow plowing operations by enabling decision makers to allocate their available resources more effectively (Salim et al. 2002).

As these advanced technologies and digital tools have become more commonly adopted, digital data-based project delivery is expected to eventually entirely replace the traditional paper-based project delivery process and an integrated management solution becomes crucial for transportation agencies so that upper management personnel can make more effective, data-driven decisions to achieve greater success. Civil Integrated Management (CIM), a new concept developed by the Federal Highway Administration, the American Road & Transportation Builders Association, the American Association of State Highway and Transportation Officials, and the Associated General Contractors of America (FHWA, AASHTO, ARTBA, & AGC) (2013), could potentially serve as such an integrated management solution. CIM focuses on the collection, organization, managed accessibility, and use of data and information throughout the entire lifecycle of a transportation asset. However, implementation of CIM would be enhanced if

a clearer understanding about the CIM concept were established, and if guidance or roadmaps were available for transportation agencies describing how to utilize CIM to transition to a digital data-based project and program delivery approach.

Dissertation Structure

To address these issues, this dissertation was developed in the form of three journal-quality papers related to the CIM concept and CIM-related technologies. The first paper introduces the CIM concept and develops an overall framework for CIM utilization in transportation agencies. The second paper documents current applications of LiDAR technology and develops a workflow for effective LiDAR data utilization for 3D modeling of horizontal infrastructure projects. The third paper investigates various existing electronic document management (EDM) systems that can be used to support CIM implementation.

The data included in the first paper were collected from the NCHRP domestic scan 13-02 project on CIM practices whose purpose was to explore current state of transportation agency practices related to the overall implementation of CIM-related technologies. Two weeks of on-site visits were conducted at seven leading state transportation agencies to learn about their current practices related to CIM. A questionnaire was developed and sent out in advance to the participating agencies. Based on the responses to questions included in the questionnaire and host agencies' own experiences with CIM, presentations were provided by employees from various divisions within the host agencies to facilitate further discussion about lessons learned and future directions for CIM implementation. Based on a qualitative analysis of the data collected during the on-site visits, a framework for facilitating effective CIM implementation for transportation projects and programs was developed.

The purpose of the second paper was to explore current LiDAR applications in the transportation industry. A web-based survey with 12 questions was sent to 28 LiDAR professionals, and 57.1% of them provided responses reflecting on their experiences with LiDAR. On one-on-one phone interviews were also conducted, using the Delphi method, with five LiDAR experts to develop recommendations for more efficient ways of using LiDAR data in transportation project design. Based on the experts' consensus, a finalized workflow was developed as a recommended approach to developing 3D design models from LiDAR data.

The purpose of the third paper was to explore the utilization of various EDM systems that can support CIM implementation. Five case studies regarding EDM usage were presented in the paper. From the domestic scan 13-02 project, four state transportation agencies with relatively mature experiences with EDM systems were identified. Data were collected mainly from the detailed notes that address EDM practices of leading agencies during the on-site visits and other supplementary documents provided by these agencies. Follow-up questions were also sent out to these agencies, and their responses were obtained either through email or phone conversations. One additional case study was conducted on one Chinese construction company whose EDM system was also used for enterprise-level management. After analysis of the case studies, the benefits and challenges of each EDM system were identified and guidelines were developed for selecting and using an appropriate EDM system within a transportation agency.

CHAPTER 2 CIVIL INTEGRATED MANAGEMENT: AN EMERGING PARADIGM FOR CIVIL INFRASTRUCTURE PROJECT DELIVERY AND MANAGEMENT

Fangyu Guo[1], Charles T. Jahren[2], Yelda Turkan[3], and H. David Jeong[4]

Abstract

With the advancement of various technologies, transportation agencies are transitioning from 2D -paper-based to 3D digital data-based project delivery. This transition results in an increasing amount of digital data exchange throughout project delivery process and a holistic framework is required to better manage data for improved decision making. A recently developed concept, Civil Integrated Management (CIM) could potentially assist transportation agencies to transition to digital data-based project and program delivery by providing appropriate stakeholder access to an agency wide data pool. The purpose of this paper is to further define this vision and concept and establish an initial framework for CIM implementation. An extensive amount of information was collected through two weeks of on-site visits to seven transportation agencies in the United States on their current CIM-related practices. The results obtained from using qualitative research methods are expected to serve as a foundation for further investigation on CIM-related practices and to provide a roadmap for CIM implementation.

Key Words: Civil Integrated Management (CIM), 3D Engineered Models, transportation data asset, qualitative research

Introduction

The information revolution that has occurred over the last few decades has made a noticeable impact on people's lives and global businesses. With the advancement of various information technologies, people can have instant access to a tremendous amount of information and share this information with others real-time. Business structures and strategies were adjusted to accommodate the changes brought by information revolution (Land 2001). The emergence of digital technologies in engineering design and construction dates back to the 1960s (Fig. 1) when early uses of geographic information systems (GIS) for spatial analysis were introduced (AASHTO 2015). During the 1970s, computer aided design (CAD) was developed and adopted to assist in developing engineering drawings. In the early 1980s, personal computers (PCs) were initially used by many engineering and construction firms. Simultaneously, software packages were developed to support various tasks such as planning, drawing, and word processing (Matheu 2005). Commercial versions of GIS software were also made available in the market at that time (AASHTO 2015). In the mid-1980s, global positioning systems (GPS) and laser scanning were started to be used for surveying purposes (FHWA 2000; LiDAR UK 2015). During the 1990s, 3D capabilities became available for road design (Tardy 2012). In the late 1990s, GPS-based machine control was introduced for guiding earth moving operations (Moore 2004). To date, a wide range of software packages have been made available to support a variety of applications in various disciplines in the construction industry (Matheu 2005; Martínez-Rojas et al. 2015).

PC, GPS,
laser
scanning,
commercial   3D design,
GIS   AMG

GIS   CAD

1960s   1970s   1980s   1990s
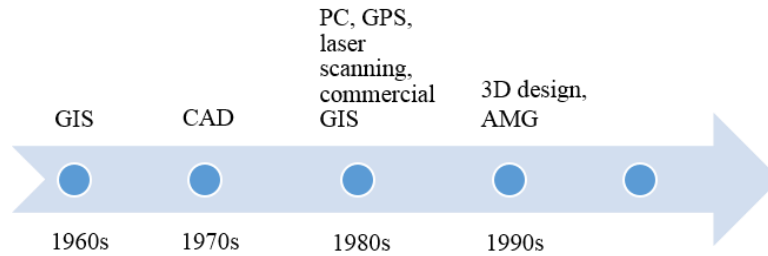
Figure 1. *Technological evolution from 1960s to 1990s*

Traditionally executed transportation projects frequently experience insufficient

communication among various project partners, which often results in schedule delays and cost

overruns. Since paper plans and hard copy documents must often be shared physically within

agencies and between project participants, additional time investment is needed, which inhibits

from instant and effective communications (Weippert et al. 2003). Today, with the use of various

web-based communication or management tools, information sharing among various business

partners has become easier and more effective (Wang et al. 2007; Martínez-Rojas et al. 2015).

Another drawback of traditional transportation project and program execution is the difficulty of

detecting design errors early, which can cause failures or disruptions during the construction

phase (Lopez et al. 2010). Now, with the use of 3D information models, design problems or

errors can be detected early in the process while increasing the overall design quality (O'Brien et

al. 2012). Moreover, 3D information models dramatically improve the visualization, planning,

and coordination for engineering projects (Grilo and Jardim-Goncalves 2011). Safety on a

construction job site is always a major concern. Various technologies such as GIS, virtual reality

(VR), augmented reality (AR), sensing and warning technologies, and 3D / 4D information

models have been investigated to improve construction safety over the years (Zhou et al. 2011,

Ray and Teizer 2013, Wang et al. 2015, Zhang et al. 2015, and Behzadan et al. 2008). Overall,

the construction process is better controlled and managed with the assistance of advanced

technologies and tools (Wang et al. 2007). The implementation of all these advanced

technologies and tools produces a considerable amount of digital data during the lifecycle of a

transportation project or program, which makes digital data another important asset for a

transportation agency. Now, the entire transportation industry is rapidly transitioning from

traditional paper-based project and program delivery to digital data-based delivery. This

transition will inevitably influence business and management decisions for all entities involved

in a transportation project.

In order to accommodate a transition to digital data-based project and program delivery,

there is a need for an integrated management solution to assist transportation agencies in better

managing and utilizing their digital data assets that result from the use of various advanced

technologies and tools, so that better decisions can be made to ensure successful delivery. A

broad vision and innovative methods are required to develop such an integrated management

solution. Civil Integrated Management (CIM) is a new concept developed by Federal Highway

Administration, American Road & Transportation Builders Association, American Association

of State Highway and Transportation Officials, and the Associated General Contractors of

America (FHWA, AASHTO, ARTBA, & AGC) (2013). CIM addresses the collection,

organization, and management of data and information throughout transportation projects and

programs. Though the definition of CIM is given, there is neither a clear and coherent

understanding of the CIM concept nor a framework to guide transportation agencies for making

appropriate adjustments to implement CIM. Thus, the goal of this study is to establish an initial

framework for CIM implementation to help agencies transition toward digital data-based project

and program delivery that accesses a common data pool for the entire project and program

lifecycle. The central research question is how the CIM concept can be better interpreted and

how transportation agencies should precede toward the implementation of CIM. Accordingly, qualitative research methods were selected and used in this study. The data were collected from presentations, discussions, and supplementary documents provided by seven transportation agencies (91 experts and practitioners) during the two weeks of site visits. A group of transportation agency leaders who were likely to be involved in the implementation of CIM systems assisted in the collection and initial analysis of this data. Coding strategies (combination of descriptive coding and values coding) were adopted for the qualitative data analysis. Based on the extensive collaboration with various transportation agencies, this study was able to further extend the definition of CIM concept and provide a roadmap for implementation.

Research Methodology

Ninety-one industry experts and practitioners from seven host agencies formally participated and provided input for this study which was executed using qualitative research methods. The purpose of a qualitative research is to establish a more in-depth understanding about a phenomenon within its context (Morrow 2007; Lietz and Zayas 2010). The focus of qualitative data analysis is mainly on concepts and meanings rather than particular variables (AlMaian et al. 2015). A qualitative research investigation is more inductive compared to a quantitative research investigation which is more deductive (Bogdan and Biklen 2007). The findings obtained through qualitative research are difficult to predict prior to conducting the study (Mack et al. 2005). CIM is a new concept that is still under development, therefore it is desirable to seek a better understanding of CIM and generalize how it can be creatively applied in the industry. Thus, it is appropriate to conduct qualitative research to investigate CIM. Fig. 2 presents the three stages of the research methodology adopted in this study: preparation, on-site visits, and data analysis.

```
                                    ┌─────────┐
                                    │  Start  │
                                    └─────────┘

        ┌──────────────┐    ┌──────────────┐    ┌──────────────┐
        │   Experts'   │    │  Literature  │    │Questionnaire │
        │  Knowledge   │    │    Review    │    │              │
        └──────────────┘    └──────────────┘    └──────────────┘
Preparation
                            ┌──────────────┐
                            │ Selection of │         Questions
                            │ Participants │         delivered to
                            └──────────────┘         agencies

                         Permissions from
                         target agencies
                            ┌──────────────┐
                            │Prepare for Visit│
                            └──────────────┘

        ┌──────────────┐    ┌──────────────┐    ┌──────────────┐
        │Presentations │    │ Interactions │    │Supplementary │
On-site │from Agencies │    │with Agencies │    │  Documents   │
Visits  └──────────────┘    └──────────────┘    └──────────────┘

                            ┌──────────────┐
                            │Reflect on Visit│
                            └──────────────┘

                            ┌──────────────┐
Data                        │Coding Strategies│
Analysis                    └──────────────┘

        ┌──────────────────┐            ┌──────────────┐
        │Observer Triangulation│        │Member Checking│
        └──────────────────┘            └──────────────┘
```

Figure 2. *Research methodology flowchart*

Preparation

In order to establish a general understanding of the CIM concept and to identify the current practices, technologies and tools that could support CIM, preliminary preparations were made, which involved conducting a literature review, consulting with experts, developing questionnaire, and identifying target agencies for subsequent field visits.

The literature review was conducted to establish a better understanding about current practices and research efforts regarding CIM-related practices and technologies. The introduction to the CIM concept and practices presented in the research findings section was also partially based on the literature review as well as the observations and discussions during the on-site visits. Professionals with strong knowledge on both technical and management aspects of transportation projects were selected and included in the expert panel of this study. The 10-member expert panel was composed of leaders from transportation agencies who are responsible for their particular area (e.g. design, construction, asset management, or the entire highway system) on a statewide basis as well as the second author who is a professor from Iowa State University (ISU) and has served as a subject matter expert on national level projects involving digital data exchange for transportation agencies. Three additional researchers from ISU joined the panel to assist with the study. Major CIM-related concerns and issues were collected from the expert panel and included in the questionnaire of 55 questions. The participating agencies were expected to provide presentations to demonstrate their CIM-related practices and technologies based on the questions included in the questionnaire.

The selection of target participating agencies was based on the following criteria: having a current project that includes some aspects of CIM related practices and/or technologies; or having previously implemented several components of CIM and having plans for moving toward full CIM implementation. A leader from each of the seven target agencies was contacted for explaining the purpose of the study, and the questionnaire was also sent to them at this time. After they agreed to participate in the study, the leader of each agency selected their own presentation team.

On-site visits

The second stage of the project comprised two weeks of on-site visits conducted by the expert panel and researchers to gather data from the seven participating agencies. During these visits, employees from the host agencies provided all day presentations/workshops and supplementary documents to address the interview questions and to demonstrate their current CIM related practices. Presenters included various levels of personnel (specialists, engineers, superintendents, managers, directors, etc.) from various divisions (business development, design, construction, asset management, IT, etc.). In some cases, external stakeholders such as contractors and consultants were also included. In total, 91 industry experts and practitioners from host agencies formally participated and provided input for this study. The team also interacted extensively with the participants to exchange ideas and experiences. Field notes were typed in personal laptop computers concurrently with all presentations and discussions.

Data analysis

At the end of the on-site visits, a round table discussion was conducted among all expert panel members and researchers to reflect on the key findings identified through the visits. Notes were taken to document the discussion. For the process of data analysis, field notes, presentations, and supplementary documents were first reviewed. Then, the field notes taken for each state transportation agency's presentations were incorporated into one summary document and categorized by the following: geospatial collaboration, 3D model and automatic machine guidance (AMG), surveying, paperless construction, asset management, utilities, real-time verification, legal issues, and organizational issues. The notes for round table discussion and the summary document for all field notes were used as the major sources for data analysis, and the

presentation slides and supplementary documents were used as the secondary sources for supporting evidence.

The coding strategies described by Maxwell (2013) and Saldana (2016) were adopted as the primary approach for further data analysis. In particular, descriptive coding and values coding techniques were both applied in the data analysis process. Descriptive coding uses a word or short phrase (usually a noun) to summarize the basic topic of the qualitative data, and values coding identifies a participant's values, attitudes, and beliefs from the qualitative data (Saldana 2016). After reviewing the notes of the expert round table discussion, 13 codes were developed including upper management support, motivate team, mobile devices, communication among stakeholders, interoperability, data usage throughout the lifecycle, geospatial data, LiDAR, models, IT support, engage partners, think forward, and share lessons learned. Similarly, after reviewing the summary notes of the on-site visits, 12 codes were developed including LiDAR, geospatial data, document, models, AMG, machine, mobile devices, tablet, smartphone, format, training, and communications with public. Subsequently, the first author coded the data manually by using the identified codes to extract raw notes and to further categorize similar ideas into the key findings. An example of this data analysis process is provided in Table 1. By reviewing the notes documenting expert round table discussion, sentences containing the meaning of the code(s) were extracted and used to identify the key findings. Similarly, Table 2 provides another example of the process used for extracting on-site visits summary notes to identify the key findings.

Table 1. Extraction of Round Table Discussion Notes for Emerging Key Findings

Code	Raw Notes from Expert Round Table Discussion	Key Findings
Data usage throughout the lifecycle (7)	1. Look at the entire life cycle- the big payoff will be for operations and maintenance 2. We must communicate benefits to other areas aside from design and construction in order to get buy in from upper management 3. Emphasize a life cycle approach in order to make the CIM concept attractive to decision makers 4. Data needs to be enterprise-centric in addition to being useful for particular projects 5. It is important to be able to use data throughout the project life cycle 6. Need to identify the downstream value of CIM data and find tools that facilitate this. Currently, these are not mature. 7. Implementing CIM beyond the design and construction phases is likely where bigger pay offs will occur.	• Use data throughout the life cycle of a facility • Develop an enterprise data pool to store or extract the facility data whenever necessary

Table 2. Extraction of On-site Visits Summary Notes for Emerging Key Findings

Codes	Raw Notes from Summary Note of On-site Visits	Key Findings
LiDAR, geospatial data (8)	1. LIDAR captures all roadway image and conditions (measures the distress, high/median/low) for the entire state, updates every two years. Documents are maintained for road existing condition, problems, solutions, to avoid any future disputes 2. As-built data are likely to be collected through LIDAR and construction equipment in the future. Permits or maintenance might be challenging. 3. More concerned about the data than the model. Store the geospatial data, so that the data could be imported into other models 4. Expect that the agency will use 3D modeling software as the source software, and use GIS as a visualization tool. GIS can also be used to identify locations with steep slopes and conduct traffic analysis 5. Use smartphone to collect data (take pics with coordinates), the data could be shown on a publicly facing GIS map 6. Web-based GIS to store geospatial data 7. There is a plan to develop a database system containing data from design, as-built plans, permits, and maintenance. Also, it is anticipated to use more LIDAR in the future. 8. Develop the utility database that contains all as-built utility information. Ultimately, develop database for all existing transportation systems. This requires everything to be updated with its as-built information, and likely could be achieve by using LIDAR.	• Lidar is useful for spatial data collection and potentially for collecting as-built data • Imported spatial data should be incorporated into GIS for better visualization

Meanwhile, the codes were further combined into appropriate sub-categories and categories as shown in Table 3.

Table 3. Grouping of Codes

Codes	Sub-Categories	Categories
Lidar, geospatial data	Lidar & Spatial Data	
Documents	EDM	
Models, AMG, machine	3D Engineered Models & AMG	Technical Considerations
Mobile devices, tablet, smartphone	Mobile Devices	
Interoperability, format	Interoperability	
Communications between stakeholders	Communications between Stakeholders	
Communications with public	Communications with Public	Organizational Considerations
Upper management support	Upper Management Support	
IT support	IT Support	
Data usage throughout the lifecycle	Data Usage Throughout the Lifecycle	
Engage partners	Support from Stakeholders	
Motivate team, think forward	Motivate Team and Think Forward	Philosophy for Success
Training	Effective Training	
Share lessons learned	Share Lessons Learned with other agencies	

Finally, the key findings and the corresponding categories and sub-categories were summarized for use in the discussion that is included in the research findings section of this paper. In addition, two qualitative research validation methods, namely observer triangulation and member checking, were executed to verify the data analysis results. Observer triangulation was applied when multiple analysts (ISU researchers and expert panel members) were involved to reach an agreement on the analysis results. Member checking was adopted when the selected participants were asked to review and verify the results and to provide feedback as necessary (Padgett 2008, Lietz and Zayas 2010).

Research Findings

The following sections discuss the findings from the data analysis, which includes CIM concept and practices and framework for the implementation of CIM. CIM concept and practices,

which were mainly identified during the preparation phase of the project and modified after the

on-site visits, provide more detailed explanations of CIM and what practices are involved in a

CIM system. The framework for the implementation of CIM contains the key findings associated

with three major categories (i.e. technical considerations, organizational considerations, and

philosophy for success) that were generated from the data collected during on-site visits.

Technical and organizational considerations for CIM implementation are provided to suggest

how agencies could proceed toward CIM implementation, while the philosophy for success is

provided as key philosophical factors that determine the level of success of a CIM

implementation effort. In addition, the vision for CIM implementation at enterprise level is

proposed based on these findings identified in the study.

CIM concept and practices

The original definition of CIM was provided by FHWA, AASHTO, ARTBA, & AGC

(2013) as: "the collection, organization, and managed accessibility to accurate data and

information related to a highway facility." Based on the discussions during the on-site visits, the

panel revised this definition to the following in order to emphasize the life cycle aspect of CIM

concept: "CIM refers to the collection, organization, managed accessibility, and the use of

accurate data and information throughout the life cycle of a transportation asset." The CIM

concept could be integrated into practices such as geospatial collaboration, surveying, utility

identification, information modeling, real-time verification, asset management, and file

collaboration and management, and the results of CIM implementation results would be

enhanced with the utilization of various advanced technologies and tools (Table 4). It should be

noted that alternative contracting/partnering options and legal issues should be carefully

considered and dealt with to ensure smooth implementation of CIM concepts. The descriptions

of these practices or issues and the possible technologies or tools that can be adopted for each

practice or issue are detailed below.

Table 4. CIM Involved Practices and Supporting Technologies/Tools/Details

Practices/Issues Involved with CIM	Supporting Technologies/Tools/Details
Geospatial collaboration	GIS, cloud-based technologies
Surveying	LiDAR, robotic total stations, and RTK GPS
Utilities identification	SUE, RFID
Information modeling	3D engineered models, AMG
Real-time verification	IC, thermal imaging
Asset management	GIS
File collaboration and management	EDM
Alternative contracting and partnering	DB, CMGC, and alternative bidding
Legal issues	Model ownership, licensure, and liability

Geospatial Collaboration: Geospatial data collaboration refers to the delivery and

exchange of geospatial data and information, which is especially important during the initial

project planning phase. Technologies that can be utilized for geospatial collaboration include

GIS and cloud-based technologies. GIS enables project teams to create maps and perform

geospatial analysis. On the other hand, cloud-based technologies facilitate the sharing of spatial

data among various parties through web portals (FHWA 2012).

Surveying: Surveying is another very important task during the initial project planning

phase as the collected data are the basis for making many important design-related decisions.

Compared to traditional surveying methods, new technologies such as light detecting and

ranging (LiDAR), robotic total stations, and real time kinematic (RTK) GPS devices are capable

of capturing very accurate and comprehensive data in an efficient manner (FHWA 2014).

Utilities Identification: Utility identification should be performed correctly before the

design phase. Misidentification of utility locations could result in utility damage during

construction activities such as excavation. Subsurface utility engineering (SUE) or radio-frequency identification (RFID) subsurface marking can be used to locate and map underground utilities. Accurate utility data enable designers to optimize alignments, which would help avoid utility damage or relocation costs during the construction phase (FHWA 2011).

Information Modeling: Information modeling in civil engineering often includes the use of a database or digital model that stores a variety of project information. 3D visualization enables project stakeholders to better understand the project and thus maintain a more effective means of communication. Clash detection, as one of the important functions included in information modeling software, could help resolve design deficiencies early in the process (O'Brien et al. 2012). In addition, AMG, where 3D engineered models are downloaded to construction equipment on board computers to be used for controlling ground engaging equipment during excavation, grading and other similar activities, could help increase both accuracy and productivity of construction work (Peyret 2000).

Real-Time Verification: Real-time verification enables operators to monitor or inspect the construction work in real time. Technologies and tools such as intelligent compaction (IC) and pavement thermal imaging provide assistance in controlling compaction and paving work efficiently. IC technology ensures the quality of compaction by providing a consistent pattern of compaction work (Chang et al. 2011; Anderegg and Kaufmann 2004; FHWA 2013). Pavement thermal imaging enables the opportunity to display real-time thermal data, so that the asphalt surface temperature can be controlled within the desirable range (Sebesta et al. 2006).

Asset Management: Proper management of constructed transportation assets is important for keeping the assets functioning for a longer time. Data obtained from surveying, design, and construction phases of a facility could potentially be used during the operation, maintenance and

rehabilitation of a facility if early considerations are given for asset management needs. GIS can be used to link the digital data collected from early phases of the project with the data generated during operations and maintenance, which can be incorporated into pavement management systems, bridge management systems, or other similar asset management systems.

File Collaboration and Management: File collaboration and management is critical for sharing data during the project lifecycle and retaining the project-related data long term. Data can be easily stored, accessed, shared, and managed through the use of web-based electronic document management (EDM) systems (Guo et al. 2015). Also, the data retained in the EDM system can be useful for future reference.

Alternative Contracting and Partnering: Effective communication among stakeholders is always the key to the success of a project. Alternative contracting and partnering can often be used to make sure that a feasible design is chosen and the project is delivered smoothly. The availability and easy accessibility to digital project data promotes and facilitates the use of these advanced contracting methods. The design-build (DB), construction manager/general contractor (CMGC), integrated project delivery (IPD), and alternative bidding are all possible options for delivering a project in an efficient manner and can increase overall project success when applied properly (FHWA et al. 2013; EDC-1a 2012; EDC-1b 2012).

Legal Issues: Current practices mostly address the legal issues for traditional paper-based delivery. During the course of a project, issues regarding to ownership, licensure, and liability of project models, plans, survey and as-built data may arise and the project team must resolve them as part of the digital data exchange process. The ownership of the model and rights to make changes to the digital project data need to be defined in the contract. Standardized procedures need to be developed for digital data sharing and version control.

Framework for the implementation of CIM

Based on the analysis conducted on the data collected from on-site visits, the key findings correspond to the identified categories and sub-categories were summarized in Table 5. This table is developed to serve as a framework for the implementation of CIM within transportation agencies. The discussions for each major category (i.e. technical considerations, organizational considerations, and philosophy for success) are provided in the next few sections following this table.

Table 5. Basic Framework for implementing CIM

Category	Sub-categories	Key Findings
Technical Considerations	Lidar & Spatial Data	Lidar is useful for spatial data collection and potentially for collecting as-built data
		Imported spatial data should be incorporated into GIS for better visualization
	Electronic Document Management	EDM provides a highly efficient and transparent method of document management for design and construction
		Stakeholders should be assigned with proper levels of authorization and access
	3D Engineered Models & AMG	3D engineered models provide benefits such as better communication and visualization, clearer design intent, less rework and cost, etc.
		AMG is useful for guiding machine operations especially for grading and paving work
	Mobile Devices	Mobile devices allow workers to view project related documents, add comments, take photos, receive real-time notifications, and better communicate in the field
	Interoperability	Interoperability requires a uniform data format or specifications about acceptable data formats, software, and hardware
Organizational Considerations	Communications between Stakeholders	Create an environment for free communication and information sharing
		Use digital tools to facilitate communications among stakeholders
	Communications with Public	Use digital approaches for effective communications with public, since many public communication tools are digital (e.g. websites, social media)
	Upper Management Support	Lead with upper management develop and implement CIM
		Have a champion/leader on 3D engineered models in upper management team
	IT Support	Ensure that IT staff work closely with engineers closely to develop products
	Impact of Project Delivery	Have contractors and designers involved early in the design process

Table 5. (Continuation)

Category	Sub-categories	Key Findings
Philosophy for Success	Data Usage Throughout the Lifecycle	Use data throughout the life cycle of a facility
		Develop an enterprise data pool to store or extract the facility data whenever necessary
	Support from Stakeholders	Engage contractors, utility companies, and other parties
	Motivate Team & Think Forward	Motivate employees to adopt new advanced tools
		Incorporate the needs of later project phases into earlier project phases
	Effective Training	Conduct just in-time training
	Share Lessons Learned with other agencies	Share lessons learned and best practices with other agencies

Technical considerations

With regard to the technical aspects of CIM implementation, the following technologies and tools including LiDAR and spatial data, EDM systems, 3D engineered models and AMG, mobile devices, and data interoperability should be considered as part of the CIM implementation process.

LiDAR and Spatial Data

LiDAR technology is extensively used by six of the seven transportation agencies that were visited for spatial data collection as it enables fast, accurate and safe data collection compared to traditional surveying methods. LiDAR data can be collected from various platforms; aerial, mobile or terrestrial, and used for various applications. If collected properly with sufficient accuracy, LiDAR technology can also be used to collect as-built data for transportation asset management purposes. It is not a common practice for LiDAR technology to be used for asset management purposes as it requires extra time investment, storage space, and a change in current workflows to accommodate this new technology. However, it should be noted that lack of as-built data might cause difficulties in the long term as indicated by the six transportation agencies. For example, when a road needs to be reconstructed, agencies are required to spend

considerable time and effort to ascertain the location and size of the utilities if there is no complete record of as-built utility data. If a mistake is made when locating the utilities, it is very likely that they will be damaged during the construction phase, requiring extra time and cost for repair.

Based on the discussions during the on-site visits, it was concluded that the streamlined use of accurate and comprehensive spatial data is essential for successful and efficient CIM implementation. Spatial data collected using LiDAR, robotic total stations, or other advanced surveying tools can be imported into a GIS or similar platforms, which would help the project team better visualize project-related features. It also makes it easier to identify locations with steep slopes or to conduct traffic studies. One of the transportation agencies visited developed a customized program to store geospatial data and its key attributes. This program allows the road alignments with their mileposts to be displayed on a GIS map that is open for public access via the Internet. By clicking each milepost, agency personnel or members of the public can not only view relevant road properties but also choose Google® street view in order to experience a "walk through" animation.

Electronic Document Management (EDM) Systems

The use of EDM systems is a beneficial way for transportation agencies to manage their data assets. All seven agencies that were visited are using EDM systems to some extent. Four of these agencies have extensive experience in using either their own systems that are developed in-house or customized commercially available cloud-based systems to store and manage their electronic documents. Contractors are asked to submit project documents or models through EDM systems, so that the agency representatives can digitally review them and provide immediate comments. At the same time, other project stakeholders can also view the shared

materials. In three of the states that were visited, digital signatures are used to accelerate the approval process for submitted electronic documents. One example of an EDM systems adopted by one agency was developed based on the unique needs of that agency. It enables design groups and contractors to submit electronic project documents to the system and specify which discipline is required to review them. When any changes are made to a document, the responsible personnel receive a notification of the changes. It also enables managers to assign tasks to each individual or group, and the built-in calendar will remind users of the upcoming deadlines. Additionally, it allows personnel to easily track comments and responses, which improves the design review efficiency.

Based on the experience of the agencies that have adopted EDM systems, it was concluded that it is important that the system provide immediate data access for users with the proper level of authority (read only, read and write, etc.) based on their responsibilities. Once the project is completed, documents in the EDM systems can be transferred to an archive (either as part of the EDM system or under a separate application or system) for permanent retention. For large size data files such as LiDAR point clouds and 3D engineered models, a separate application may be required that accommodates larger storage needs which might be separate from the EDM system. Such systems that provide storage for larger files may require additional maintenance expense which should be taken into consideration when plans are made to utilize an EDM system.

3D Engineered Models and AMG

The adoption of 3D engineered models and AMG are important steps for agencies during a transition to CIM. Based on discussions during on-site visits, agencies that are using 3D engineered models have observed many benefits such as better communication and visualization,

greater clarity in design intent, less rework, reduced cost, and the opportunity for design verification in 3D. During the initial implementation stage, successful agencies found that it was useful to collaborate with construction industry personnel possibly with the help of an appropriate trade association to determine the data exchange format (e.g. LandXML, TransXML, IFC, etc.), naming convention, and other related decisions in a way that is acceptable for all stakeholders. Additionally, rules or standards should be developed to properly organize and manage documents or models, so that information can be accessed and found easily when needed.

AMG is another important technology that was identified during this study. In order for this technology to be successful, 3D engineered models are required to be uploaded to on-board computers in construction equipment in order to guide machine operations. The 3D engineered models are either developed by contractors (sometimes based on the 2D drawings provided in the contract documents) or provided by transportation agencies and reformatted for machine use by contractors. In most cases, 2D drawings that have been extracted from the agency developed 3D model, serve as the record of design and the contractor assumes risks of any inaccuracy that may result from reformatting the agency develop 3D engineered model. AMG enables operators to view the proposed models and actual field conditions through an on-board display and adjust the movement or location of machine components (e.g. bulldozer blades, motor grader moldboards, excavator buckets, and other ground engaging equipment) accordingly. In current practice, AMG is widely used for grading work due to its ability to make considerable productivity improvement and accuracy increase. Stringless paving, which is another form of AMG, shortens the overall time required for paving work and improves safety in the field by reducing the number of stakes and string lines.

Mobile Devices

Various mobile devices such as tablet computers and personal digital assistants (PDA) can assist field personnel by providing fast access to data in the field. Two of the visited agencies had extensive experiences regarding the incorporation of mobile devices into their operations, and they observed the following benefits: a tablet computer enables workers to view project-related 3D engineered models or other electronic documents (instructions, manuals, standards, etc.) on the job site and add comments about the components being constructed. Tablet computers can also be used to take digital photos of the site and upload them to the project EDM system. Other team members can receive real-time notifications when new comments are added or changes are made. Furthermore, use of mobile devices enhances communications between the field and office personnel, which will likely help solve possible issues in the field quickly. One agency was conducting a pilot project that was testing the use of mobile devices for viewing and updating 3D engineered models. Overall, construction productivity and flexibility could potentially be improved with the effective use of mobile devices in the field.

Data Interoperability

Data interoperability is very important for successful CIM implementation and needs to be addressed early in the process of CIM implementation in order to prevent possible data loss or damage. Project stakeholders often use software and hardware of their own choice, and when they need to exchange data with others, there is a high probability that a change in data format may be necessary, which may result in loss of efficiency. Development of a uniform data format that supports data transfer among various software and hardware platforms is rather challenging. Some of the current uniform exchange formats for 3D engineered models such as Land XML, Trans XML, and IFC have their own drawbacks such as excessive file size and data loss during file conversion. Five of seven agencies that were visited specified the acceptable data formats,

software, and hardware in their standards that helped them increase their efficiency during data

transfer and avoid possible incompatibility issues.

Major Benefits of the Investigated Technologies

Based on the previous discussions, Table 6 summarized the major benefits of using

important CIM technologies observed by transportation agencies.

Table 6. Major Benefits Provided by CIM Technologies

Beneficial Area	LiDAR	EDM	3D Models	AMG	Mobile Devices
Safety	✓			✓	✓
Quality	✓		✓	✓	
Productivity	✓	✓	✓	✓	✓
Error Detection			✓	✓	✓
Communication		✓	✓		✓

LiDAR allows surveying team to collect spatial data faster, safer, and more accurately.

EDM enables electronic documents to be better managed and shared, which improves the overall

productivity and communication. 3D engineered models ensure high-quality projects with the

early detection of design errors. Productivity is increased due to the reduced amount of rework

needed. Also, communication process becomes more efficient with a better design intent

delivered through the models. AMG provides greater field safety, quality, and productivity.

Errors could also be detected prior to the start of the construction work. Mobile devices provide

more flexibility to access the data in the field and enable easier communication with other

personnel to solve any field problems.

Organizational considerations

With regard to the organizational aspects of CIM implementation, the following

categories including communications between stakeholders, communication with public, upper

management support, information technology (IT) support, and impact of project delivery methods should be considered and properly addressed.

Communications between Stakeholders

Open communication between project stakeholders is necessary for data and information to flow smoothly throughout the facility life cycle. Agencies can develop standards and use advanced tools to encourage both formal and informal communications among stakeholders. In one case, a joint venture contractor (design-builder) encouraged their suppliers to use an online material management system. This online material management system allowed contractors to order materials (e.g. sand, rock, cement, etc.), track delivery, and review the order before they completed payments. Weekly meetings were held between the contractors and their sub-contractors and suppliers for the discussion of job-related problems and the use of tracking and management systems. Important benefits were observed by the contractor from establishing good relationships with their sub-contractors and suppliers.

Communications with Public

Communications with the public is important for all transportation projects. This is especially true for CIM-related practices where a large amount of digital data is involved, or where digital communication or visualization tools would be useful for agencies to efficiently convey their messages to the public. Project stakeholders need to work together to make sure the public is informed of important project updates. Currently, various digital approaches (project websites, weekly email alerts, social media postings, mobile application development, and others) have been adopted to release project information to the public. Not only should the agency use effective communication tools but also it should make strategic plans for their use in advance.

Upper Management Support

Encouragement for innovation from upper management in agencies and having

passionate people involved in CIM development are important for the development and

implementation of CIM. Also, a proper amount of investment should be allocated for the

development of software, hardware, and other infrastructure that is necessary to support CIM

implementation. Additionally, it is desirable to have a champion/leader with sufficient

knowledge about 3D engineered models in upper management team to coordinate the CIM

development process, as 3D engineered models are one of the core technologies that support

CIM. Without a champion in upper management, the implementation of 3D engineered models

and later CIM would be challenging. This champion can help adjust the organizational structure

and assign the necessary resources required for the implementation of CIM.

Information Technology (IT) Support

Collaboration between CIM users and IT staff during the development of customized

programs for the agency is very important for successful CIM implementation. Engineers and

other business staff can propose ideas based on the agency' needs and convey those ideas to IT

personnel. Then, the IT staff can consider the feasibility, security, and other IT issues and present

their concerns back to the engineers and business staff. The final negotiated results should be a

feasible plan that accommodates the agency's needs. Some transportation agencies have IT

professionals embedded into the organizational structure of their agency, and some agencies

have even IT professionals dedicated specifically to their design, construction, or asset

management divisions, so that they can work closely with the application users and set priorities

for CIM initiatives. There are cases where engineers or other business staff members have

developed sufficient IT expertise to participate in the IT coordination effort in a highly effective

way. There are other cases where IT personnel were embedded in a particular agency business

unit, even though they actually reported to statewide IT organization. No one single best solution was found, but rather it was found to depend on the existing resources and real needs of the agencies.

<u>Philosophy for success</u>

Based on the successful practices from the host agencies, a general philosophy for successful CIM implementation is identified and summarized in this section.

Data Usage throughout the Facility Lifecycle

There might be various ways of defining the CIM concept, but the principle of CIM is to use the data on a cradle-to-cradle basis throughout the life cycle of a facility including planning, design, construction, as-built assets, operations and maintenance, and returning to planning when the facility is rebuilt (rebuilding is considered to be the rebirth of the facility which is signified by the second cradle in "cradle to cradle"). Data collected or created at a particular phase of a facility should be stored in an enterprise data pool, so that the stored data can be further extracted and used in other phases of the facility or the reconstructed facility. For example, in order to reduce or possibly eliminate the necessity of collecting surveying data multiple times, original surveying data can be collected with its downstream use in mind and stored electronically, so that it can be utilized by construction, maintenance and operation personnel effectively. With this cradle-to-cradle use of data, the value of the data can be maximized for the agency.

Support from Stakeholders

Cooperation and investments from stakeholders are necessary for CIM development and implementation. During the development and implementation of CIM, agencies should consider engaging other partners such as contractors and utility companies to make use of their expertise and unique insights, and in some cases, political support. Additional training might be needed to

ensure that construction personnel have sufficient skills to use 3D engineered models and other related CIM tools effectively. Also, construction personnel should work with designers to check if additional items need to be included in design models and ensure that design is accurate and constructible. This collaboration process will improve the quality of design and accuracy of quantities, so that the resulting models can be further developed to 4D/5D models or used for AMG.

Motivate Team Members and Think Forward

Employees should be encouraged to experiment with new methods of accomplishing tasks that became available as CIM is implemented, as such experiments will help to define the value of the CIM concept. Only when the team members are convinced about the value of CIM, the chances are higher for large scale successful CIM implementation. At the beginning of CIM implementation, agencies should identify their priority for areas of investment. Also, the needs of later project phases (e.g. developing as-built documentation during construction that can be passed on for use during operation, maintenance, and future planning) should be carefully embedded during early phases of a project (e.g. planning, design, and construction).

Effective Training

Personnel who are involved with CIM implementation need to have a basic understanding of related technologies and know how to appropriately apply those technologies with the operation or work processes for which they are responsible. This requires that the agency to provide proper training for their employees. An effective approach adopted by two of the visited agencies is just in-time training, where training courses are provided for personnel just before it is needed in order to complete their job duties. Otherwise, with one-time training programs, it is unlikely that employees will remember important aspects of the training material

after 5 or 6 months without having practiced the skill on a real project. On the other hand, easy access to training materials is also important for employees. Six of the seven visited agencies offer online training courses or manuals on a wide range of topics, which allows on demand self-study based training to suit employees' needs.

Share Lessons Learned with Other Agencies

In addition, agencies need to share ideas, lessons learned, and best practices with each other during the development and implementation of CIM. In this way, CIM will gradually evolve into a more mature system that will benefit the entire transportation industry. Although the CIM development path may be unique for each agency, it is likely that another agency may have previously solved similar problems during their development process and can inform other agencies how to address a similar problem with less effort.

Proposed vision for CIM implementation at enterprise level

CIM implementation could help agencies better manage their data and information, and ultimately assist decision makers in making better decisions. Fig. 3 demonstrates the vision proposed for the future CIM implementation. CIM is not only limited to one or a few phases of a transportation project, but can be implemented throughout the entire project lifecycle, from planning, conceptual design, detailed design, procurement, construction, as-built assets, operations and maintenance, and to the planning of the next renovation phase. This is indicated by the labeled arrows that surround the cone-shaped object in Fig. 3. Moreover, CIM is not only limited to project level implementation, but can also be applied at the program or enterprise level. A primary benefit of CIM implementation is that improved data driven decisions can be made within the enterprise. Data collected from each particular phase of the project can be better managed in an enterprise data pool, and used for other phases of the project or even for other

projects as indicated by the arrows that swirl around the cone. This would help eliminate redundancy in data collection and entry, thus improve overall work efficiency. With the effective management of data, all parties involved in a project can extract useful information from the integrated data pool in an efficient manner. Furthermore, using computer applications and human judgment, the data can be transformed into information and the information can be reviewed by upper management. With the use of better information, better decisions can be made. The transformation from data to information to decisions is indicated by the upward arrows depicted on the cone in Fig. 3.

Figure 3. CIM implementation at enterprise level throughout the project lifecycle

Conclusions and Recommendations

This paper defines the CIM vision as well as CIM concept and practices to help establish a better understanding of CIM. Based on the existing CIM definition and leading transportation agencies' experiences, it is found that effective collection and management of enterprise data pool throughout the lifecycle of a transportation asset is highly desirable in order to make better decisions. Data should be collected and retained as soon as they are created or modified in a particular phase of a project or program so that those data can be used for other purposes later in

other project or program phases or even at the enterprise level. This is more likely to be achieved

through the assistance of CIM-related technologies and tools. The adoption of CIM-related

technologies and tools (LiDAR, EDM, 3D engineered models, AMG, and mobile devices) can

generally improve field safety, quality, productivity, error detection, and communication of

transportation projects. The critical technical and organizational considerations as well as

philosophy for success for CIM implementation are also identified and discussed in the paper,

thus providing a framework for CIM implementation. As a pioneering investigation regarding

CIM, it is anticipated that the findings of this paper can help to guide transportation agencies on

how to make plans to successfully implement a CIM system and lead researchers to perform

further useful investigations in CIM-related areas. The major limitation of this study resides in

the challenges in data collection during the agency visits. Due to the length of the field study (2

weeks, 8 hours per day) and the confidentiality issues which prevented from video/voice

recording, it was challenging to capture all details during the visits. However, researchers and

panel members all worked together to capture data and compared notes and share perspectives

throughout the field visits. Then rigorous qualitative methods (i.e. coding strategies) were used

to analyze the data. The results that were thus obtained were also reviewed and verified by the

researchers, panel members, and selected participants. By combining the industry experts'

experiences with panel members' perspective, the results presented in this paper are anticipated

to serve as conceptual foundation for future CIM investigations.

Future research should be conducted to further explore the CIM concept so that agencies

can implement it with comparatively less effort and use it more effectively. A detailed guideline

on how to implement CIM technologies in every phase of a project is needed. Also, a detailed

guideline on how to effectively collect, manage and share the data resulting from the use of

various CIM technologies should be developed. Although agencies might have their own unique needs, it would be beneficial to standardize the concept for an electronic platform or data warehouse as much as possible in order to support CIM implementation.

Acknowledgments

References

AlMaian, R., Needy, K., Walsh, K., and Alves, T. (2015). "A Qualitative Data Analysis for Supplier Quality-Management Practices for Engineer-Procure-Construct Projects." *Journal of Construction Engineering and Management*, 10.1061/(ASCE)CO.1943-7862.0001046, 04015061

Anderegg, R., and Kaufmann, K. (2004). "Intelligent compaction with vibratory rollers: Feedback control systems in automatic compaction and compaction control." *Transportation Research Record: Journal of the Transportation Research Board*, Trans Res Board, 1868(1), 124–134.

American Association of State Highway and Transportation Officials (ASSHTO). (2015). "Geographic Information Systems (GIS)." Center for Environmental Excellence, <http://environment.transportation.org/environmental_issues/gis/> (Jun. 05, 2015)

Behzadan, A.H., Aziz, Z., Anumba, C.J., and Kamat, V.R. (2008). "Ubiquitous location tracking for context-specific information delivery on construction sites." *Automation in Construction*, 17, 737–748.

Bogdan, R. C., & Biklen, S. K. (2007). *Qualitative research for education: An introduction to theories and methods*. Needham Heights, MA: Allyn & Bacon.

Chang G. Xu, Q., Rutledge, J., Horan, B., Michael, L., White, D.J., and Vennapusa, P. (2011). *Accelerated Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials*, Federal Highway Administration, Washington, DC.

Federal Highway Administration (FHWA). (2000). "An Investigation of the Use of Global Positioning System (GPS) Technology and Its Augmentations within State and Local Transportation Departments." Report No. FHWA-RD-00-093, Office of Research, Development, and Technology, McLean, VA.

Federal Highway Administration (FHWA). (2011). "SUE Brochure." <http://www.fhwa.dot.gov/design/sue/suebrochure.cfm> (May 30, 2014)

Federal Highway Administration (FHWA)a. (2012). "EDC 2012 Initiatives - Construction Manager General Contractor." FHWA. <http://www.fhwa.dot.gov/everydaycounts/edctwo/2012/cmgc.cfm> (Dec. 8, 2014)

Federal Highway Administration (FHWA)b. (2012). "EDC 2012 Initiatives - Design-Build." FHWA. <http://www.fhwa.dot.gov/everydaycounts/edctwo/2012/designbuild.cfm> (Dec. 8, 2014)

Federal Highway Administration (FHWA). (2012). "Geospatial Data Collaboration." <http://www.fhwa.dot.gov/everydaycounts/edctwo/2012/pdfs/edc_geo_data.pdf> (May 30, 2014)

Federal Highway Administration (FHWA). (2013). "Intelligent Compaction." <http://www.fhwa.dot.gov/construction/ictssc/> (Jun. 03, 2014)

Federal Highway Administration (FHWA). (2014). "Applications of 3D Models on the Construction Site." < http://www.fhwa.dot.gov/construction/3d/webinars/webinar04.pdf> (Dec. 08, 2014)

FHWA, AASHTO, ARTBA, & AGC (2013). "Civil Integrated Management", <http://www.efl.fhwa.dot.gov/files/technology/dv/CIM-Poster-04.12.pdf> (May 30, 2014)

Grilo, A. and Jardim-Goncalves, R. (2011). "Challenging electronic procurement in the AEC sector: A BIM-based integrated perspective." *Automation in Construction*, 20, 107–114.

Guo, F., Jahren, C.T., and Turkan, Y. (2015). "Electronic Document Management Systems for Transportation Industry." *Proceedings, 2015 International Construction Specialty Conference*, ASCE, 132-1–132-9.

Land, F. (2001). "The Information Revolution." International Encyclopedia of Business and Management, Thomson Learning, London.

<http://www.lse.ac.uk/management/documents/isig-wp/ISIG-WP-95.PDF > (Jun. 04, 2015)

LiDAR UK. (2015). "A brief history of LiDAR." < http://www.lidar-uk.com/a-brief-history-of-lidar/> (Jun. 05, 2015)

Lietz, C.A. and Zayas, L.E. (2010). "Evaluating Qualitative Research for Social Work Practitioners." *Advances in Social Work*, 11(2), 188-202.

Lopez, R., Love, P.E., Edwards, D.J., and Davis, P.R. (2010). "Design Error Classification, Causation, and Prevention in Construction Engineering." *Journal of Performance of Constructed Facilities*, 24(4), 399-408.

Mack, N., Woodsong, C., Macqueen, K.M., Guest, G. and Namey, E. (2005). *Qualitative Research Methods: A Data Collector's Field Guide*. Family Health International. North Carolina.

Martínez-Rojas, M., Marín, N., and Vila, M. (2015). "The Role of Information Technologies to Address Data Handling in Construction Project Management." *Journal of Computing in Civil Engineering*, 10.1061/(ASCE)CP.1943-5487.0000538 , 04015064.

Matheu N.F. (2005). "Life cycle document management system for construction." Master Thesis, Department Engineering and Construction. University Politecnica De Catalunya, Spain, 37-46.

Maxwell, J.A. (2013). *Qualitative Research Design (3rd ed.)*. Thousand Oaks, CA: SAGE Publications, Inc.

Moore, W. (2004). "GPS Systems for the Earthmoving Contractor." Construction Equipment, <http://www.constructionequipment.com/gps-systems-earthmoving-contractor> (Jun. 05, 2015)

Morrow, S. (2007). "Qualitative research in counseling psychology: Conceptual foundations." *The Counseling Psychologist*, 35(2), 209-235.

O'Brien, W.J., Gau, P., Schmeits, C., Goyat, J., and Khwaja, N. (2012). "Benefits of Three- and Four-Dimensional Computer-Aided Design Model Applications for Review of Constructability." *Transportation Research Record*, No. 2268, 18-25.

Padgett, D. (2008). *Qualitative methods in social work research*. Los Angeles: Sage Publications.

Peyret, F. et al. (2000). "The Computer Integrated Road Construction Project." *Automation in Construction*, 9, 447-461.

Ray, S. J., & Teizer, J. (2013). Computing 3D blind spots of construction equipment: Implementation and evaluation of an automated measurement and visualization method utilizing range point cloud data. *Automation in Construction*, *36*, 95-107.

Saldana, J. (2016). *The Coding Manual for Qualitative Researchers*. Thousand Oaks, CA: SAGE Publications, Inc.

Sebesta, S., Scullion, T., Liu, W., and Harrison, G. (2006). "Thermal imaging of hot-mix paving operations for quality assessment: State of the practice in Texas." *Transportation Research Record: Journal of the Transportation Research Board*, Trans Res Board, 1946(1), 123–129.

Tardy, R. (2012). "Why InRoads is First in 3D Road Design." *LiDAR News*, <http://www.lidarmag.com/content/view/9340/206/> (Jun. 05, 2015)

Wang, L.C., Lin, Y.C., and Lin, P.H. (2007). "Dynamic mobile RFID-based supply chain control and management system in construction." *Advanced Engineering Informatics*, 21, 377–390.

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

Weippert, A., Kajewski, S.L., and Tilley, P.A. (2003). "The implementation of online information and communication technology (ICT) on remote construction projects." *Logistics Information Management,* 16(5), 327 – 340.

Zhang, S., Boukamp, F., & Teizer, J. (2015). Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA). *Automation in Construction*, *52*, 29-41.

Zhou, W., Whyte, J., and Sacks, R. (2012). "Construction safety and digital design: A review." *Automation in Construction*, 22, 102–111.

CHAPTER 3 LIDAR DATA UTILIZATION AND RECOMMENDED WORKFLOW FOR

TRANSPORTATION DESIGN

A paper will be submitted to the Journal of Computing in Civil Engineering

Fangyu Guo[1], Yelda Turkan[2], and Charles T. Jahren[3],

Abstract

As LiDAR has become increasingly popular in the transportation industry, it has been necessary to establish better understanding regarding the current application of LiDAR technology and more completely study issues such as decision-making in using LiDAR, the major challenges of using LiDAR, and how LiDAR data are stored and managed. More importantly, because LiDAR data can be potentially used for facilitating development of 2D and 3D design models, it is crucial to investigate whether there is an efficient way to develop such design models from LiDAR data. To address these issues, a web-based survey was conducted to assess the state of current LiDAR applications in transportation agencies. One-on-one phone interviews using the Delphi method were also performed to develop a standard process for initiating design models from the LiDAR data. The finalized workflow is expected to provide transportation agencies a better idea regarding how to better collect and utilize LiDAR data for design purposes.

Key words: *LiDAR data, 3D design models, Delphi method, workflow*

Introduction

Back in the 1960s, surveyors began to use lasers for range or distance measurement and, since the 1970s, mercury or tungsten vapor lamps and other early types of electronic distance measurement instruments began being replaced with lasers for field surveying work, but such laser-based devices could only measure distances and not angles back then (Shan and Toth 2009). Over the past 50 years, Light Detection and Ranging (LiDAR) has become an important 3D data acquisition tool used to obtain 3D measurements of scanned objects, and today LiDAR is widely used in environmental, topographic, cultural, and industrial heritage domains (Vosselman and Maas 2010). An increasing number of transportation agencies began using LiDAR technology after the enactment of the Moving Ahead for Progress in the 21st Century (MAP 21) legislation that required the U.S. national highway system to be digitally mapped (Williams et al. 2015).

Various types of LiDAR have been adopted in the transportation industry for use in a number of applications. Airborne LiDAR is suitable for collecting large amounts of spatial data over large surface areas, while mobile ground-based and static LiDAR are suitable for collecting spatial data in specific areas where a high level of detail is required (Williams et al. 2013; Barber et al. 2008). The efficiency and safety of the surveying process are greatly improved with the implementation of LiDAR technology to produce more accurate surveying results that can be used by transportation agencies over an asset's entire lifecycle (Autodesk 2014).

LiDAR is still a relatively new and continuously evolving technology with respect to the transportation industry. In order for transportation agencies to better utilize LiDAR, standard workflows and processes must be established and the following questions must be answered: (1) How should transportation agencies choose to use LiDAR technology (e.g. types of projects, types of LiDAR equipment, and application areas)? (2) What are the common challenges and

concerns of using LiDAR? (3) How should LiDAR data be stored and managed? On the other hand, 3D models have become a tool that Federal Highway Administration (FHWA) encourages transportation agencies to use for accelerating project delivery and enhancing project quality and field safety (FHWA 2015), and there is an increasing trend toward using LiDAR data to develop 3D models for project design. Though some agencies have developed effective approaches for producing design models from LiDAR data, it would be desirable to establish a general standardized workflow to assist agencies with less experience in developing 3D models from LiDAR data in an efficient manner and to allow agencies with more experience to share best practices. Accordingly, the main purpose of this paper is to answer the previously posed questions and to establish a standard workflow for developing 3D design models from LiDAR data. This workflow is expected to be applicable to LiDAR data collected by static, mobile ground-based, or airborne LiDAR.

Web-based surveys, phone interviews, and the Delphi method are the major qualitative methods used in this study. A survey including 12 questions was sent to 28 participants who were LiDAR professionals in various transportation agencies. It should be noted here that 25 of the participants were either members or friends of TRB AFB80 committee - Geospatial Data Acquisition Technologies in Design and Construction. The survey response rate reached 60.7%. A proposed workflow for utilizing LiDAR data for developing 3D models is also included as a survey question through which participants were asked to make recommendations regarding the proposed workflow. Based on survey feedback, researchers modified the workflow using the Delphi Method, a commonly used method in qualitative research to collect feedback from experts who are anonymous to one another to produce a final consensus after several rounds of data collection (Hsu and Sandford 2007). Subsequent one-on-one phone interviews were

conducted with 5 participants to learn more about their practices and further refine the proposed workflow.

Literature Review

The basic principle of LiDAR is to calculate range to a reflecting object based on the time interval between when a laser beam is emitted and reflected back to the scanner. Data can be collected during either day or night, and a point cloud is the direct deliverable result (Greenfeld 2014). LiDAR sensors can be installed on either static or mobile platforms. Common platforms include ground-based vehicles, airplanes, unmanned aerial vehicles (UAVs), and others. Static and mobile ground-based LiDAR are referred to as terrestrial LiDAR. With advancements in technology over the past 50 years, both terrestrial and airborne LiDAR technologies have become more mature in collecting accurate and high resolution spatial data (Vosselman and Maas 2010). State DOTs have recognized the value of LiDAR technology, as can be seen from the doubling in application rate of mobile LiDAR every 18 months. While there might be concerns about high initial cost, LiDAR technology could ultimately produce a huge amount of cost savings through the long-term benefits of collecting LiDAR data (Fisher 2013).

Types of LiDAR

In general, there are three commonly used types of LiDAR in the transportation industry, i.e., mobile ground-based LiDAR, static LiDAR, and airborne LiDAR, and the characteristics and applications of each are introduced in the following sections.

Mobile ground-based LiDAR

The major components of a mobile ground-based LiDAR unit are positioning hardware, a 3D laser scanner, photographic/video recording capability, computer and data storage, and a mobile platform (Olsen et al. 2013). Positioning hardware consists of a combination of an inertial

measurement unit (IMU) and one or more global positioning system (GPS) / global navigation satellite system (GNSS) receivers, which in combination are capable of finding the best possible positional information. When the satellite signal level is poor, the IMU provides the positional information, while when the satellite signal level is good, the IMU updates positional information from the GPS (Barber et al. 2008). The laser scanner orientation affects the quality of the collected data, so sometimes more than one scanner is used to obtain better coverage (Yoo et al. 2010). Photographic or video recording incorporates color information (red, green, and blue values) into the collected geo-referenced points, and the image or video itself can also be a useful resource for further data processing and other project-related uses. The computer must be able to store and perform initial processing tasks consistent with the large amount of field data collected. A mobile platform allows assorted data collection hardware to be integrated into one complete unit (Olsen et al. 2013).

Static LiDAR

A static LiDAR unit is usually mounted on a tripod. A 2D scanning device, either window-like or a panoramic scanner, is commonly used for static LiDAR. A window-like scanner would capture a rectangular view of the object, while a panoramic scanner would capture a 360° horizontal view and a 80-90° angle vertical view (Vosselman and Maas 2010). Static LiDAR produces the highest accuracy and resolution as well as a greater level of detail compared to all other forms of LiDAR. Users have more flexibility in choosing places for setting up a static LiDAR, and less operator training is needed than for either mobile ground-based or airborne LiDAR (Olsen et al. 2013, Greenfeld 2014). Since scanning is conducted at a static position, static LiDAR requires more time to finish survey work than the other forms of LiDAR.

To increase the efficiency of static LiDAR, a stop-and-go method can be used in which a vehicle equipped with a static laser scanner can periodically stop to make a static scan (Olsen et al. 2013).

Airborne LiDAR

The basic components of an Airborne LiDAR are similar to those of a mobile ground-based LiDAR. They include a laser scanner assembly, an airborne GPS antenna, an IMU, a control and data recording unit, an operator laptop, and a flight management system. The scanner assembly is comprised of scanning mechanics, optics, and a laser. The airborne GPS antenna is placed on top of the aircraft to ensure reception of strong signals from GPS satellites. The IMU collects rotational rates and acceleration data to further determine orientation and position of the platform. The control and data recording unit stores positioning and ranging data collected from the scanner, the GPS, and the IMU. An operator laptop is used to set up the target parameters before the flight and oversee performance during the flight. The flight management system helps a pilot to view and follow the planned flight routes. A digital camera is also usually attached to such a system (Vosselman and Maas 2010).

Airborne LiDAR units are used for capturing data over large areas and in places where ground-based LiDAR is difficult or impossible to operate. The point density of airborne LiDAR data is usually more uniform than that of mobile ground-based LiDAR. For mobile ground-based LiDAR, the point density near the vehicle path is higher than the density at greater distance from the vehicle path. Airborne LiDAR produces better results for flat or gently sloping areas but poorer results for vertical or steeply sloping surfaces (Barber et al. 2008, Olsen et al. 2013). Airborne LiDAR also exhibits greater post-processing efficiency than either static or mobile ground-based LiDAR (Greenfeld 2014).

LiDAR applications and data processing issues

This section introduces LiDAR applications in the transportation industry, including a discussion of data processing requirements and data processing and transfer challenges .

LiDAR applications in the transportation industry

Many studies have investigated LiDAR applications for tasks such as earthwork inspection, roadway safety inspection, urban mapping, pavement roughness measurement, and many others. Duffell and Rudrum (2005) discussed using LiDAR for highway earthwork inspections because the scanned data are highly accurate and can be viewed in a variety of forms such as contour plans, cross sections, and 3D models (Duffell and Rudrum 2005). Pu et al. (2011) described the use of LiDAR for road safety inspections. Features related to road safety analysis can be recognized and classified from a point cloud obtained through mobile scanning (Pu et al. 2011). Haala et al. (2008) studied using a StreetMapper mobile laser scanning system to depict an accurate trajectory within a referenced 3D city model. Chang et al. (2006) evaluated using a 3D laser scanning system to measure pavement roughness. Overall, LiDAR has been widely applied in the transportation industry.

Data processing

While LiDAR does bring many benefits to agencies, it also requires a considerable amount of investment with respect to data processing requirements. Registration, a necessary step for processing raw point clouds, combines multiple point clouds taken from different angles to produce a more complete image of the scanned object (Jaselskis et al. 2005). Filtering, another necessary step for processing point clouds, preserves the form of the terrain while removing obstructions such as vegetation. Filtering reduces the data file size to permit more efficient further processing. Filtered point clouds can be further developed into 2D or 3D models using

various techniques (Vosselman and Maas 2010). The Point Cloud Library, an ongoing project,

provides technical support and resources for point cloud filtering, feature estimation and

extraction, surface reconstruction, model fitting, and segmentation (PCL 2016). The final

deliverables of the scan data generally include point clouds, CAD models, and digital terrain

models (DTMs) (Yoo et al. 2010).

<u>Challenges of data processing and transfer</u>

There are also several challenges associated with LiDAR data processing and transfer,

including data interoperability issues and managing extremely large data file sizes. Since the

LiDAR data must be sequentially processed through multiple software applications, it is

relatively easy to lose or damage part of data during such a process. The large files are also

challenging to transfer to stakeholders either inside or outside the organization, so they are often

divided into sections for processing with output then delivered to end users in sections (Williams

et al. 2013, Yoo et al. 2010).

<div align="center">Research Methodology</div>

This study focused on investigating the current level of LiDAR implementation within

transportation agencies. It adopted qualitative research tools, including web-based survey tools,

phone interviews, and the Delphi method. Based on responses obtained from the agencies and

the use of the Delphi method, the research team established a workflow for standardizing the

process of developing 3D design models from LiDAR data. The following sections describe the

selection of participants, the manner in which the web-based survey was conducted, and how the

workflow was developed and refined.

Selection of target participants

To investigate the level of LiDAR implemented at the transportation agencies, 28 state

DOT personnel with extensive experience using LiDAR data were selected as participants in this

study. Among the 28 participants, 25 were members or friends of the Transportation Research

Board (TRB) standing committee AFB80 – on Geospatial Data Acquisition Technologies in

Design and Construction. The TRB AFB80 committee focuses on "applications of high accuracy

geospatial data acquisition technologies in support of the digital infrastructure for design and

construction of transportation facilities" (National Academies of Sciences 2016). Three other

state transportation agency personnel were also included in the study because of their extensive

knowledge and experience in working with LiDAR data. LiDAR is one of the most commonly-

used geospatial data acquisition technologies.

Web-based survey

A web-based survey with 12 questions was distributed to participants using the Qualtrics

survey tool (Qualtrics, Provo, UT). Qualtrics is specialized survey research software that

supports survey distribution and analysis. Before distributing the web-based survey, an email

describing the purpose of the study and the type of participation sought was sent to the

participants ahead of time. The questions were intended to capture the level of LiDAR

utilization (e.g. experience in using LiDAR, LiDAR implementation based on project types,

types of LiDAR equipment used, applications of LiDAR data, and challenges associated with

using LiDAR data), LiDAR data storage issues (e.g. storage locations, formats, file types, and

users), as well as integration with 3D models (e.g., whether or not to import point cloud into

design models, challenges of integrating LiDAR data with 3D design models, and workflow for

such integration processes). Among the 28 participants selected, 17 responded to the survey. The

authors included a draft workflow for using LiDAR to produce 3D design models (Figure 1) in the survey, and participants were asked to provide suggestions on how to improve that workflow to better produce a standard efficient process for developing 3D design models from LiDAR data.

Workflow development and refinement

A graphical representation of the workflow was developed using Icam DEFinition for Function Modeling (abbreviated IDEF0), where 'ICAM' is an acronym for Integrated Computer Aided Manufacturing. IDEF0 can be used in a structured diagram to represent activities, functions, and decisions and their relationships. For the IDEF0 model shown in Figure 1, the functions (or activities) to be performed are shown as boxes with inputs and outputs labeled on the arrows between the boxes. The necessary tools, known as mechanisms, are labeled as arrows pointing upward at the bottom of the boxes, while existing/potential challenges also known as controls for each function are labeled on arrows pointing down to the box tops. (Kim and Jang 2000). The forgoing details are summarized on the legend at the bottom right of Figure 1.

The Delphi method was adopted to verify and improve the proposed workflow. The main purpose of using the Delphi method was to achieve an experts' consensus by eliminating possible impediments sometimes present in regular conference room settings; anonymity and feedback are the main characteristics of the Delphi method. The traditional Delphi method involves multiple rounds of data collection. Within each such round, researchers ask for opinions on a particular topic through either surveys or interviews of individual participants. Researchers then present all the responses to the participants and ask for their feedback during the next round. This process continues until a final consensus has emerged among all participants (Greenfeld et al. 2014; Gordon 2009; Czinkota and Ronkainen 2005; and Hallowell and Gambatese 2009).
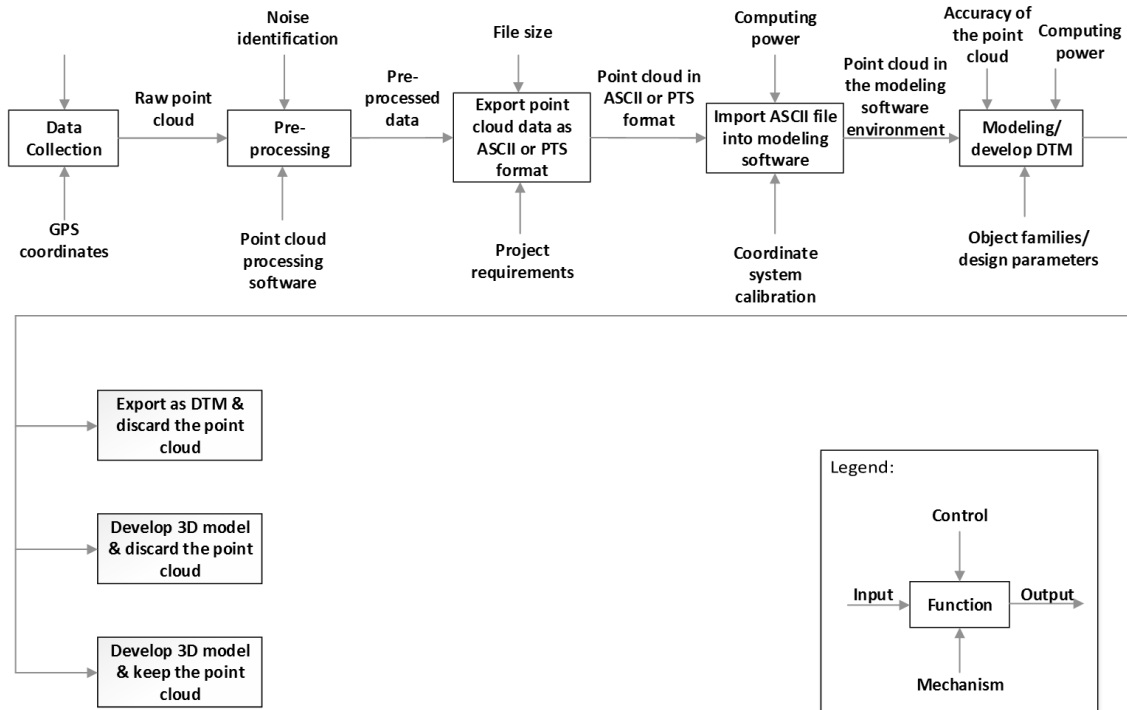
Figure 1. *Proposed IDEF0 workflow for developing 3d project design models from LiDAR data (Notes: A function is an activity or task that must be performed. Input refers to the data or information needed to perform the activity. Output refers to the deliverable produced by performing the activity. Mechanism refers to the resources or tools required for the activity. Control refers to the challenges or constraints for the activity.)*

In modern applications of the Delphi method, in-depth interviews can also be conducted in a "feed-forward" approach where the experts' consensus emerges from previous one-on-one interviews (Gordon 2009). The "feed-forward" approach requires less time compared to the traditional method while still accomplishing the main purpose of using the Delphi method, and this is why the authors decided to adopt the "feed-forward" approach for this study. The proposed workflow was first revised based on the suggestions collected from the survey respondents, then one-on-one phone interviews were conducted with five of the survey respondents known by the authors to have extensive experience in using LiDAR data and 3D models. After each phone interview, the workflow was revised based on interviewee suggestions and forwarded on to the next interviewee. After all revisions had been made based on the

feedback from the last phone interview, the workflow was returned to all interviewees one more time for their verification. The finalized workflow presented in Figure 3 is the product of this process.

<div align="center">Results</div>

This section presents results obtained from the survey and the phone interviews. It is divided into the major themes of current LiDAR utilization, LiDAR data storage, and LiDAR data utilization for design model development. Within each of these themes, related issues were discussed with the support of qualitative data obtained from the web-based survey. The proposed IDEF0 workflow as well as the modified one that was developed using the Delphi method was also included in this section as the recommended workflow for developing 3D design models from LiDAR data.

Current LiDAR utilization within transportation agencies

Seventeen out of the twenty-eight individuals contacted responded to the survey (60.7% response rate). These 17 participants were from various state department of transportation agencies within the United States representing various levels of experience in using LiDAR data (Figure 2). The number of years of experience in using LiDAR data reported by participants themselves ranged from 1 to 15 years, with an average of 7.7 years and a standard deviation of 4.4 years, reflecting a relatively diverse group in terms of years of experience. Based on these responses to the survey, the following paragraphs will describe the types of projects where LiDAR data were used, the types of equipment owned by participants' agencies, the primary application areas of LiDAR data, and the major challenges encountered in using LiDAR data.
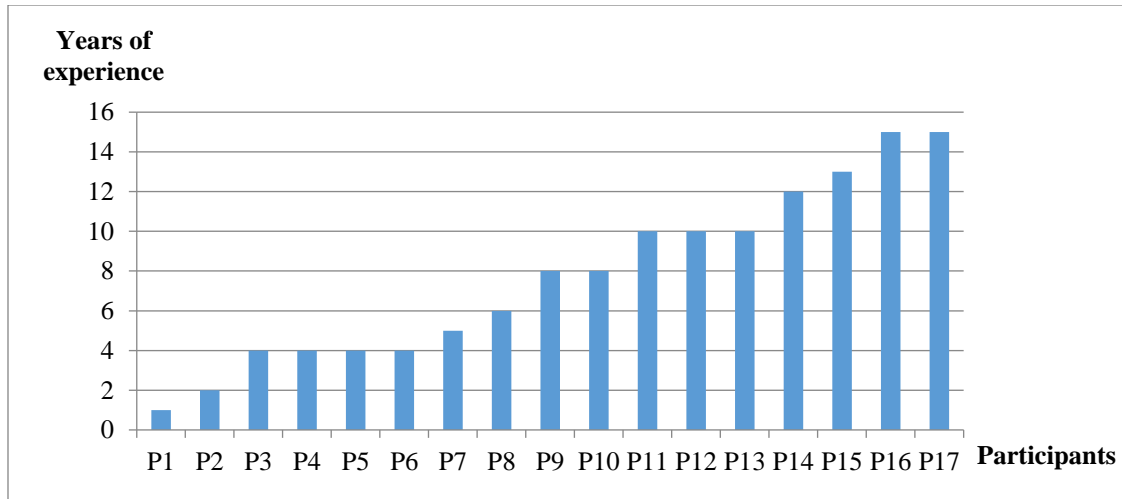
Figure 2. *Participants' Level of Experience with LiDAR*

LiDAR usage based on project types

LiDAR has been used on various types of transportation projects within the state

departments of transportation participating in this study. Tables 1 and 2 list the number of the

participants' organizations that are using LiDAR for highway and bridge projects with various

levels of costs and complexity. The results presented in Table 1 are based on the 13 responses

obtained that addressed the corresponding survey question. 92.3% of the respondents'

organizations have been using LiDAR for high-cost (greater than US $250k) highway projects

with a regular level of complexity. LiDAR has also been used for other types of highway

construction projects, and each organization might have different preferences in terms of using

LiDAR on projects involving various levels of cost and complexity. The summarized results

presented in Table 2 are based on the 7 responses that addressed the corresponding survey

question; all the respondents' organizations have been using LiDAR for high-cost bridge projects

with a regular level of complexity, and it has also been used for other types of bridge

construction projects as well. LiDAR has typically been used for projects with relatively higher

costs, possibly because it may be easier to use other surveying tools to collect and process data

for very small and low-cost projects.

Table 1. LiDAR Usage for Highway Construction Projects

Cost \ Complexity	Easy	Regular	Complex
< $25k	5	7	5
$25k - $250k	5	10	7
> $250k	7	12	8

Table 2. LiDAR Usage for Bridge Construction Projects

Cost \ Complexity	Easy	Regular	Complex
< $25k	2	4	3
$25k - $250k	3	5	4
> $250k	5	7	4

Types of LiDAR

Various types of LiDAR are used within the participants' organizations, and the survey

results indicated that mobile ground-based and static LiDAR have been the most commonly

adopted LiDAR types at the respondent's agencies, with implementation rates of 82.4% and

94.1%, respectively. The implementation rate of aerial LiDAR has been 52.9%, relatively lower

than the other two types of LiDAR. The popularity of each type of LiDAR coincides with the

results obtained from the study conducted by Olsen et al. (2013). Since airborne LiDAR is

typically used for capturing spatial data over relatively large areas with relatively low density

demands, it is not as commonly used as the other two types of LiDAR by most transportation

agencies.

LiDAR applications

LiDAR implementation is limited not only to one particular phase of a project but rather

may extend through the entire project lifecycle, including activities of planning, design,

construction, and asset management. Based on the survey results, LiDAR is more commonly

used in the design, planning, and asset management phases (with implementation rates of 82.4%, 64.7%, and 35.3%, respectively) and less commonly used in the construction phase (with an implementation rate of 29.4%).

LiDAR technology has a variety of applications. The options described in the web-based survey responses for LiDAR applications included data collection from existing features and measurements, data collection from new as-built features and measurements, data input for GIS, quality assurance / quality control (QA/QC), 3D model development, and others; participants had an option of selecting more than one application area. Based on the survey results, all participants use LiDAR to collect data from existing features and measurements. The rates of using LiDAR for 3D model development, QA/QC, data input to GIS, and data collection from new as-built features and measurements were 58.8%, 41.2%, 35.3%, and 35.3%, respectively. Four of the participants also listed other uses of LiDAR, including geologic hazard mapping, documenting historic bridges as part of environmental mitigation requirements, capturing data pavement surface design data (using mobile LiDAR), developing DTMs for planning, data input for steeper terrain environment design, and orthorectification (with aerial LiDAR). Orthorectification refers to the process of mitigating distortion effects resulting from the tilt of aerial sensors and variations in the earth surface to create a corrected image with more accurate positional information (Liu et al. 2007, Yoon 2008).

Challenges associated with using LiDAR data

Although LiDAR technology has proven to be beneficial for transportation agencies, some challenges remain, including data storage, data processing, computing power, and noise in LiDAR point clouds. Participants were asked to choose those they thought were most challenging and to provide a rating (1 being least challenging and 5 being the most challenging).

Thirteen participants responded to this question and according to their responses, the agreement rate for each of the listed issue (i.e. data storage, data processing, computing power, and noise in the point cloud) as a challenge was 86.7%, 100%, 93.3%, and 93.3%, respectively.

Table 3 shows the number of participants who gave a particular score for each listed issue, with a zero value given for issues that were not selected by participants (i.e. participants do not consider the listed issue challenging). The ratings varied quite a lot, which could be a result of different skill levels, existing hardware and software capabilities at their agencies, and or other issues. The average ratings for data storage, data processing, computing power, and noise in the point cloud were 2.9, 3.0, 2.5, and 1.9, respectively. Data processing seems to be the most challenging issue while noise in point clouds seems to be the least challenging. One participant also commented that it is difficult to hire dedicated analysts for LiDAR data processing. Two participants listed other challenges, including difficulty in maintaining equipment and manual or semi-manual feature extraction (i.e. need for more accurate/reliable automatic feature extraction tools) in addition to these four major challenges.

Table 3. Rating Counts for Common Challenges Associated with using LiDAR Data

Rating score	Data storage	Data processing	Computing power	Noise in the point cloud
score 0	2	0	1	1
score 1	2	2	1	6
score 2	2	4	5	3
score 3	2	3	5	4
score 4	4	3	3	1
score 5	3	3	0	0

LiDAR data storage

Based on seventeen participant responses to the survey, the following paragraphs discuss data storage location and format as well as file types and users of LiDAR data.

<u>Storage place and format</u>

LiDAR data are typically stored in a standardized format (mostly LASer (LAS)) on an agency's server or on hard drives. Because of the large data file sizes, 62.5% of participants' agencies store their LiDAR data on a server and 37.5% of participants store their LiDAR data on hard drives. One of the agencies currently storing LiDAR data on hard drives is in the process of moving all data to cloud storage services, while another has aerial LiDAR data managed separately by the State Floodplain Mapping Agency and made available to the public through a website. One participant reported that they usually download data from another state agency server and delete it once they are finished with it.

LiDAR data are usually stored in a standardized format like LAS, because such files are easy to integrate with other modeling tools. For example, they can be converted to MicroStation file format and easily imported into design software after cleaning and processing in a 3D workflow. One participant mentioned that they work with LiDAR data in LAS and Hexagon Point Cloud format (HPC) and archive it in LASzip (LAZ) while retaining the raw data in a proprietary format.

<u>File types and users</u>

Various types of files, including raw point clouds, registered point clouds, processed point clouds, and DTMs or other derivative products, can be produced from LiDAR data, and each such file requires a large amount of storage space. Based on the survey results, only 23.5% of participants' agencies store all these files on their server system, while others store only one of the several types of these files depending on their agencies' needs. One participant mentioned in particular that they typically store raster datasets, LAZ point cloud data, and vector data.

Storing LiDAR data can be quite useful for agencies in the long term because it can be used for design surveys and for archival as well as asset management purposes. DTMs can be developed from LiDAR data and passed over to designers. One participant noted that point cloud data can be processed into hillshade, digital elevation model (DEM) and contours, to fulfill a variety of uses, ranging from MicroStation/Bentley Map for designers' use to ArcGIS for GIS analysts/planners' use. Another participant explained that their .las data have been used for line-of-sight analysis along their scenic byways to develop viewsheds based on data collected using terrestrial LiDAR, and added that they are very likely to be increasingly used by their environmental personnel and even by the agency's aviation office in the future. One participant also mentioned use of regular cloud storage backup for offsite data backup and retrieval after a defined period that usually varied by project.

LiDAR data use for 3D design model development

Thirteen out of seventeen participants import their point clouds into modeling software. Based on the survey results, participants' agencies usually use one or more modeling software applications for their design. Bentley products, including MicroStation, GeoPAK, InRoads, and Open Roads, were the most commonly used design applications by these agencies. Autodesk Civil 3D in conjunction with Bentley products was also used by two agencies. The participants' agencies also used various types of software, including Leica Cyclone, 3D Reshaper, TopoDOT, Quick Terrain Modeler, and ArcGIS Pro, for LiDAR data processing.
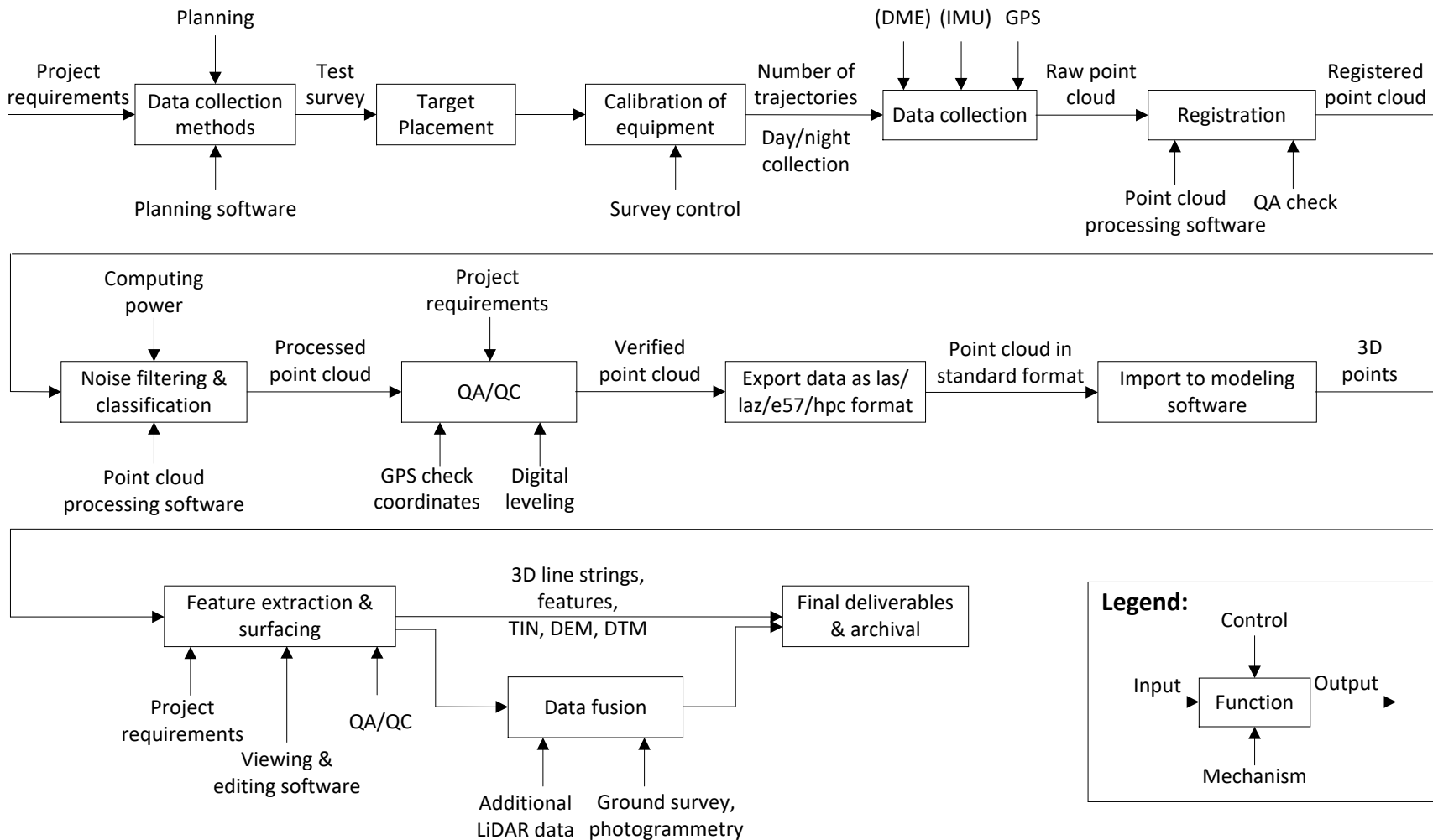
Workflow for developing design models from LiDAR data

Our study developed the draft workflow presented in Figure 1 for developing 3D design models from LiDAR data, and revised this workflow based on responses obtained from the survey. The workflow was then successively improved after each of the five phone interviews

conducted with LiDAR experts. Figure 3 presents the final version of the proposed workflow for developing 3D design models from LiDAR data followed by a narrative description.

Depending on project requirements for existing conditions and/or as built data collection, appropriate data collection methods (including static, mobile ground-based or airborne LiDAR) and integrated survey methods should be selected at the very beginning of a project or program because the level of planning effectiveness determines the overall success of the data collection and processing activity in achieving project requirements. Specialized software, such as TopoPlanner and TopoMission (Certainty 3D Inc.), can be used to assist with the planning process at this stage. It should also be noted that static and mobile ground-based LiDAR systems perform better on hard surfaces like pavement compared to soft surfaces like vegetated ground surfaces and ditches. If soft surfaces must be scanned, a follow-up survey using a total station and/or airborne LiDAR could be used for collecting spatial data.

High-accuracy targets must be located, surveyed, and leveled (elevations can be determined by differential leveling). Only with proper placement of targets will horizontal coordinate accuracy and vertical elevation of point cloud matches be ensured. When using a mobile LiDAR, targets are typically placed on the ground, and an additional leveling process is used to ensure that the point clouds have the desired level of vertical coordinate accuracy., Equipment should be calibrated prior to data collection to ensure accuracy. Furthermore, survey control to tie the point clouds to real world X/Y coordinates and to reduce errors for the vertical coordinates of LiDAR point clouds is required.

Figure 3. *Finalized workflow for developing design models from LiDAR data (Notes: Function is an activity or task that needs to be performed. Input refers to the data or information needed to perform the activity. Output refers to the deliverable produced by performing the activity. Mechanism refers to the resources or tools required for the activity. Control refers to the challenges or constraints for the activity.)*

After equipment calibration, the number of required trajectories must be determined to ensure that desirable data acquisition coverage by the scanning process can be achieved. For airborne LiDAR, trajectories are usually represented as flight paths. For static and mobile ground-based LiDAR, trajectories are usually represented as multiple lanes or static positions. Without careful planning of trajectories, additional scanning trips might be required to collect missing data that could have been acquired during the first scanning process. For actual scanning work, the accuracy of the collected data is usually determined by the combined accuracies of the distance measurement equipment (DME), GPS, and the inertial measurement unit (IMU) (GPS only for the static LiDAR). Day scanning for most operations is typical but to reduce the occurrence of artifacts night scanning can also be performed with supplemental day image overlays.

Raw point clouds are the very first products produced by a LiDAR scanning process in the field. Registration must be performed using a point cloud processing software application specific to the hardware used to collect the data so that multiple point clouds collected from various angles can be integrated into a comprehensive point cloud portraying a complete picture of the scanned site. Small pieces of point clouds might sometimes be produced by this process to reduce the size of the data file and ease the subsequent processing load. During the registration process, point clouds will be projected onto the project coordinate system specified by the agency. A quality assurance check would be conducted to ensure that the point clouds meet the required level of accuracy specified for the project. This check would involve comparing the position of scanned targets (additional targets that were not used for registration) to their survey coordinates. The relative accuracy of the collected point clouds from the IMU and DME is usually improved by using surveyed level control targets. Because LiDAR produces four returns

per pulse, registration will typically identify different components, including vegetation, features, and bottom surface (bare earth return), by color.

After the registration process, the noise in the registered point clouds must be filtered so that unnecessary artifacts can be removed from the point clouds. The filtered point clouds must then be classified into appropriate categories based on the type of features they represent. Noise filtering and classification can be conducted using commercial off the shelf (COTS) point cloud processing software, and considerable computing power is usually needed for this process.

The processed point clouds (after filtering and classification process) will typically be subjected to another QA/QC step to ensure that the required level of accuracy is met. Data validation of QA/QC with field survey spot points should be conducted to check the accuracy of the processed point cloud. For projects with high accuracy requirements, digital leveling can also be used to ensure the accuracy of the vertical coordinates of the processed point clouds.

The verified point clouds can be exported using a standard format such as las, laz, e57, hpc, etc., with additional processing for 3D points of features, 3D lines (including xml) for breaklines, and 3D DTMs for surfaces. The point clouds in standard format can be easily imported into most modeling software for further modeling steps. Some modeling software might also accept verified point clouds in their original format, but keeping data in a standard format is always a good choice since data in such a format can be easily transferred whenever necessary.

When point clouds are imported into modeling software applications, the data is still represented as 3D points (with accurate x, y, z values). The modeling software enables feature extraction and further modeling, and while this process can be automated to provide modest accuracy, manually intensive processes are often required to generate sufficiently accurate

comprehensive planimetric features. The final products of this step can be 3D line strings, feature points, or DTM surfaces, depending upon project requirements. QA/QC will be conducted to ensure that the required level of accuracy is met.

The final products will be merged from various sources (e.g. additional LiDAR dataset, ground survey, or photogrammetry) and fused to create a single dataset to be delivered to agencies, consultants, and contractors, who typically verify accuracy through a data validation process. At the same time, these products will typically be appropriately stored on the cloud, on a USB drive, or at an FTP site, based on a particular agency's needs and policies. Data gaps will be noted for areas that are obscured or may otherwise present data acquisition challenges, along with recommendations for acquisition of data necessary for additional fusion.

It should be noted that the workflow described is for developing design models from LiDAR data, and if registered or processed point clouds are the required deliverables, the later steps would not be necessary.

Conclusions and Recommendations

LiDAR is becoming a main stream technology adopted by transportation agencies, so it is worthwhile to establish a better understanding with respect to how LiDAR is actually utilized to assist with transportation projects and to further identify more efficient ways of collecting and processing LiDAR data. The following key findings were revealed by the web-based survey among LiDAR data experts working at transportation agencies. First, LiDAR is more commonly used for high-cost highway and bridge projects. Second, static LiDAR is most commonly owned type used by transportation agencies compared to mobile ground-based and airborne LiDAR. Each LiDAR type has its own advantages, so transportation agencies should select the most appropriate LiDAR type to meet their own demands. Third, LiDAR is most commonly used for

collecting spatial data and measurements of existing features, but is also commonly applied in many other application areas such as developing design models, QA/QC, data input to GIS, collecting data and measurements of new as-built features, and others. Fourth, the biggest challenges of implementing LiDAR reside in its data processing and storage requirements. Fifth, LiDAR data are usually exported in a standardized format (mostly LAS) and stored on a central server along with other associated deliverables. A standard workflow for developing design models from LiDAR based on phone-interviews conducted using the Delphi method has been developed. This workflow is expected to provide other transportation agencies with a more standard and effective methodology for collecting and processing LiDAR data for further design modeling purposes.

Future research could be conducted to further investigate more efficient tools or approaches for extracting features and developing surface models from point clouds since the current feature extraction and modeling process is not entirely automatic and convenient. This is most likely to be achieved through coordinated efforts with software vendors or programmers.

References

Autodesk. (2014). "LiDAR Scanning: Definitely Worth the Trouble."
<http://www.mdconstructionnet.net/wp-content/uploads/2014/05/Lidar-whitepaper.pdf>
(April 13, 2016)

Barber, D., J. Mills, and S. Smith-Voysey. (2008). "Geometric validation of a ground-based mobile laser scanning system." *ISPRS Journal of Photogrammetry and Remote Sensing, 63*(1), 128–141.

Chang, J.R., K.T. Chang, and D.H. Chen, (2006). "Application of 3D Laser Scanning on Measuring Pavement Roughness." *Journal of Testing and Evaluation, 34*(2).

Czinkota, M. R., and Ronkainen, I. A. (2005). "A forecast of globalization, international business and trade: report from a Delphi study." *Journal of World Business*, Elsevier, 40(2), 111–123.

Duffell, C. and Rudrum, D. (2005). "Remote Sensing Techniques for Highway Earthworks Assessment." *Site Characterization and Modeling*. 1-13.

Federal Highway Administration (FHWA). (2015). "EDC-2 Innovations (2013-2014)." <http://www.fhwa.dot.gov/innovation/everydaycounts/edc-2.cfm> (May 16, 2016)

Fisher, D.D. (2013). "The Benefits of Mobile LiDAR in Transportation Projects." Geodatapoint, <http://geodatapoint.com/articles/view/the_benefits_of_mobile_lidar_in_transportation_projects> (May 18, 2016)

Glennie, C. (2009). "Kinematic Terrestrial Light-Detection and Ranging System for Scanning." *Transportation Research Record: Journal of the Transportation Research Board*, 2105(1), 135–141.

Gordon, T. (2009). "The Delphi Method." *Futures Research Methodology* V3.0, The Millennium Project, Washington DC. <http://millennium-project.org/FRMv3_0/04-Delphi.pdf> (April 27, 2016)

Greenfeld, J. (2014). "Terrestrial and Mobile LiDARmapping Systems: Understanding the Technology, Applications and Opportunities." <http://c.ymcdn.com/sites/www.njspls.org/resource/resmgr/SurvCon_2015_Handouts/NJSPLS_TLS_and_MLS_mapping_S.pdf> (April 17, 2016)

Hallowell, M. R. and Gambatese, J. A. (2009). "Qualitative research: Application of the Delphi method to CEM research." *Journal of construction engineering and management*, 136(1), 99–107.

Hsu, C.-C., and Sandford, B. A. (2007). "The Delphi technique: making sense of consensus." *Practical assessment, research \& evaluation*, 12(10), 1–8.

Jaselskis, E. J., Gao, Z., and Walters, R. C. (2005). Improving transportation projects using laser scanning. *Journal of Construction Engineering and Management*, 131(3), 377–384.

Kim, S. and Jang, K. (2000). "Designing performance analysis and IDEF0 for enterprise modelling in BPR." International Journal of Production Economics 76, 121-133.

Liu, X., Zhang, Z., Peterson, J., and Chandra, S. (2007). "LiDAR-derived high quality ground control information and DEM for image orthorectification." *GeoInformatica*, 11(1), 37–53.

National Academy of Sciences. (2016). "Standing Committee on Geospatial Data Acquisition Technologies (AFB80)." <https://www.mytrb.org/CommitteeDetails.aspx?CMTID=1313> (April 26, 2016)

Olsen et al. (2013). "NCHRP 15-44 Guidelines for the Use of Mobile Lidar in Transportation Applications." Transportation Research Board of the National Academies.

PCL. (2016). "What is PCL?" < http://pointclouds.org/about/ > (April 17, 2016)

Pu, S., Rutzinger, M., Vosselman, G., and Elberink, S.O. (2011). "Recognizing basic structures from mobile laser scanning data for road inventory studies." *Journal of Photogrammetry & Remote Sensing*, 66(6), s28-s39.

Qualtrics. (2005). *Qualtrics*. Provo, Utah, USA. < http://www.qualtrics.com >

Shan, J. and Toth, C.K. (2009). *Topographic Laser Ranging and Scanning Principles and Processing*. Taylor & Francis Group, Boca Raton, Florida, US.

Vosselman, G., H. G Maas, and others. (2010). *Airborne and terrestrial laser scanning*. Whittles Publishing, Dunbeath, UK.

Williams, K., Olsen, M.J., Roe, G.V., and Glennie, C. (2015). "Consider the Benefits of Mobile LiDAR for Transportation Projects." Earth Imaging Journal. <http://eijournal.com/print/articles/consider-the-benefits-of-mobile-lidar-for-transportation-projects> (May 18, 2016)

Williams, K., Olsen, M.J., Roe, G.V., and Glennie, C. (2013). "Synthesis of transportation applications of mobile LiDAR." *Remote Sensing*, 5(9), 4652–4692.

Yoo, H. J., F. Goulette, J. Senpauroca, and G. Lepere. (2010). "Analysis and Improvement of Laser Terrestrial Mobile Mapping Systems Configurations." *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences,* 38(5), 633-638.

Yoon, J. S. (2008). "Ortho-rectification of a Digital Aerial Image using LiDAR-derived Elevation Model in Forested Area." *Korean Journal of Remote Sensing*, 24(5), 463–471.

CHAPTER 4 ELECTRONIC DOCUMENT MANAGEMENT SYSTEMS FOR THE

TRANSPORTATION CONSTRUCTION INDUSTRY

A paper to be submitted to the Journal of Construction Engineering and Management

Fangyu Guo[1], Charles T. Jahren[2], and Yelda Turkan[3]

Abstract

The implementation of various advanced technologies typically produces a considerable amount of digital data for transportation agencies, so it is desirable to have electronic document management (EDM) systems to promote efficient data-sharing with stakeholders. Although EDM systems with well-understood benefits have been implemented in the building construction industry, they are not as common in the transportation design and construction industry, and few agencies have broadly implemented EDM. Given differences between the building and the transportation industries, it would appear to be useful to analyze early examples of EDM implementation to establish a viable framework for further implementation. The purpose of this paper is to present and analyze the current state of EDM system implementation within the leading transportation agencies and to recommend a previously described framework. Four transportation agencies and selected stakeholders present their considerable experience with EDM related practices and tools, and in this paper, the EDM implementation processes and practices used by the four agencies and one construction company are documented and analyzed in detail.

Key words: Electronic Document Management, Civil Integrated Management, Digital Project Delivery

Introduction

Electronic Document Management (EDM) systems refer to computer solutions that allow users to electronically create, store, and manage various documents (EDMS 2014). Without EDM systems, a considerable number of hard copy documents must be physically exchanged within agencies and between various partners, requiring considerable time and effort. Obtaining signatures on hard copy documents usually incurs undesirable delays and shipping costs, and field personnel may be required to carry heavy binders, files, and plan sets around construction sites. When EDM systems are implemented, documents can be electronically created and submitted to a shared platform, allowing authorized users to instantaneously view, download, provide comments, approve, or take other actions (Sulankivi et al. 2002). In some cases, non-document files such as 3D models and LiDAR point clouds can be also exchanged on the same or similar platforms. Documents and files can also become permanent assets that can be archived with relative ease and be extracted later as needed.

The Moving Ahead for Progress in the 21st Century (MAP 21) legislation has encouraged the use of advanced technologies and tools such as EDM systems, GIS, 3D modeling, automatic machine guidance (AMG), and others that have been tested and implemented by various transportation agencies. The Federal Highway Administration (FHWA) Every Day Counts (EDC) program was also created to encourage the development and implementation of innovations, including EDM, for transportation projects; this was done under the moniker of e-Construction — a paperless construction administration delivery process (FHWA 2015).

However, to facilitate wide application of EDM systems within the transportation industry, it is necessary to develop a framework for implantation, and this can be accomplished by addressing the following questions: (1) Why are EDM systems are important? (2) How are

EDM systems actually implemented? (3) What type of systems they should select? The purpose

of this study is to answer these questions and to develop such a framework. Five case studies

were selected to illustrate the use of a particular EDM system within a transportation agency or

construction company. The first four case studies were conducted at four leading transportation

agencies in the U.S., with most data being collected as part of the National Highway Cooperative

Research Program (NHCRP) Domestic scan project - 13-02 Advances in Civil Integrated

Management (CIM). CIM uses various advanced technologies and tools to accurately collect,

organize, and manage data produced throughout the lifecycle of a transportation project, and an

EDM system is one of the major tools included in the CIM concept. After the scan was

completed, the authors conducted follow-up interviews to collect more insights from these

agencies. The fifth case study was related to a construction company located in Northwestern

China whose its EDM system was recently developed to incorporate not only project-level but

also enterprise-level execution. The case study results indicated that EDM systems are especially

beneficial in maintaining data integrity and transparency as well as in improving overall

communication efficiency. The common functionalities as well as the uniqueness of the EDM

systems studied are also summarized in this paper so that transportation agencies can gain

insights into choosing an appropriate EDM product for their own benefits.

Background

A variety of tools for the purpose of electronic collaboration, including emails, instant

messaging, calendars, discussions, polling, file sharing, and document management software

(Munkvold and Zigurs 2005), have been adopted by transportation agencies and construction

companies. Issa et al. (2003) indicated that about half of large contractors in the U.S have been

using a variety of technologies for project collaboration.

Typically, when transportation agencies are executing transportation/infrastructure projects, at the beginning of the project a large number of hard copy documents, including design drawings, schedules and estimates, meeting minutes, bill of quantities, and others, are created. Various organizations in various countries have made several attempts to develop standards for such documents typically produced throughout a project's duration. As computer word processing, spreadsheets, and computer-aided design (CAD) applications have become more commonly used in the industry, many electronic documents have been produced and shared with stakeholders through email, CDs, external hard drives, and/or in other ways; traditional hard copy documents are beginning to be replaced with electronic documents. Greater convenience for all parties involved in projects has resulted through the emergence of EDM systems that enable all project-related electronic documents to be stored, updated, and shared through a common web server (Björk 2006). With EDM systems, loss or misplacement of files is rare and the web server can provide a means for transmitting files, thus providing further advantages over other methods. With information stored all in one place, work can be performed in a smoother and more efficient manner (Bartosh 2011).

Such EDM systems have typically been developed by an agency or company's in-house staff, project participants, or by a third party (Bjork 2003), and these systems are often either developed for project/team or enterprise level execution (Munkvold and Zigurs 2005). King (2011) described the important issues that should be considered when selecting appropriate EDM software. They included business objectives, expected gains from EDM software, desired functionalities, change of process to accommodate new software, efficiency measurement, evaluation and improvement of software, level of access and security, and regulations for retaining documents (King 2011). Consideration also should be given beforehand regarding the

possibility of allowing EDM system access through personal mobile devices (e.g., smartphone and ipad). Though it might be convenient for personnel to access such systems through mobile devices, this may engender a greater risk that malware could infect the agency's EDM system (Leikums 2013).

Each EDM system is enhanced by containing its own metadata, because directory structures embedded within metadata can help mitigate damage that may result from possible loss of data or document files. Document searches may also become easier and more precise using a directory structure that can be devised from the metadata (Tough and Moss 2003). Standardization of metadata and data storage is very important, because this provides considerable convenience for downstream users (Bjork 2003).

According to case studies conducted by Sulankivi et al. (2002), utilization of EDM systems produced 29saved work days and prevented 1700 days of delay for information distribution, together saving 17,300 USD for a single project in Finland. There are also considerable difficult to quantify benefits from using EDM systems, including convenient document distribution and publishing, easy access to the most up-to-date versions of documents, and quick access to real-time information (Sulankivi et al. 2002). On the other hand, there are some challenges associated with the utilization of EDM systems. Mohamed and Stewart (2003) concluded that proper training and support were necessary for effective implementation of EDM systems within an organization. Becerik (2004) indicated that more studies demonstrating EDM systems' benefits should be conducted to promote their development and popularization. Munkvold and Zigurs (2005) also recommended that easy-to-use EDM systems should be developed, or else personnel may be likely to prefer reverting to previously-used methods while

performing their jobs. Guidelines and support should also be developed for instructing new users in using the system.

Methodology

According to Yin (2012), a case study is a preferred approach when a researcher is exploring how or why a contemporary phenomenon works when there is little or no control over events. Furthermore, the case study approach enables researchers in construction engineering and management fields to answer "how" and "why" types of questions and to assess the influence of certain new technologies on projects (Tayloret al. 2010). EDM systems designed to help personnel electronically create, store, and manage their documents are relatively new in application to transportation agencies, so a case study approach was selected in this study for investigating how EDM systems have been implemented within transportation industry why they are important in that arena. The instructions and procedures given by Creswell (2013) for conducting a case study were used as guidance for the research design. Multiple cases were included to explore EDM systems in use within four leading state transportation agencies (STA) in the U.S. and a construction company located in northwestern China.

Selection of participants

During on-site visits to seven state DOTs through the NCHRP Domestic Scan 13-02 - Advances in CIM - project, four state DOTs located in the western, northeastern, and Midwestern regions of the U.S were identified as agencies with relatively mature experiences with EDM systems and having plans to continuously improve such systems. Three of these DOTs were also identified by EDC-3 as adopters of paperless construction delivery processes (FHWA 2015), so these four state DOTs were selected as participants in studying the implementation of EDM systems in agency-wide environments. A construction company located

in northwestern China was also included in this study because they had developed their own

EDM system that is supportive at both the project level and the enterprise level.

Data collection

Before the on-site visits, semi-structured interview questions addressing Civil Integrated

Management (CIM) implementation issues, including the implementation of EDM systems, were

sent to the study participants. During the on-site visits, participating agencies provided all-day

presentations and supplementary documents to demonstrate their CIM-related practices,

including EDM implementation. Detailed field notes were recorded during those presentations.

To further study the benefits and challenges of EDM systems, follow-up questions were emailed

to selected participants from the four state DOTs identified with relatively mature EDM

experience. Some of these selected participants emailed their responses back to the researchers,

and phone interviews were conducted with the others. In addition, a video interview was

conducted with the person in charge of the EDM system development and implementation at the

selected Chinese construction company. The Chinese version of the interview questions

addressing EDM implementation issues were sent to that participant prior to the interview, and

detailed notes were taken during the video interview.

Data analysis

Documents, field notes, and participants' responses to follow-up questions were major

sources for the data analysis process. These sources were first sorted based on the cases (i.e., the

four transportation agencies and one construction company), and an analysis was conducted of

each case, with each being considered as an individual study. A rich description was provided for

each case, and the results are presented in the findings and discussion section. The cross-case

synthesis technique (Yin 2012) was then applied to compare and contrast the patterns residing in

each individual case. The general patterns discovered and uniqueness across cases are summarized in the later portion of the findings and discussion section. A taxonomy technique (El-Diraby et al. 2005; Reisman 2005) was also applied to classify the general functionalities of EDM systems reviewed in this study.

Trustworthiness

A good qualitative research study needs to be trustworthy. Evaluation of the trustworthiness of a qualitative study is usually based on four major concepts, i.e., creditability, transferability, dependability/auditability, and confirmability (Lincoln and Guba 1985, Shenton 2004, and Lietz and Zayas 2010). This section introduces each of these four concepts and describes various strategies adopted to achieve high levels of creditability, transferability, dependability/auditability, and confirmability of this study.

Credibility. Credibility measures how closely a study's findings reflect the participants' opinions or meanings (Lincoln and Guba 1985). Triangulation, thick descriptions, and member checking strategies (Creswell 2013; Lietz and Zayas 2010) were adopted to enhance the creditability of the study. Data triangulation was achieved by using multiple data sources (four state DOTs and a construction company) and multiple data collection tools (presentations, documents, and follow-up questions) to gather a comprehensive picture of the EDM system implementation. Thick descriptions were provided for each case allowing readers to establish a better understanding of the study. For the purpose of member checking, the analysis results were sent back to participants for further verification.

Transferability. Transferability measures how meaningful a study's findings would be to theory, practice, or future study (Lincoln and Guba 1985, Creswell 2013, and Lietz and Zayas 2010). It is anticipated that this study will help transportation agencies better understand and

implement EDM systems. The rich descriptions provided for the research findings will help personnel from other agencies understand the context of how EDM was implemented in the case studies so they can infer similarities and differences in comparisons to their own situation. The adoption of triangulation and peer debriefing also enhanced the transferability of this study by providing further insight regarding which items should be emphasized to enhance transferability.

Dependability/auditability. Dependability or auditability measures whether similar results can be produced when the work is replicated using the same methods, the same context, and with the same participants (Shenton 2004; Lietz and Zayas 2010). To the extent possible, this research was strictly performed in conformance with the proposed research design, but there were times when adjustments were necessary to accommodate unexpected changes. The actual research process was documented in this methodology section, but participants' personal information cannot be disclosed due to the Institutional Review Board (IRB)'s requirements. To enhance the quality of this study, research methods and decisions were always discussed among all researchers involved to ensure a thoughtful and deliberate process.

Confirmability. Confirmability measures how others confirm the study findings (Shenton 2004; Lietz and Zayas 2010). To avoid personal bias affecting the research results, the research work (analysis results and conclusions) underwent review and comment from other researchers within the authors' university.

Findings and Discussion

Execution of the data collection and analysis methods described in the methodology section produced the case study results presented in this section. The main characteristics and working mechanisms of the adopted EDM system are introduced for each case along with the reported benefits and challenges. The common functions and differences of these systems were

identified by comparing and contrasting amongst cases; the results of such comparison are discussed at the end of this section. In some cases, the benefits and challenges reported by transportation agency personnel involved in horizontal transportation projects are similar to those reported in the past by personnel involved in vertical building projects. Nevertheless, the findings are reported here because they show the extent to which transportation agency personnel and building construction personnel see similarity in benefits and challenges.

Categories of EDM systems

EDM systems adopted by participants' agencies, based on the main purpose of each category, can be generally categorized as shown below. Generic designations are used in lieu of commercial product names.

- Team communication and file management application (by agency A)

- Project management and collaboration application (by agencies B and C)

- Paperless contracting application (by agency D)

- Enterprise comprehensive management system (by construction company)

Case 1 – team communication and file management solution by agency A

A customized team communication and file management application was developed and adopted within this agency. Though the application is still under development, it currently serves both designers and contractors in various projects. Eighteen construction projects were processing documents through this construction portal at the time of researchers' visit to this agency, and it was expected that all such projects would be similarly processed in the near future. The major capabilities of the current application include document submission, task management, meeting minutes processing, and design review.

Document submission capability allows various groups to submit their documents or design models to a common platform. Users can assign various attributes to the submitted documents, such as assigning a document filter according to the relevant division or office (e.g. planning, design, or construction), type (e.g. contract documents, shop drawing, or request for information), subtype, phase, event date and due date, etc., so that documents can be easily searched and organized in terms of the designated properties. At the same time, they can specify certain personnel from particular groups (e.g., first to person X under the contractor group then to person Y under the lead inspector group) to receive or review the submitted document, and the specified personnel will receive immediate notice once the documents are submitted.

Task management allows various groups to better manage all project-related tasks. Tasks can be assigned to individuals or groups. A task calendar reminds responsible parties to perform the required tasks (e.g., review documents, project budget allocation, etc.) before the scheduled due dates. Incomplete tasks are marked as open, and users can view task status (e.g., not started, in progress, and completed), due date, and personnel responsible for each open task. Open tasks will be closed once they are finished.

Meeting minutes can be easily tracked through this application. Meeting minutes, along with meeting-related information (e.g., creator, meeting organizer, time, location, type, and attendees), can be stored in the system and searched whenever needed. Tasks can also be assigned to appropriate individuals or groups through the meeting minutes stored in the system. The agency also tried to integrate such meeting minutes with other applications such as the agency's email platform, but success was not achieved because of data integration issues.

The design review process becomes more effective if the application is allowed to track comments and responses. Design reviews usually occur at 15%, 30%, 60%, and 90% completion

of design within this agency. The design documents submitted at each milestone will undergo a digital review process during which the reviewers and designers will exchange comments and responses through the application. Different code colors are used to represent the review status of each design document (e.g., not needed, no response, in progress, complete, etc.). If changes are made to the documents, the responsible disciplines will be notified and directed to review them; resolutions to all comments are usually discussed in the next design review meeting. Between design review meetings there are intermediate meetings conducted by project managers to track design progress. The number and timing of reviews sometimes changes depending on whether the project is intended to use the design-bid-build project delivery system or some other approach such as design-build.

This application can also facilitate interoperability among other applications by transferring data through tables provided internally by the application. Because of limited storage space, this application is not used for storing large files such as LiDAR point clouds or 3D engineered models; another project management and collaboration application is used for such large file storage and for archiving files after project completion.

This agency reported the following benefits based on users' own experiences of using this application: (1) The application allows them to manage, streamline, and create more efficient workflows for their documents; (2) The security of documents can be established by giving only the right person the necessary authority (e.g., who can view, edit, delete, etc.) and can be enhanced by distinguishing between internal and external access (e.g., DOT, contractor, consultants, etc.); (3) The application allows them to use working files that can be shared back and forth more readily while recording tracking history; (4) The option of selecting descriptions from dropdown lists rather than requiring data entry makes future reporting and tracking easier;

and (5) The application greatly increases the efficiency and flexibility of the process for refining design products and also maintains a permanent record for comments and responses that result from the digital design review process.

On the other hand, the following challenges associated with this application were also reported by the agency: (1) Considerable initial investment in application customization by relatively skilled information technology workers is required; (2) Difficulties exist in identifying the optimum amount of development effort that should be invested at agency or program-wide levels versus how much development effort should be invested on a project-by-project basis; and (3) Users often express their desires for features that cannot be provided with a reasonable amount of effort allocated for programming and are disappointed when such requests are not acted upon.

Case 2 – project management and collaboration application by agency B

This agency requires submission of the most current version of each document to the project management and collaboration application. The only exceptions to this requirement are delivery tickets for aggregate, concrete, and hot mix asphalt (HMA), all of which are still stored as hard copy documents. The contractor is the party responsible for coordinating and uploading electronic documents submitted by their subcontractors, suppliers, fabricators, and others involved in the construction phase of various projects. Payment to the contractor will be delayed if any required documents are not uploaded on a timely basis. Training courses are provided to instruct contractors on how to use this application.

Standard rules have been established regarding document format, folder structure, and user authorizations to support better organization and management of the submitted documents. For example, incoming files must be placed in one of the following folders: correspondence,

materials, payrolls, shop drawings, and sub-contractor inbox. The levels of authorization for

various must to be carefully determined and monitored so that files can be accessed when

necessary while at the same time maintaining data security. In general, the use of this application

allows all information to be stored in one place and ensures that stakeholders can easily access

the latest project-related data whenever necessary.

To improve efficiency for the document approval process, this agency uses digitally

encrypted electronic signatures, electronic "objects" that include unique identities, date and time,

and a password. The agency uses a proprietary mass-market portable document application for

facilitating all of the electronic signatures; it assigns a unique digital identification (ID) and

password to each individual user. The user is required to enter the assigned password before

being allowed to create an electronic signature. Once an electronic signature is created, the

digitally signed electronic document will be considered as having the same legal effect as that of

a signed paper document. When a digitally signed electronic document is sent to its recipient, the

recipient can check whether the document has been signed by the correct signer and whether it

has been sent from an agency/company's correct email account. A detailed instructional

document has been developed by the agency to assist users.

The agency considers its EDM application as a "single source of truth," since it is used to

store documents created from all phases of a project, ranging over planning, design, procurement,

construction, through asset management, and all data are stored in one server managed by the

agency. Only a job number is needed for locating a particular file stored on the server. According

to the agency, some other major benefits provided by this application include greater

transparency, better security, and improved efficiency. The status of each document submitted to

the application is very clear to stakeholders. Once stored in the system, data won't be lost or

destroyed in normal cases. Data security is also enhanced by using the statewide firewall and protection systems for every project. In addition, since the application provides an audit trail, it is easy to track who did what at a particular time, and the payment approval processing time is reduced from the original 60-90 days to 30 days or less.

There are, however, several challenges involved with the use of this application. It is not possible to easily send a reminder message to a particular person via the application, and a document must be advanced along the workflow established by programmers until final completion. Since this workflow cannot be automatically adjusted when necessary, sometimes multiple workflows need to be developed to cope with unusual situations that might occur in reality.

Case 3 – project management and collaboration application by agency C

Similarly to the second agency discussed above, this agency also requires that all project-related electronic documents be submitted and stored in its project management and collaboration application in accordance with its specific requirements. The types of documents required to be stored in this application include studies, permits, maps, plan sheets, digital terrain models, reports, control, calculations, photos, correspondence, and other items. Emails related to project decisions must also be stored in the system.

When uploading a document to the application, it is important for the document creator to assign appropriate attributes (metadata) to enhance information retrieval. When a user downloads a file, it will be marked as "checked out" and cannot be changed by other personnel. The document can be checked back into the application after a revision is completed. The "update server copy" option can be selected so that the person who checked out the file can upload a partially revised version while continuing to retain the original document for further processing.

Access by various project stakeholders to this system is usually determined by their

responsibilities during various project phases. Within the agency, the work groups with active

duties on a particular project phase are granted both read and write access, while the non-active

work groups are granted with read access only. Each work group's access is assigned by a

regional data manager and will be adjusted as the project progresses. For employees outside the

agency such as consultants, contractors, and other partners, the minimum access required to

execute their work is provided.

This application has two DataSources, the DOT's DataSource and an archived

DataSource, with various documents, folders, and the supporting database as the major

components of each DataSource. The DOT's DataSource is a place for storing all documents

related to a still-active project, and such documents should be created and sorted based on

designated rules for managing the folder and subfolder structures. Electronic documents stored in

the DOT's DataSource are also used for developing official project records (e.g., right-of-way

maps, record plans, etc.). Because archiving is important for effective data management, there

are rigorous rules for how to archive the necessary documents throughout the project duration.

Data owners can determine whether documents must be kept or deleted according to such a set of

rules, and they must notify the data manager regarding their decisions. The rules also specify

what data are important enough at each project stage (e.g. scoping, design, and construction) to

require them being maintained in the archive. After a project has been completed, the data

manager is required to move all the necessary data to an archive DataSource for retention as a

permanent record.

This agency notes many advantages afforded by this application. (1) Engineering data

and project-related documentation following standardized formats and file structures are always

stored in a central location, making for easier data governance and management; (2) Users can access necessary data from both on-site and remote locations; (3) Most of the types of files created by software applications (documents and design models) and used throughout a project lifecycle can be stored in the application; (4) Since the same developer provides both the EDM and design modeling applications, the functionality and compatibility of the stored data are greatly improved; (5) A repository for inter-departmental project data can be easily established through this application; and (6) The status of files can be easily tracked and local copies of files can be also saved outside of the application.

Various challenges were also reported by the agency as follows: (1) Dedicated staff (one agency employee and one consultant employee in this case) are required to provide technical support to the application; (2) A manager with computer programming and other IT knowledge is required to manage the application and plan effectively; (3) It is difficult to change an established archiving strategy since an alteration requires manipulation of millions of archived files; (4) Security protocols imposed by the agency limit the degree of file access by external business partners; an approach that enhances accessibility while maintaining security needs to be developed for sharing the files with external partners; (5) Switching from local servers to a statewide central data/server bank increases the amount of time needed to access files; (6) There is a separate interface for on-network users that cannot be accessed by web client users, and some functionalities are limited or not available for such web client users; and (7) It is challenging to identify which employees should be set up and which should not with respect to ready/automatic access to the application.

Case 4 – paperless contracting application by agency D

The paperless contracting application adopted by this agency was produced by its partner Info Tech. Detailed instructions were provided to guide its contractors and suppliers on how to effectively use this application. Project contracts can be viewed and sorted based on users' preferences and, once a document is submitted, users can select a preferred mode (e.g. real-time, daily summary) and notifications (e.g. ready to be processed, rejected) for the selected contracts. Users can also select various virtual "(file cabinet) drawers", such as Contract Documents, Pay Items, Payrolls, Contract Modifications, Working, Shop Drawings, Signatures, and Plans to perform further activities.

The appropriate type of drawer needs to be selected when submitting a document so that documents can be grouped correctly. Agency and prime contractor personnel have access to all documents retained in a drawer for which they have access authority. Subcontractors and suppliers have access to only their own documents, although they might be able to view some of the metadata for some of the other documents. Electronic signatures can be placed on a document when the electronic signature box is checked during its submittal. After the document is submitted, no changes can be made unless a newer version is uploaded. Comments and responses can be added by other personnel and document creators.

The Contract Documents drawer is intended to collect contract documents associated with a particular project. This drawer is most frequently used by agency personnel, but sometimes prime contractors might also make submissions to this drawer, and users can attach their comments to the documents during the submittal process. Similarly, the Pay Items drawer is intended to collect all documents related to pay items; agency personnel can mark a submittal as "received" or "audited". An "audited" status means that a materials audit has been conducted for

an item and there is no need for further checking. The Payroll drawer is used to store certified payrolls. When subcontractors submit their payroll documents to the prime contractor, the prime contractor must review them, check to make sure that they are properly certified, and in turn submit them to this drawer.

The Contract Modifications drawer is used to collect modifications to the contract or change orders usually made through a specialized application that handles the field portion of construction administration. Users with access to this drawer have the option to be instantly notified when contract modifications are submitted to this drawer. Prime contractors should review such submittals and electronically sign them to indicate their approval. Contract modifications are approved in the previously-mentioned separate specialized field construction administration application once all required signatures are collected. All activities occurring as part of this process can be easily tracked through this drawer.

The Working Drawer is provided to store documents that require continuous updating as a project progresses. Once a document is finalized, it will be transferred to an appropriate drawer by an agency user. The Shop Drawings drawer is used to store all project-related shop drawings and prime contractors must collect and submit all shop drawings to this drawer. The assigned reviewers can open or download the submitted documents and add comments as necessary. The Signature Drawer is used to store various types of forms that require one or more electronic signatures; it is mostly used by internal agency personnel. The Plans Drawer is used to store original and updated project plans. Both original "as advertised" plans and "as let" plans should be submitted to this drawer by agency personnel, and further updates should be also submitted to this drawer until the plan is finalized. The final version of the project plan should be transferred to the Contract Documents drawer.

The adoption of this EDM system has brought many benefits to the agency. Loss of documents is very unlikely to occur with the use of this EDM system because all information is retained electronically with extensive security and backup. Digital signatures can be easily obtained for any electronic documents shared through the system. The EDM system can also be used to push notifications through emails, facilitating effective communication and responsiveness to tasks among users. Additionally, since project documents stored in the EDM system can also be accessed through tablets and smart phones, field inspection becomes more efficient because users don't have to return to an office to interact with the system. Although significant investments were required for purchasing new IPads and software every year, these investments were justified by the time savings and increased efficiency associated with the system. Overall, the EDM system is designed to be easy to use with only a modest amount of training.

Case 5 – enterprise comprehensive management system by a Chinese company E

EDM systems and other management software are often combined to support overall information management at the enterprise level. The authors have noted considerable anecdotal evidence that Chinese contractors have accomplished such implementation at the enterprise level. This case documents the use of an EDM system that is part of such an enterprise level information technology system being implemented by a construction company located in Northwestern China. The company has 36 branches and 3000 projects spread across China and other undeveloped countries. After its implementation, the system is expected to support management all aspects of project management, including time, costs, quality, safety, techniques, contracts, procurement, financing, risks, communication, and project completion.

Throughout the entire project duration, all project-related information is expected to be uploaded to the system by all responsible personnel. Construction sites are included; at these locations uploads are accomplished with laptops through an Internet connection. There are also standard rules about how, when, and in what format (e.g. table form) particular data should be uploaded. Once all project-related information is stored in the system, it is easy for others to view, search, and manage the data and documents. The system can also execute various statistical analyses of the retained data. From the system, personnel can easily assess the status of a project, its usage of time and costs, quality issues indicated by inspections, and other important information to support upper management level decisions.

Multiple projects can also be viewed and searched using the system. By highlighting a particular area on the location map, a user can view a list of projects located in the highlighted area. Based on the role of a particular user, project information that corresponds to his or her level of authority will be displayed. Statistical analyses are also available for management of multiple projects.

Considerable benefit at the enterprise level was already realized when the EDM system had been only partially implemented: Information transparency increased, allowing upper management to track project status and resource utilization across more of the organization with less effort than before. The considerable amount of data accessible from one location could be more easily transformed into useful information and thus help upper management in making better decisions to better manage assets using a longer term planning horizon.

Some institutional barriers for implementing the system were also encountered. In most cases, pre-existing workflows had to be changed to use the new system and some staff members found that it was challenging to adapt to these changes. Considering the size of the company and

the various organizational styles within various branches, the new system was first implemented

in a few pioneering branches and is expected to subsequently expand into the rest of the

company. Since the system has not yet been fully developed in terms of covering all aspects of

enterprise management, long term cooperation with the software vendor will be necessary to

facilitate completion. Allocating sufficient funding for purchases of hardware, software, and

system maintenance, arranging for training, and maintaining alignment of managers are other

challenges that have been associated with the implementation process.

Common functionalities of various EDM systems

Although each EDM system has been designed with a specific purpose and

characteristics for a particular transportation agency, they share some common functionalities.

Generally, the authors have classified the phases for EDM implementation, based on

chronological order, as information initiation, information exchange, and information

management. Within each phase, common functionalities of EDM systems and their main

purposes are identified using the taxonomy technique (El-Diraby et al. 2005; Reisman 2005)

shown in Table 1.

These functionalities facilitate the transformation of data into information for electronic

documents to be generated, shared, and managed within the system. For each of the case studies,

transportation agency personnel reported that this electronic process of passing information is

more efficient and secure in compared to traditional methods. Data integrity and overall

productivity were reported to be noticeably improved with the use of the enabling functionalities

of the EDM systems. Moreover, communication and collaboration were reported as being eased

within the organizations and between various stakeholders. Stakeholders were reported to have

provided generally positive feedback regarding the use of the EDM systems. The functionalities

reported to be useful for transportation agencies are similar to those that have been reported elsewhere for building construction projects. To facilitate more advanced use of their EDM systems, agency personnel reported that additional features have been successfully added to existing systems.

Table 1. Common functionalities of EDM systems

Phase	Common Functionalities of an EDM System	Purpose
Information initiation	Submission of documents or design models	submission
	Assignment of attributes to documents (e.g. creation and due dates, phase, etc.)	assignment
Information exchange	Notification of responsible personnel to accomplish review	notification
	Reminding personnel to complete work tasks promptly	reminding
	Sharing of documents with other personnel	sharing
	Tracking comments and responses	tracking
	Signing documents digitally	signing
	Allowing access of information based on a predesignated level of authority	access
Information management	Organization of documents based on standard rules	organization
	Searching of documents based on assigned attributes	locating
	Archiving files for the long term future reference	archiving

Comparisons between various EDM systems

Cases 1 through 5 demonstrate that there is no single formula for success in EDM system implementation; various approaches have been successful for the various agencies. A comparison highlighting the unique approaches of each agency is summarized below.

In Case 1, team communication and file management application are the most prominent features (e.g., task management, meeting minutes, and design review tracking) that support team communication and collaboration. The EDM was customized to meet the actual needs of Agency

A, and this was reported as requiring a larger investment of development effort compared to that involved with a commercially available (out of the box) software application. However, it was reported that agency staff perceived that this customization investment was offset by improvement in overall work efficiency. For example, the capability of being able to track design comments and responses enabled a more efficient design review process, and agency staff perceived that, with more investment in the application, more worthwhile features can be developed to better fit the agency's demands.

In Cases 2 and 3, the cores of the EDM systems are existing commercial products that have had considerable use by state transportation agencies. These applications are intended to store a variety of file types, including those of very large size such as 3D model design files and LiDAR point clouds, thus addressing the issues involved with large file storage. Additionally, due to the relatively wide use of these applications, existing user guides and training opportunities facilitate training considerably.

In Case 4, the transportation agency agreed to cooperate with a software developer interested in developing an EDM application specifically designed to meet the needs or a transportation agency. By striking this deal, the agency was able to obtain the use of a commercial product that was already reasonably well customized to its needs. Contract and other related documents (e.g., contract documents, pay items, contract modifications, etc.) could be sorted and placed in specific virtual "file cabinet drawers" Such a virtual "file cabinet" process mirrors the use of physical file cabinets familiar to many construction administrators, agency personnel, and other stakeholders. Since the EDM system closely fit their needs, agency personnel reported that the application was highly intuitive for use by its staff members and required only a modest training investment.

In Case 5, the enterprise level comprehensive EDM system is being newly developed to manage portfolios of specific projects followed by data and information being "rolled up" to allow effective management at the enterprise level. During the development process, it has been reported that enterprise level management has been noticeably improving as the system has become more fully implemented. Reported benefits include enhanced ability to perform statistical analyses and providing capability for upper managers to make more accurate and timely decisions.

Conclusions and Recommendations

Based on the five case studies investigated in this research, it can be concluded that EDM systems have significant potential to provide important benefits for transportation agencies at the project level and also most likely at the enterprise level. The common functionalities of EDM systems were identified and summarized in this paper, and these functionalities make it possible for information contained as electronic documents to better be created, exchanged, and managed throughout an entire project duration. In addition to these common functionalities, it was found that each EDM system in the case studies was designed with its own unique features that matched specific needs of the agency, so it seems important for transportation agencies to choose products suitable for meeting their own unique needs. When certain features were deemed necessary for a particular agency, its personnel reported success with customization efforts. Such effort was variously supplied by in-house personnel, consultants, and software developers. Considerable initial investments (both time and money) were required, but the resulting improvements were deemed by agency personnel to be worthwhile. Challenges were also reported, most often in terms of providing the extra time and budget required for maintenance and ongoing improvements.

In addition, the EDM system considered in Case Study 5 could possibly indicate a future direction for evolution of EDM systems for transportation agencies. It is possible that EDM systems will provide benefits not only for managing project level decisions but also to support enterprise level decisions. This advancement is most likely to be achieved by providing advanced features to accommodate "roll-up" of project-level EDM data and information to the enterprise level.

Acknowledgements

References

Bartosh, Brian. (2011). "Comprehensive Document Management." *Rough Notes* 154(12): 52-54.

Becerik, Burcin. (2004). "A review on past, present and future of web based project management & collaboration tools and their adoption by the US AEC industry." *International Journal of IT in Architecture Engineering and Construction* 2: 233-248.

Bjork, Bo-Christer. (2003). Electronic document management in construction-research issues and results. ITcon.

Björk, Bo-Christer. (2006). "Electronic document management in temporary project organisations: Construction industry experiences." *Online Information Review* 30 (6): 644-655.

EDMS. (2014). "EDMS - Electronic Document Management System", <http://www.edms.net/> (Feb. 25, 2016)

El-Diraby, T., Lima, C., and Feis, B. (2005). "Domain taxonomy for construction concepts: toward a formal ontology for construction knowledge." Journal of Computing in Civil Engineering, 19(4), 394–406.

Elo, Satu, and Helvi Kyngäs. (2008). "The qualitative content analysis process." *Journal of advanced nursing* 62 (1): 107-115.

Federal Highway Administration. (2015). "e-Construction." <http://www.fhwa.dot.gov/everydaycounts/edc-3/econstruction.cfm> (Jun. 15, 2016)

Issa, R. R. A., I. Flood, and G. Caglasin. (2003). "A survey of e-business implementation in the US construction industry." *Journal of Information Technology in Construction* 8: 15-28.

King, Rebecca. (2011). "Determine Your Document Management Software Needs." *Journal of Financial Planning*: 18-19, <http://search.proquest.com.proxy.lib.iastate.edu/docview/867684110?accountid=10906> (May 2, 2016)

Leikums, T. (2013). "Document Management System Mobility - Main Trend in Future Document Management." *International Journal of Computer and Communication Engineering* 2(4), 505-509.

Lincoln, Y. and Guba, E. (1985). *Naturalistic inquiry*. Beverly Hills, CA: Sage.

Mohamed, Sherif, and Rodney A. Stewart. (2003). "An empirical investigation of users' perceptions of web-based communication on a construction project." *Automation in construction* 12 (1): 43-53.

Munkvold, B.E., and Zigurs, I. (2005). "Integration of e-collaboration technologies: Research opportunities and challenges." *International Journal of e-Collaboration (IJeC)* 1 (2): 1-24.

Neuendorf, K. A. (2002). *The content analysis guidebook*. Sage.

New York State DOT (2006). " Project Development Manual Appendix 14, Project Data Management." < https://www.dot.ny.gov/divisions/engineering/design/dqab/dqab-repository/pdmapp14.pdf> (Jun. 15, 2016)

Reisman, A. (2005). "Transfer of technologies: a cross-disciplinary taxonomy." Omega, 33(3), 189–202.

Shenton, A.K. (2004). "Strategies for ensuring trustworthiness in qualitative research projects." Education for Information 22, 63-75.

Sulankivi, K., Lakka, A., and Luedke, M. (2002). "Project management in the concurrent engineering environment." *VTT Publications*. <http://www.vtt.fi/inf/pdf/publications/2002/P470.pdf> (Jun. 15, 2016)

Taylor, J. E., Dossick, C. S., & Garvin, M. (2010). "Meeting the burden of proof with case-study research." *Journal of Construction Engineering and Management*, *137*(4), 303-311.

Tough, Alistair, and Michael Moss. (2003). "Metadata, controlled vocabulary and directories: electronic document management and standards for records management." *Records Management Journal* 13 (1): 24-31.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

This dissertation focused on the CIM concept and CIM related technologies for transportation agencies. CIM facilitates the efficient use of various advanced technologies and enables upper management personnel to make more informed decisions based on data and information collected throughout the lifecycle of a transportation asset. Several technologies such as LiDAR, 3D engineered models, EDM Systems, and AMG are typically used throughout the lifecycle of a transportation project as part of a CIM framework. In this study, two of these technologies, LiDAR and EDM, were investigated in more depth. This dissertation proposed a viable framework for transportation agencies for implementing CIM within their organizations. Furthermore, recommendations related to the CIM concept on how to implement LiDAR and EDM systems more effectively within transportation agencies are provided. The study also revealed that it would be expected that considerable benefit would result from using LiDAR and EDM in transportation projects, suggesting even greater potential benefit for full CIM implementation as well as many potential opportunities for conducting research in this domain. Agencies planning to implement CIM could begin by first implementing LiDAR and EDM technologies and adopting the framework provided in this study as general guidance. Nevertheless, each agency will need to find its own pathway to CIM implementation suited to its unique needs. The next three paragraphs detail and discuss the findings of the study.

The first paper provides an overall introduction to the CIM concept and practices and proposes a framework for effective CIM implementation. Through two weeks of on-site visits with seven state transportation agencies, leaders in terms of implementing CIM-related technologies, a definition of the CIM concept was refined, and the best CIM-related practices and technology implementations were described. A framework was then introduced to guide

transportation agencies on how to implement CIM in an effective manner from both technical and organizational aspects. Overall, the adoption of CIM-related practices and technologies can bring many benefits to transportation agencies so long as a mechanism is developed to effectively manage the collection of digital data and information that results from utilizing various technologies. A recommended approach is to create and use a centralized data pool. After data are generated for a certain phase of a transportation project, they should be collected and stored in this centralized data pool so they can be extracted and utilized whenever needed in other phases of the current project or even for other projects. In addition, when data is processed and transformed into information, knowledge, and decision-making, the results of these activities can also be retained in the data pool. Adopting this approach allows data, information, knowledge, and decisions to be collected, organized, and managed more effectively, enabling the generation of additional information and knowledge to further support the decision-making processes of upper management level personnel.

The second paper explores current practices and applications of LiDAR technology and develops a standard workflow for utilizing LiDAR data for transportation design. LiDAR, an enabling technology for CIM, allows accurate spatial data to be more efficiently collected and utilized. Challenges still exist, however, especially with regard to LiDAR data processing and utilization. Through web-based surveys targeting a population of LiDAR professionals from various transportation agencies, current LiDAR utilization characteristics (i.e. project types, LiDAR types and applications, and challenges of using LiDAR data) were revealed, along with considerable concern with respect to data storage issues. Furthermore, by conducting five one-on-one phone interviews using the Delphi method, a workflow was developed and recommended as an approach for using LiDAR data to create 3D models for design purpose. This workflow is

intended to assist transportation agencies in more efficiently developing design models from the LiDAR data.

The third paper focuses on the use of EDM systems, another important enabling technology for CIM, within transportation agencies. Using specific data relative to EDM systems and collected during the two weeks of on-site visits studying CIM implementation previously mentioned in discussion of first paper, four state transportation agencies were identified as leaders with regard to EDM implementation. These agencies along with one additional construction company that had implemented an enterprise-level EDM system, were selected as the targets of case studies. Within each case study, the EDM system adopted and the associated benefits and challenges identified by the agency were discussed in detail. By comparing and contrasting between various adopted EDM systems, conclusions were developed regarding the common functionalities and uniqueness of these EDM systems. Accordingly, general guidance is provided to help transportation agencies make proper decisions in selection of an appropriate EDM system.

Based on the findings provided in this dissertation, further investigations should be conducted to test the proposed CIM implementation framework at other transportation agencies, and to address the identified challenges associated with using LiDAR and EDM. Future research should investigate how to effectively implement other CIM-related technologies.

REFERENCES

AlMaian, R., Needy, K., Walsh, K., and Alves, T. (2015). "A Qualitative Data Analysis for Supplier Quality-Management Practices for Engineer-Procure-Construct Projects." *Journal of Construction Engineering and Management*, 10.1061/(ASCE)CO.1943-7862.0001046, 04015061

American Association of State Highway and Transportation Officials (ASSHTO). (2015). "Geographic Information Systems (GIS)." Center for Environmental Excellence, <http://environment.transportation.org/environmental_issues/gis/> (Jun. 05, 2015)

Anderegg, R., and Kaufmann, K. (2004). "Intelligent compaction with vibratory rollers: Feedback control systems in automatic compaction and compaction control." *Transportation Research Record: Journal of the Transportation Research Board*, Trans Res Board, 1868(1), 124–134.

Autodesk. (2014). "LiDAR Scanning: Definitely Worth the Trouble." <http://www.mdconstructionnet.net/wp-content/uploads/2014/05/Lidar-whitepaper.pdf> (April 13, 2016)

Bansal, V.K. and Pal, M. (2009). "Construction schedule review in GIS with a navigable 3D animation of project activities." *International Journal of Project Management*, 27(5), 532-542.

Barber, D., J. Mills, and S. Smith-Voysey. (2008). "Geometric validation of a ground-based mobile laser scanning system." *ISPRS Journal of Photogrammetry and Remote Sensing,* 63(1), 128–141.

Bartosh, Brian. (2011). "Comprehensive Document Management." *Rough Notes* 154(12): 52-54.

Becerik, Burcin. (2004). "A review on past, present and future of web based project management & collaboration tools and their adoption by the US AEC industry." *International Journal of IT in Architecture Engineering and Construction* 2: 233-248.

Behzadan, A.H., Aziz, Z., Anumba, C.J., and Kamat, V.R. (2008). "Ubiquitous location tracking for context-specific information delivery on construction sites." *Automation in Construction*, 17, 737–748.

Bjork, Bo-Christer. (2003). Electronic document management in construction-research issues and results. ITcon.

Björk, Bo-Christer. (2006). "Electronic document management in temporary project organisations: Construction industry experiences." *Online Information Review* 30 (6): 644-655.

Bogdan, R. C., & Biklen, S. K. (2007). *Qualitative research for education: An introduction to theories and methods*. Needham Heights, MA: Allyn & Bacon.

Chang, J.R., K.T. Chang, and D.H. Chen, (2006). "Application of 3D Laser Scanning on Measuring Pavement Roughness." *Journal of Testing and Evaluation, 34*(2).

Chang G. Xu, Q., Rutledge, J., Horan, B., Michael, L., White, D.J., and Vennapusa, P. (2011). *Accelerated Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials*, Federal Highway Administration, Washington, DC.

Cheng, M. and Yang, S. (2001). "GIS-Based Cost Estimates Integrating with Material Layout Planning." *Journal of Construction Engineering and Management*, 10.1061/(ASCE)0733-9364(2001)127:4(291), 291-299.

Cheng, M.-Y., and Chang, G.-L. (2001). "Automating utility route design and planning through GIS." *Automation in Construction*, Elsevier, 10(4), 507–516.

Cylwik, E. and Dwyer, K. (2012). "Virtual Design and Construction in Horizontal Infrastructure Projects." Engineering News-Record.

Czinkota, M. R., and Ronkainen, I. A. (2005). "A forecast of globalization, international business and trade: report from a Delphi study." *Journal of World Business*, Elsevier, 40(2), 111–123.

Dadi, G., Goodrum, P., Taylor, T., and Maloney, W. (2014). "Effectiveness of communication of spatial engineering information through 3D CAD and 3D printed models." *Visualization in Engineering*, 10.1186/s40327-014-0009-8.

Du, Y., Zlatanova, S., and Liu, X. (2006). "Management and 3D visualisation of pipeline networks using DBMS and AEC software." *Proceedings of the ISPRS commission IV symposium on geospatial databases for sustainable development*, 27–30.

Duffell, C. and Rudrum, D. (2005). "Remote Sensing Techniques for Highway Earthworks Assessment." *Site Characterization and Modeling*. 1-13.

EDMS. (2014). "EDMS - Electronic Document Management System", <http://www.edms.net/> (Feb. 25, 2016)

El-Diraby, T., Lima, C., and Feis, B. (2005). "Domain taxonomy for construction concepts: toward a formal ontology for construction knowledge." Journal of Computing in Civil Engineering, 19(4), 394–406.

Elo, Satu, and Helvi Kyngäs. (2008). "The qualitative content analysis process." *Journal of advanced nursing* 62 (1): 107-115.

Federal Highway Administration (FHWA). (2000). "An Investigation of the Use of Global Positioning System (GPS) Technology and Its Augmentations within State and Local Transportation Departments." Report No. FHWA-RD-00-093, Office of Research, Development, and Technology, McLean, VA.

Federal Highway Administration (FHWA). (2011). "SUE Brochure." <http://www.fhwa.dot.gov/design/sue/suebrochure.cfm> (May 30, 2014)

Federal Highway Administration (FHWA)a. (2012). "EDC 2012 Initiatives - Construction Manager General Contractor." FHWA. <http://www.fhwa.dot.gov/everydaycounts/edctwo/2012/cmgc.cfm> (Dec. 8, 2014)

Federal Highway Administration (FHWA)b. (2012). "EDC 2012 Initiatives - Design-Build." FHWA. <http://www.fhwa.dot.gov/everydaycounts/edctwo/2012/designbuild.cfm> (Dec. 8, 2014)

Federal Highway Administration (FHWA). (2012). "Geospatial Data Collaboration." <http://www.fhwa.dot.gov/everydaycounts/edctwo/2012/pdfs/edc_geo_data.pdf> (May 30, 2014)

Federal Highway Administration (FHWA). (2013). "Intelligent Compaction." <http://www.fhwa.dot.gov/construction/ictssc/> (Jun. 03, 2014)

Federal Highway Administration (FHWA). (2014). "Applications of 3D Models on the Construction Site." < http://www.fhwa.dot.gov/construction/3d/webinars/webinar04.pdf> (Dec. 08, 2014)

FHWA, AASHTO, ARTBA, & AGC (2013). "Civil Integrated Management", <http://www.efl.fhwa.dot.gov/files/technology/dv/CIM-Poster-04.12.pdf> (May 30, 2014)

Federal Highway Administration (FHWA). (2015). "EDC-2 Innovations (2013-2014)." <http://www.fhwa.dot.gov/innovation/everydaycounts/edc-2.cfm> (May 16, 2016)

Federal Highway Administration. (2015). "e-Construction." <http://www.fhwa.dot.gov/everydaycounts/edc-3/econstruction.cfm> (Jun. 15, 2016)

Federal Highway Administration. (2016). "EDC 2012 Initiatives – Three-Dimensional Modeling." <http://www.fhwa.dot.gov/everydaycounts/edctwo/2012/3d.cfm> (Oct. 8, 2016)

Fisher, D.D. (2013). "The Benefits of Mobile LiDAR in Transportation Projects." Geodatapoint, <http://geodatapoint.com/articles/view/the_benefits_of_mobile_lidar_in_transportation_projects> (May 18, 2016)

Glennie, C. (2009). "Kinematic Terrestrial Light-Detection and Ranging System for Scanning." *Transportation Research Record: Journal of the Transportation Research Board,* 2105(1), 135–141.

Golparvar-Fard, Bohn, J., Teizer, J., Savarese, S., and 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.

Gordon, T. (2009). "The Delphi Method." *Futures Research Methodology* V3.0, The Millennium Project, Washington DC. <http://millennium-project.org/FRMv3_0/04-Delphi.pdf> (April 27, 2016)

Grilo, A. and Jardim-Goncalves, R. (2011). "Challenging electronic procurement in the AEC sector: A BIM-based integrated perspective." *Automation in Construction*, 20, 107–114.

Guo, F., Jahren, C.T., and Turkan, Y. (2015). "Electronic Document Management Systems for Transportation Industry." *Proceedings, 2015 International Construction Specialty Conference*, ASCE, 132-1–132-9.

Greenfeld, J. (2014). "Terrestrial and Mobile LiDARmapping Systems: Understanding the Technology, Applications and Opportunities." <http://c.ymcdn.com/sites/www.njspls.org/resource/resmgr/SurvCon_2015_Handouts/NJSPLS_TLS_and_MLS_mapping_S.pdf> (April 17, 2016)

Hallowell, M. R. and Gambatese, J. A. (2009). "Qualitative research: Application of the Delphi method to CEM research." *Journal of construction engineering and management*, 136(1), 99–107.

Hartmann, T., Gao, J., and Fischer, M. (2008). "Areas of Application for 3D and 4D Models on Construction Projects." *Journal of Construction Engineering and Management*, 10(776), 776-785.

Heikkilä, R., Lasky, T. A., and Akin, K. (2009). "Construction Automation Process Development-Advancing the Collaboration between Finland and California." *26th International Symposium on Automation and Robotics in Construction (ISARC)*, 389-396.

Hsu, C.-C., and Sandford, B. A. (2007). "The Delphi technique: making sense of consensus." *Practical assessment, research & evaluation*, 12(10), 1–8.

Jaselskis, E. J., Gao, Z., & Walters, R. C. (2005). "Improving transportation projects using laser scanning." *Journal of Construction Engineering and Management*, 131(3), 377-384.

Issa, R. R. A., I. Flood, and G. Caglasin. (2003). "A survey of e-business implementation in the US construction industry." *Journal of Information Technology in Construction* 8: 15-28.

Land, F. (2001). "The Information Revolution." International Encyclopedia of Business and Management, Thomson Learning, London. <http://www.lse.ac.uk/management/documents/isig-wp/ISIG-WP-95.PDF > (Jun. 04, 2015)

LiDAR UK. (2015). "A brief history of LiDAR." < http://www.lidar-uk.com/a-brief-history-of-lidar/> (Jun. 05, 2015)

Lietz, C.A. and Zayas, L.E. (2010). "Evaluating Qualitative Research for Social Work Practitioners." *Advances in Social Work*, 11(2), 188-202.

Lopez, R., Love, P.E., Edwards, D.J., and Davis, P.R. (2010). "Design Error Classification, Causation, and Prevention in Construction Engineering." *Journal of Performance of Constructed Facilities*, 24(4), 399-408.

Jaselskis, E. J., Gao, Z., and Walters, R. C. (2005). Improving transportation projects using laser scanning. *Journal of Construction Engineering and Management*, 131(3), 377–384.

Kim, C., Son, H., and Kim, C. (2013). "Automated construction progress measurement using a 4D building information model and 3D data." Automation in Construction, 31, 75-82.

Kim, S. and Jang, K. (2000). "Designing performance analysis and IDEF0 for enterprise modelling in BPR." International Journal of Production Economics 76, 121-133.

King, Rebecca. (2011). "Determine Your Document Management Software Needs." *Journal of Financial Planning*: 18-19, <http://search.proquest.com.proxy.lib.iastate.edu/docview/867684110?accountid=10906> (May 2, 2016)

Leikums, T. (2013). "Document Management System Mobility - Main Trend in Future Document Management." *International Journal of Computer and Communication Engineering* 2(4), 505-509.

Lincoln, Y. and Guba, E. (1985). *Naturalistic inquiry*. Beverly Hills, CA: Sage.

Liu, X., Zhang, Z., Peterson, J., and Chandra, S. (2007). "LiDAR-derived high quality ground control information and DEM for image orthorectification." *GeoInformatica*, 11(1), 37–53.

Mack, N., Woodsong, C., Macqueen, K.M., Guest, G. and Namey, E. (2005). *Qualitative Research Methods: A Data Collector's Field Guide*. Family Health International. North Carolina.

Martínez-Rojas, M., Marín, N., and Vila, M. (2015). "The Role of Information Technologies to Address Data Handling in Construction Project Management." *Journal of Computing in Civil Engineering*, 10.1061/(ASCE)CP.1943-5487.0000538 , 04015064.

Matheu N.F. (2005). "Life cycle document management system for construction." Master Thesis, Department Engineering and Construction. University Politecnica De Catalunya, Spain, 37-46.

Maxwell, J.A. (2013). *Qualitative Research Design (3rd ed.)*. Thousand Oaks, CA: SAGE Publications, Inc.

Mohamed, Sherif, and Rodney A. Stewart. (2003). "An empirical investigation of users' perceptions of web-based communication on a construction project." *Automation in construction* 12 (1): 43-53.

Moore, W. (2004). "GPS Systems for the Earthmoving Contractor." Construction Equipment, <http://www.constructionequipment.com/gps-systems-earthmoving-contractor> (Jun. 05, 2015)

Morrow, S. (2007). "Qualitative research in counseling psychology: Conceptual foundations." *The Counseling Psychologist*, 35(2), 209-235.

Munkvold, B.E., and Zigurs, I. (2005). "Integration of e-collaboration technologies: Research opportunities and challenges." *International Journal of e-Collaboration (IJeC)* 1 (2): 1-24.

National Academy of Sciences. (2016). "Standing Committee on Geospatial Data Acquisition Technologies (AFB80)." <https://www.mytrb.org/CommitteeDetails.aspx?CMTID=1313> (April 26, 2016)

Neuendorf, K. A. (2002). *The content analysis guidebook*. Sage.

New York State DOT (2006). " Project Development Manual Appendix 14, Project Data Management." < https://www.dot.ny.gov/divisions/engineering/design/dqab/dqab-repository/pdmapp14.pdf> (Jun. 15, 2016)

O'Brien, W.J., Gau, P., Schmeits, C., Goyat, J., and Khwaja, N. (2012). "Benefits of Three- and Four-Dimensional Computer-Aided Design Model Applications for Review of Constructability." *Transportation Research Record*, No. 2268, 18-25.

Olsen et al. (2013). "NCHRP 15-44 Guidelines for the Use of Mobile Lidar in Transportation Applications." Transportation Research Board of the National Academies.

Padgett, D. (2008). *Qualitative methods in social work research*. Los Angeles: Sage Publications.

PCL. (2016). "What is PCL?" < http://pointclouds.org/about/ > (April 17, 2016)

Peyret, F. et al. (2000). "The Computer Integrated Road Construction Project." *Automation in Construction*, 9, 447-461.

Pu, S., Rutzinger, M., Vosselman, G., and Elberink, S.O. (2011). "Recognizing basic structures from mobile laser scanning data for road inventory studies." *Journal of Photogrammetry & Remote Sensing*, 66(6), s28-s39.

Ray, S. J., & Teizer, J. (2013). Computing 3D blind spots of construction equipment: Implementation and evaluation of an automated measurement and visualization method utilizing range point cloud data. *Automation in Construction*, *36*, 95-107.

Reisman, A. (2005). "Transfer of technologies: a cross-disciplinary taxonomy." Omega, 33(3), 189–202.

Saldana, J. (2016). *The Coding Manual for Qualitative Researchers*. Thousand Oaks, CA: SAGE Publications, Inc.

Sebesta, S., Scullion, T., Liu, W., and Harrison, G. (2006). "Thermal imaging of hot-mix paving operations for quality assessment: State of the practice in Texas." *Transportation Research Record: Journal of the Transportation Research Board*, Trans Res Board, 1946(1), 123–129.

Shan, J. and Toth, C.K. (2009). *Topographic Laser Ranging and Scanning Principles and Processing*. Taylor & Francis Group, Boca Raton, Florida, US.

Shenton, A.K. (2004). "Strategies for ensuring trustworthiness in qualitative research projects." Education for Information 22, 63-75.

Sulankivi, K., Lakka, A., and Luedke, M. (2002). "Project management in the concurrent engineering environment." *VTT Publications*. <http://www.vtt.fi/inf/pdf/publications/2002/P470.pdf> (Jun. 15, 2016)

Tardy, R. (2012). "Why InRoads is First in 3D Road Design." *LiDAR News*, <http://www.lidarmag.com/content/view/9340/206/> (Jun. 05, 2015)

Taylor, J. E., Dossick, C. S., & Garvin, M. (2010). "Meeting the burden of proof with case-study research." *Journal of Construction Engineering and Management*, *137*(4), 303-311.

Tough, Alistair, and Michael Moss. (2003). "Metadata, controlled vocabulary and directories: electronic document management and standards for records management." *Records Management Journal* 13 (1): 24-31.

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

Vosselman, G., H. G Maas, and others. (2010). *Airborne and terrestrial laser scanning*. Whittles Publishing, Dunbeath, UK.

Walters, R., Jaselskis, E., Zhang, J., Mueller, K., and Kaewmoracharoen, M. (2008). "Using scanning lasers to determine the thickness of concrete pavement." *Journal of construction engineering and management*, 134(8), 583-591.

Wang, L.C., Lin, Y.C., and Lin, P.H. (2007). "Dynamic mobile RFID-based supply chain control and management system in construction." *Advanced Engineering Informatics*, 21, 377–390.

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

Weippert, A., Kajewski, S.L., and Tilley, P.A. (2003). "The implementation of online information and communication technology (ICT) on remote construction projects." *Logistics Information Management,* 16(5), 327 – 340.

Williams, K., Olsen, M.J., Roe, G.V., and Glennie, C. (2015). "Consider the Benefits of Mobile LiDAR for Transportation Projects." Earth Imaging Journal. <http://eijournal.com/print/articles/consider-the-benefits-of-mobile-lidar-for-transportation-projects> (May 18, 2016)

Williams, K., Olsen, M.J., Roe, G.V., and Glennie, C. (2013). "Synthesis of transportation applications of mobile LiDAR." *Remote Sensing*, 5(9), 4652–4692.

Yoo, H. J., F. Goulette, J. Senpauroca, and G. Lepere. (2010). "Analysis and Improvement of Laser Terrestrial Mobile Mapping Systems Configurations." *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences,* 38(5), 633-638.

Yoon, J. S. (2008). "Ortho-rectification of a Digital Aerial Image using LiDAR-derived Elevation Model in Forested Area." *Korean Journal of Remote Sensing*, 24(5), 463–471.

Zhang, S., Boukamp, F., & Teizer, J. (2015). Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA). *Automation in Construction*, *52*, 29-41.

Zhou, W., Whyte, J., and Sacks, R. (2012). "Construction safety and digital design: A review." *Automation in Construction*, 22, 102–111.