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Civil Integrated Management for Highway Infrastructure Projects: Analyses of Trends, Specifications, Impact, and Maturity

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Civil Integrated Management for Highway Infrastructure Projects: Analyses of Trends, Specifications, Impact, and Maturity

by

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Dedication

எம் சிறுவயது முதலே கல்வியின் மகத்துக்குவதையும்
முக்கியத்துவதயும் உணர்த்திய எனது பாட்டனாரின் அன்பு
நினைவிற்கு இந்த ஆய்வேடையை பணிவோடு சமர்ப்பிக்கிறேன்

I humbly dedicate this dissertation to the loving memory of my grandfather who has instilled in me, right from my childhood, the importance and the transformative power of education.

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"*There is no greater journey than the one that you must take to discover all of the mysteries within you*

"… Michelle Sandlin

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Abstract

Civil Integrated Management for Highway Infrastructure Projects: Analyses of Trends, Specifications, Impact, and Maturity

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Highway projects are delivered in a complex environment that involves the participation of diverse stakeholders with different objectives. Stakeholders have to deal with a multitude of information coordination and project execution challenges. Conventional solutions that often depend on traditional surveying methods, document-based design and construction work processes have proven inadequate to consistently meet the information requirements for project delivery processes. Over the past few decades, the advent of modern technologies in data collection, design, and in-field positioning systems have been transforming the work processes both in the planning and the execution of highway projects.

Civil Integrated Management (CIM) is a terminology that encompasses all such tools and technologies that can facilitate the process of digital project delivery and asset management. Nonetheless, much of the advancements in digital delivery have essentially been limited to a few projects or particular phases. While owner agencies have recognized the significance of CIM technologies, widespread implementation and standardization of

these tools remain a futuristic goal. Driven based on findings of a national state of practice survey, this dissertation compiles three chapters that studied principal issues concerning enhanced CIM implementation namely standardization of project work processes, empirical validation of benefits, and formulation of a reliable benchmarking tool. Chapters 5 and 6 examine utilization of CIM at the project level. Extensive inputs from selected case study projects from the U.S. and the U.K. helped identify unique practices and transforming specifications that the agencies deployed to streamline usage of these tools. These case study inputs were then methodically coded to analyze the combined impact of CIM technologies and supporting factors on project performance measures. Chapter 7 broadens the focus of the research to examine agency-level implementation issues. This chapter proposed a quantitative maturity model for benchmarking the usage. The model considers 16 pertinent attributes encapsulating technical, contract, legal, and organizational issues. A national survey of agency champions and other CIM experts helped assess the relative importance of these attributes towards CIM workflow and appropriately weight their usage levels in determining CIM maturity.

The study contributes uniquely to the body of knowledge and also has considerable practical implications for the highway industry. The project-level objectives produced valuable insights in terms of distinct practices that agencies adopted to facilitate CIM. It also empirically validated the complex interactions between CIM and process factors for validating the performance improvements. The maturity assessment tool produced a trustworthy model and a repeatable general research framework for benchmarking CIM implementation at agencies.

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Chapter 1 Introduction

State Highway Agencies execute projects in a complex environment with direct and indirect participation from multiple stakeholders. They had to efficiently manage and deliver the projects complying with the regulations that arise due to public procurement framework. Furthermore, the complicated financing schemes and the competing objectives to deliver projects on time, within budget and to the stipulated quality create managerial challenges for stakeholders and increases uncertainty in the project delivery process (Taylor et al. 2012). Besides these strategic problems at the planning level, typical highway projects also face operational and coordination issues during Right-of-Way (ROW) acquisition, utility coordination and relocation, public information, and management of traffic (Warne 2011).

The traditional way of information management that relied on documents for design and construction processes have become ineffective in addressing these execution challenges (Khwaja and Schmeits 2014). In an instance, 2-D design deliverables that include plans, profiles, cross sections, and detailing, creates a lapse in the hitherto digital design process and downgrades the utility of electronic data that generated them. Furthermore, activities requiring collaboration and data integration such as design reviews and constructability analysis can either be time-consuming or produce incomplete and unreliable outcomes (O'Brien et al. 2012). They can also pose technical challenges in quality control and quantity estimation tasks after construction. In addition, they can create difficulties towards meeting visualization and communication needs and public outreach efforts. Driven by similar issues and challenges, the construction sector, all across the world has recognized the need for undergoing a paradigm shift to applying technologies and processes that enable digital workflow for infrastructure projects (Dodge data & analytics 2012). Design or scope complexity, compressed project schedules, shrinking profit margins, funding regulations, and work-zone traffic management have been catalysts for this transformation. Moreover, the amount of information generated during each phase has become so huge that it has become difficult to track and manage with traditional methods of information and data sharing (O'Brien et al. 2012).

Technological advancements in design software, sensing equipment, and real-time positioning systems are now enabling pathways to transcend to the digital workflow for project delivery and asset management. This research will study such digital technologies and practices under the terminology "Civil Integrated Management (CIM)". The use of information modeling for surveying and design has been around for the past decade and been investigated by many researchers, implemented in parts by projects and agencies (FHWA 2012). Nonetheless, formalizing the digital tools under CIM is necessitated by the functional interdependencies of several technologies relevant for functions from surveying to Operations & Maintenance (O&M). More broadly, CIM encompasses the system of digital technologies and practices that enable collection, organization, management, and use of accurate data and information throughout the lifecycle of a transportation asset. In order to keep the study scalable and meaningful, transformative solutions have been identified from past research and literature on foundational and emerging digital tools and practices – GIS-based planning and integrated surveying, model-based design process, n-D modeling for project management, automated machine guidance (AMG) for construction, and electronic archival for asset management (Jahren 2014). The construct of CIM gains both theoretical relevance and practical significance from the underlying foundational and emerging digital technologies. Figure 1-1 illustrates the functional interdependency between modern technologies and asset lifecycle at a conceptual level. Initiated by the important federal and State Transportation Agencies (STAs) in the U.S., the study of CIM can help bring useful insights to all the stakeholders about current practices, driving factors, implementation challenges, and future for both fundamental and emerging CIM technologies.

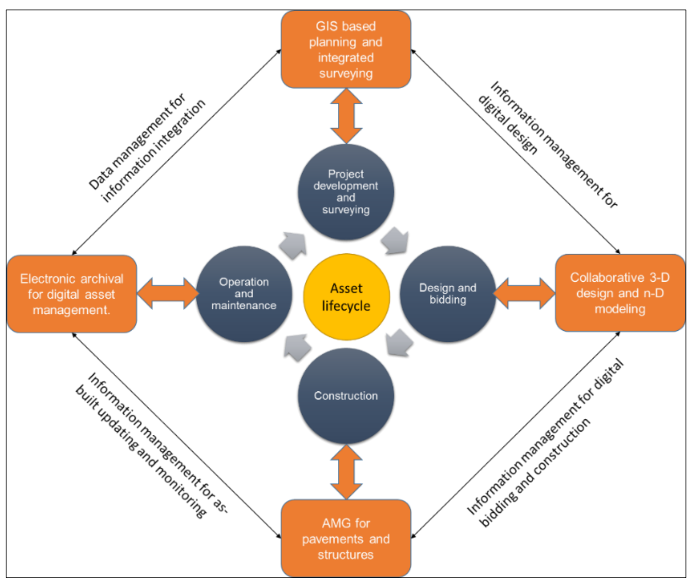


Figure 1-1 Integration of CIM practices into asset lifecycle - a conceptual depiction

READER'S GUIDE

Broadly speaking, this dissertation formulates objectives and solves problems related to the practical and process-related queries for CIM. The rest of the dissertation is organized as follows: Chapter 2 provides a background review of the engineering and project management challenges of conventional workflow that served as a major driver for

CIM for highway infrastructure delivery. Chapter 3 presents the analysis of a survey that was performed to gauge the current state of practice and the significant insights from the survey are presented. Noticeably, the inferences from this survey helped inform pertinent gaps in the literature and practice and hence, form the foundation of research objectives for this study. Sections of chapter 3 are reprinted from the following manuscript currently under review in Journal of Automation in Construction (as of writing of this dissertation): **Sankaran, B., Newett G., O'Brien, W. J., Goodrum, P. M. (2017), "Civil Integrated Management: Empirical Study of Digital Practices in Highway Project Delivery and Asset Management.** Subsequently, Chapter 4 includes the discussion of primary objectives (and research questions) and chosen research methodology. Chapter 5 explores the implementation of Civil Integrated Management (CIM) practices on four exemplary case studies and documents the lessons learned to enhance CIM inclusion in project delivery processes. This chapter includes contents reprinted from **Sankaran, B., O'Brien, W. J., Goodrum, P. M., Khwaja, N., Leite, F. L., and Johnson, J. (2016). "Civil Integrated Management for Highway Infrastructure: Case studies and lessons learned" Transportation Research Record: Journal of the Transportation Research Board, 2573, 10–17**. Chapter 6 leverages the detailed case study data from 12 projects and models the effect of CIM practices on the resulting reduction in change orders, savings in the schedule, improvements in quality of work, and safety benefits. The contents of this chapter are republished from a manuscript currently under review in ASCE Journal of Construction Engineering and Management: **Sankaran, B., O'Brien, W.J. (2017), "Impact of CIM technologies and agency policies on the performance of highway infrastructure**

projects". Subsequently, Chapter 7 presents the national survey of state transportation agencies and other CIM experts for developing a quantitative approach to benchmark an agency's CIM capability. The contents of this chapter are republished from a manuscript accepted for publication (October 2017) in ASCE Journal of Construction Engineering and Management: **Sankaran, B., O'Brien, W.J. (2017), "Empirical formulation of a measurement model for CIM maturity benchmarking at highway agencies".** Finally, Chapter 8 presents the conclusion of this research along with the contribution to the body of knowledge and the practice. The appendix section includes the questionnaires utilized for data collection at various stages of the study and the detailed outputs of the data analyses.

Chapter 2 Background review of CIM

CIM encompasses the technologies and methods that facilitate the transition from traditional ways of project delivery and facility management (2D drawings, specifications) to data-centric project delivery and asset management (modern surveying methods, model-based design, integrated design, and construction process and digital databases for asset management). The necessity of transitioning to the digital practices, particularly for design and construction of assets can be better understood if the challenges implicit in conventional "paper-based" mechanism are analyzed. The next section provides specific details on some of the commonly noted challenges in the literature.

2.1 Challenges of conventional project delivery

The principal engineering deliverables from design include plans, profiles, and cross sections for pavements and structural elements. Design engineers and consultants often use "cross-sectional" drops at a regular interval in order to provide assembly detailing for subbase, base, and surface course for pavements. This issue creates problems during spatial or design conflict analysis of pavements or structures with surrounding contextual data missing at some places, thereby leading to potential field issues during construction. While some agencies (DOTs) have started using the 3-D design for terrain and pavement design, they use 2-D plans for detailing purpose (Vonderohe et al. 2010) increasing the possibilities of encountering the design coordination problems quite often. The discrepancies and inefficiency of design coordination process in 2-D format can also cause major problems for structural entities and utilities. Design coordination among various disciplines such as bridges, retaining walls, noise walls, and signage infrastructure are quintessential to avoid spatial conflicts and costly changes in the field (Teizer et al. 2005). Incidents with utility conflicts are still common in the highway construction leading to schedule delays. Although the utility coordination process is a significant issue on its own as it involves agreements across multiple organizations, the project-level conflicts are also aggravated by the design and modeling in 2-D formats (Quiroga et al. 2012).

Conventional data collection technologies are also ineffective in aiding the 3-d design process. While the variants of total stations and digital levels help perform triangulation survey and terrain modeling, they are not adequate in producing complete information on subsurface and above-ground infrastructure necessary for new project development in digital formats. Unless such precise information exists, it can become often challenging to transition to collaborative and coordinated design among all design disciplines (Williams et al. 2013).

Another important aspect of highway projects is contributing sufficiently towards public outreach efforts. Many agencies spend considerable time and resources to keep the public (commuters) informed about the objectives of the new project. The neighborhood communities can also participate in evaluating alternatives and inform the decision-making process. When the project moves to the construction stage, the "Public Information" requirements for the State agencies necessitate them to keep the commuters informed of the construction activities, lane closures, and detours, among other traffic control measures (Hartmann et al. 2008a). This process is achieved through the project website, social media, and Public Information Offices (PIOs). 2D plan sheets could pose challenges in effectively communicating the pertinent project information in the public outreach efforts as they would contain complex engineering and technical details difficult for the public to comprehend (Khwaja and Schmeits 2014).

During construction, the literature shows that contractors use specialty consultants to recreate the 3-D models from primary engineering deliverables, a process called “Reverse engineering”. In a notable instance, this process is quite common for re-creating pavement layers and terrain models from engineering drawings. The reverse-engineered models from document-based data are not always advantageous and it is essential that agencies recognize the related issues. This procedure increases the probability of errors since original design intent may be lost. It can also create redundancies since the same information is created twice (Singh 2013). Examples exist in the literature for reverse-engineering structural models for bridges and retaining walls since they assist in visualization, communication, and constructability studies (Kim et al. 2011, Koo and Fischer 2000).

Finally, Quality control (QC) and quantity verification processes get challenging with document-based as-builts leading to inaccurate estimates and archival information. This issue can be best understood by looking at the specific case of earthwork and pavement construction activities. With the conventional method of QC and quantity estimation, the agencies had to use “end-area” method for quantity calculation and contractor payments and this method is prone to inaccurate results. Whereas the presence of terrain models and advanced QC equipment can help agencies transition to volumetric estimation procedures, that are less time-consuming, more accurate, and reliable for archival (Vonderohe et al. 2010). A similar theory is also true for QA/QC checks for structural elements using design drawings vs information-rich 3-D models.

In summary, it can be seen that traditional project work processes are prone to unnecessary redundancies and pose challenges essentially throughout the lifecycle. Over the past decade, the use of information modeling practices has seen considerable rise owing to the principal challenges discussed herein. Interestingly, adopting a model-driven approach to highway infrastructure projects is relatively new (Dodge data & analytics 2012). Although an emerging practice, it would be useful to translate the experiences and lessons learned of Building Information Modeling (BIM) and delineate the unique characteristics of its application for highway projects leading to the formalization of Civil Integrated Management (CIM).

2.2 BIM FOR HIGHWAY INFRASTRUCTURE

As per the National Building Information Modeling Standard Committee, a Building Information Model (BIM) is "a digital representation of physical and functional characteristics of a facility". The information embedded in the model can be utilized to support different decisions taken during the lifecycle of the facility (NBIMS 2014). Adopting a model-driven approach to highway infrastructure projects is relatively new in comparison to the building sector. Some of the unique characteristics of transportation projects that make application of BIM challenging are explained below:

Large horizontal footprint: Highway infrastructure involves horizontal construction that is characterized by being spatial and linear in nature. As such, surveyors and designers have to be more precautious in delineating the modeling boundary for a given project. Adequate considerations had to be given for traffic control plans that can often extend beyond physical project limits. Instances exist in the literature where the BIM model had been extended to include additional boundaries based on TCP (O'Brien et al. 2012).

Earthwork: Surveyors have to adopt suitable, perhaps multiple, data collection techniques to address data uncertainties and enhance the accuracy of terrain and roadway modeling. This issue can affect the estimates of cut and fill volumes and can have major implication in the cost of earthwork operations

Coordination with external stakeholders: Unlike building projects, highway agencies are regulated and they operate under public procurement framework for project delivery. They often deal with external organizations for tasks such as Right of Way (ROW) acquisition and utilities coordination and relocation. Consequently, the information source that could ultimately help in integrating BIM for work processes may reside with multiple agencies causing institutional difficulties in seamless data sharing. The most notable example being creating a data exchange framework and agreements with utility companies; the utility companies may refuse to share the data often citing security concerns (Barden 2014). Public Information is another major component that can influence the extent of BIM adoption on projects.

However, evidence suggests that workflow of these projects are equally aligned well to stand benefitted through the application of BIM (Dodge data & analytics 2012). Liapi (2003) employed CIM to visualize the construction sequencing of a highway project to assist in a collaborative effort for decision-making on construction scheduling and traffic control planning. Hartmann et al. (2008), also highlighted through actual case studies the support offered by CIM towards addressing vital communication requirements to a public interest group. Other significant areas of application include constructability analysis using 4D scheduling (3D model and schedule), clash detection, and design coordination in 3D. Kim et al. (2011) used 4-D CAD models in a case study of a cable-stayed bridge to illustrate its benefits in the areas of materials management, temporary construction, and work-zone management. Robust integration of model-based practices in these work areas can help in averting disruptive change orders thus resulting in cost and time savings on construction projects (Parve 2012). This evidence demonstrates that, despite the execution and coordination challenges, the extent of BIM usage for highway projects has seen a considerable increase over the past decade

2.3 Transition from BIM to CIM

Researchers and practitioners who had studied the benefits and challenges of BIM adoption had argued the true value of the technology might occur at other phases downstream. Recent studies hint at the systemic interdependencies and shared implementation benefits and challenges of the several digital technologies across the asset lifecycle (Vonderohe et al. 2010**.** It is also worthwhile to note a few agencies in the U.S. (and across the world) have foreseen the penetration of the system of digital technologies in their office and field environments and created plans for joint implementation of these tools in their project work processes ((Reeder and Nelson 2015); (Vonderohe 2013); (Munsi 2012)

"Civil Integrated Management (CIM)" formalizes the system of such digital technologies that are connected and offer synergistic benefits in the project delivery process. The workflow created by adopting CIM technologies is categorized as "digital workflow" because of the potential to eliminate document-based design and construction wherever opportunities exist. While digital technologies can undergo changes or efficiency improvements, the functional changes they create for work processes can be considered consistent for the purpose of analysis. The focal CIM practices for this study include- GIS-based planning and integrated surveying, model-based design process, n-D modeling for project management, automated machine guidance (AMG) for construction, and electronic archival for asset management. The major transitions in the workflow of highway projects due to the infusion of CIM are shown in Figure 2-1.

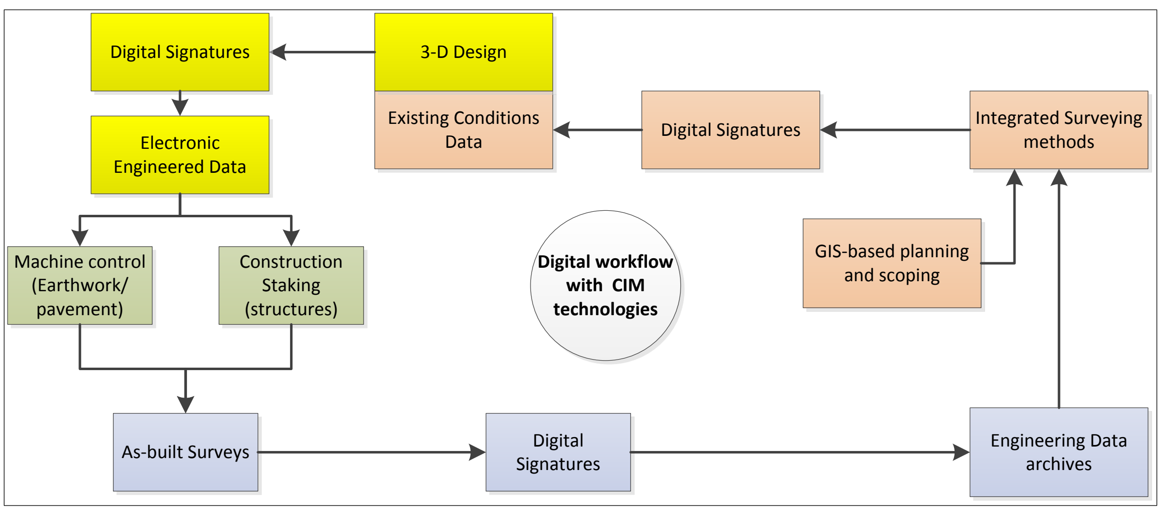


Figure 2-1 Graphical representation of CIM workflow (Adapted from Singh (2008))

During project development and scoping phases, project managers' decision-making processes are significantly facilitated by having access to accurate geospatial data. Well-compiled and integrated data sources, besides enhancing the reliability of the impact assessments and alternative analysis, can inform the surveying needs for new construction or maintenance works (NASCIO 2013). The data on existing conditions can be augmented with advanced surveying methods such as Mobile LiDAR, UAVs, digital photography, and photogrammetry. These methods provide semantically rich, digital information—such as point clouds, 3D mesh models, high-resolution images, and Digital Terrain Models (DTMs). In fact, researchers have identified Mobile LiDAR and UAVs as being important tools with applications across the lifecycle of a highway facility ranging from topographic mapping, general measurements, the 3-D design of alternatives, clash detection, as-built surveys and inventory mapping (Williams et al. 2013).

Having good quality survey data helps stakeholders in various design disciplines do their project design in 3-D and produce digital deliverables. The uncertainties that attend utility relocation and coordination can be reduced through planned applications of various Subsurface Utility Engineering (SUE) tools on projects; such applications also produce geospatial 3-D data that can be integrated during design (Jeong et al. 2003). The model-based design also plays a vital role in producing information that can be directly leveraged for design coordination, clash detection, and construction schedule. 4-D modeling and advanced scheduling practices have demonstrated the potential benefits to be gained in managing and resolving uncertainties associated with engineering deliverables for construction, on-site materials management, and labor productivity issues (CII IR 272 2013).

The quality and completeness of the model-based design positively affect the potential to transform the data into machine-readable formats (such as eXtensible Markup Language (XML)). The contractors can use this data along with sophisticated positioning systems such as Real Time Network (RTN) to automate field construction activities such as excavation, grading, milling, paving, and construction of curbs and retaining walls (Singh 2013). Pavement operations for asphalt and concrete slip-form paving generally require augmentation of vertical accuracy for machine control; Robotic Total Stations (RTS) are commonly used for this purpose (Vonderohe 2012). AMG for on-field construction has proven beneficial as it improves productivity, provides better quality control for pavements and structures, and enhances the safety records onsite (Reeder and Nelson 2015). Another CIM practice is Intelligent Compaction (IC) of soils and pavement materials. IC encompasses computer, measurement, and control systems that digitally capture the compaction parameters and dynamically adjusts the operation (Anderegg and Kaufmann 2004). Recent advancements in automated construction have also enabled the use of 3-D data in constructing retaining walls and construction staking of other structural elements (Singh 2008). After construction, the as-built data can be updated for a digital archive of information to facilitate asset management and future project development. Agencies and consultants have used digitally encrypted electronic signatures to expedite review and approval processes and enhance the overall quality of information flow (Thomas 2013).

These technologies and practices best describe the integration of CIM practices for the digital workflow. Table 2-1 summarizes the important analogies and deviating characteristics between BIM and CIM.

Table 2-1 Thematic comparison of BIM and CIM

Attribute	BIM	CIM
Definition	A semantically-rich representation of both physical and functional characteristics of the facility.	Refers to the set of technologies and practices for digital project delivery and asset management -Inclusive of BIM for highway infrastructure
Major applications	MEP Clash detection, 4D scheduling, Construction Staging, 5-D estimating, energy performance analysis	Utilities clash detection, 4D/5D modeling, Public Information, Automated Machine Guidance, Traffic Control Plans
Institutional Challenges	Comparatively lower due to private owners, contractors, flexible data-sharing mechanisms and project management	Higher due to regulations and laws, transparent procurement, privacy and security concerns in data sharing.
Adoption rate by the industry and research in academia	Higher; Fairly experienced integration and presence of best practices	Lower; Emerging practices with limited knowledge on implementation best practices
Ownership mode	Largely private; innovative practices can be infused rapidly but non-uniformity/inconsistency can be challenging	Largely public; innovative practices can be infused rapidly but non-uniformity/inconsistency can be managed.
Design data usage for construction	downstream applications benefit from design data (e.g. field supervision, progress monitoring, archival for O&M)	downstream applications directly use design data for construction (such as AMG for grading, excavation, pavement, structures)

As mentioned in Table 2-1, there is a limited consolidation of prior knowledge in highway infrastructure regarding integration of information modeling practices and CIM in its entirety. Considering the presence of public agencies and the emerging nature of CIM practices, it was considered worthwhile to conduct a survey of the state of practice of U.S.

agencies. Unlike building projects that involve numerous private owners and contractors, the controlling agencies for highways are public and sizeable in numbers. This observation provides opportunities for researchers to collect data and identify the state of practice of CIM technologies. Such a study would serve as a representation of influential factors, inform identify some of the national CIM leaders, and help select candidate projects that best implemented CIM technologies for detailed examination

Chapter 3 Motivation – State of practice Survey

The objective of this survey is twofold. First, it aims to define a strategy to measure current levels of CIM implementation across STAs; second, it aims to evaluate the STAs' state of practice and determine, through statistical analysis, the factors that have a significant effect on enhanced CIM practices. Figure 3-1 presents the two principal stages of the survey. The first stage focused on developing a formal evaluation system for assessing utilization of CIM practices across STAs. This process was followed by data collection and statistical analysis.

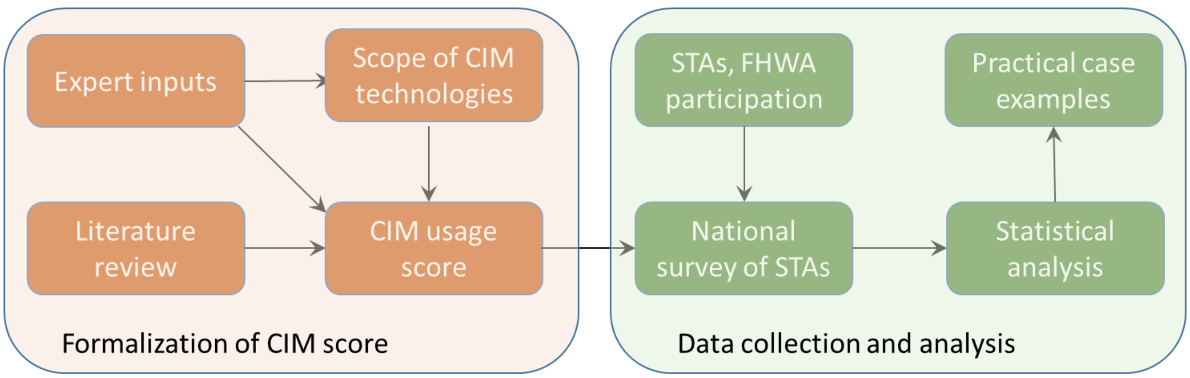


Figure 3-1 Data collection and analysis methodology for survey

The first stage involved scoping the CIM tools and devising a methodology to formalize and measure the level of CIM implementation. The expert inputs came from the panel of National Cooperative Highway Research Program (NCHRP) Project No. 10-96). The panel identified various technologies, which are thematically presented in Table 3-1. Based on the broader context of their applications for project delivery, the tools were grouped into three clusters—modeling, sensing, and data management. Modeling tools (3-D/n-d) include the technologies supporting virtual and digital representations of project data. Sensing tools consist of advanced surveying tools that improve such aspects of data collection as coverage, speed, cost, and data accuracy. Data management tools include software platforms and technologies to manage the information generated throughout the project life cycle. These tools are also essential to the process of implementing 3D design tools and supporting the model-based deliverables. These tools define the scope of interest this study has in CIM.

Table 3-1. List of key CIM technologies

3-D/n-D (5 tools)	Sensing (8 tools)	Data Management (6 tools)
1. 3D Visualization during construction (e.g. isometric drawings, physical models, etc.) 2. 3D Design and deliverables 3. 4D Modeling Analysis (3D + schedule) 4. 5D/nD Modeling Analysis (model-based quantity takeoff/model-based cost estimating) 5. Work Packaging Software / Advanced Scheduling	1. Geographical Information Systems (GIS) 2. Global Positioning Systems (GPS) 3. Intelligent Transportation Systems (ITS) 4. 3D Imaging (e.g. LiDAR, photogrammetry) 5. Automated Machine Guidance and Control (AMG) 6. Field Sensors (e.g. RFID, ground penetrating radar,) 7. Intelligent Compaction (IC) of soil and asphalt 8. Utility Clash Detection / Coordination	1. Electronic archival and updating of plans 2. Digital Asset Management 3. Materials Management System (e.g. Spreadsheets and RFIDs) 4. Mobile Digital Devices for onsite applications (tablets, smartphones, etc.) 5. Data Connectivity Other than Cellular Towers 6. Digital Signatures

The second stage of the research framework involved developing a comprehensive survey questionnaire to capture the current state of practice across agencies. The questions were formulated to capture the agencies' orientation towards integrating CIM in the following areas: project controls, electronic data creation and archival, formalization and usability of specifications, contract and legal issues, and alignment of organizational goals and mission statements. The questionnaire asked STAs to indicate the CIM technologies they or their collaborators typically used. Since the objective is to assess the overall utility of CIM, all the identified technologies were assigned equal weight. If the STA had used these tools on two or more projects, a value of “1” was assigned to the technology for the STA. If the STA had either experimented with the relevant tool once (piloting) or had not used it a value of “0” was assigned.

The count variables were then aggregated to determine a composite CIM usage score for each STA, with a possible range from one (sole usage of 2-D) to 19 (full usage of CIM). Previous researchers have used similar scoring methods to gauge design and information technology usage (Thomas et al. 2004) and technology use integration (Kang et al. 2013a). STAs’ CIM scores were also checked for consistency to account for hierarchical nature and functional dependence of the CIM tools. For example, 4-D/5-D modeling cannot exist without 3-D modeling. Secondly, GIS and GPS are fundamental sensing technologies and often serve as pre-requisites for advanced sensing tools. In this regard, when the overarching CIM score was calculated, survey responses were found to be consistent. The survey also recorded the type of work processes these CIM tools (2-D, 3-D/n-D, Sensing, and Data Management) accomplished on projects to understand their utility in areas ranging from Surveying to Operations and Maintenance. The survey so conducted had complete from 42 STAs that are selected for further statistical analysis.

3.1 Descriptive statistics – managerial attributes

Measures of central tendency and dispersion were analyzed from the data for important numeric and categorical attributes (Table 3-2). On average, 43% of the design work was performed in-house; the actual value varied widely across the sampled STAs from 5% to 95%. Twenty-five agencies reported using or actively developing methodologies to track return on investment. Most STAs reported using two of the three alternate delivery methods. Another key issue considered was the functional capabilities of STAs to integrate CIM-related tools with project controls across the facility lifecycle—such as cost estimating, scheduling, contract administration, daily work monitoring, and change management. It was found that only three STAs had evolved in this direction.

This study also examined the development and formalization of contract specifications for CIM practices. Twenty-nine STAs reported having specifications for the CIM tools utilized or being in the process of formalizing and validating them. Interestingly, only thirteen agencies had ascertained potential clauses in federal or state regulations influencing the level of CIM integration in their workflow. The study identified the key issues in this category as being legal regulations concerning digital seals and signatures for endorsing 3-D model-based data and concerns regarding digital methods for quantity estimation. Finally, using five categories the study examined STAs for availability and common usability levels of guidelines. The categories were technical training, standards for design and construction processes integration, contract specifications, dispute resolution, and digital information ownership. On average, STAs reported possessing two of the five guidelines, usually technical training, and contract specifications. More than three out of four STAs (76%) reported using electronic document management systems.

Table 3-2 Summary of the descriptive statistics for examined attributes

Attribute	Type	N		Mean	Median	Std. Deviation	Yes	No
		Valid	Missing					
Budget ($ Billions)	Numeric	42	0	3.24	2.39	3.36	-	-
Design in house (%)	Numeric	28	14	42.96	45	23.849	-	-
Internal investment guidelines for CIM (Y/N)	Nominal	39	3	-	-	-	25	14
Alternate delivery methods (D-B/PPP/CMGC)	Numeric	41	1	1.61	2	0.919	-	-
Integration of CIM software with project controls (Y/N)	Nominal	40	2	-	-	-	3	37
Cumulative CIM technologies (count)	Numeric	42	0	9.14	10	3.482	-	-
Federal/state legislations impacting CIM (Y/N)	Nominal	41	1	-	-	-	13	28
Use of CIM technologies in contracts (Y/N)	Nominal	42	0	-	-	-	29	13
Availability of guidelines_Total (count)	Numeric	42	0	2.62	2	1.622	-	-

Note: Y = Yes (dummy coded as 1 in the survey); N = No (dummy coded as 0); Count = Aggregation of usage levels of the pertinent sub-components for the attribute; - indicates attribute not applicable to data type.

The survey also asked STAs to indicate the work processes where they had adopted CIM tools and where they still used 2-D data (plan sets, and other document-based specifications). Figure 3-2 summarizes the findings from the 42 STAs (Note: Each value in the chart represents the number of STAs who are using the specified technology for the specified work processes). Welch test conducted for testing the mean differences across four technology clusters indicates statistically significant difference across groups (p-value <0.05) with 2-D category significantly higher than the other three.

It is interesting to note that the greatest utilization of CIM technologies occurred in the design and construction areas, the least in O&M. Less than 2% of respondents used 3D/nD tools for their O&M activities. Evidently, the implementation here could be improved to enhance lifecycle utilization of CIM at an agency-level.

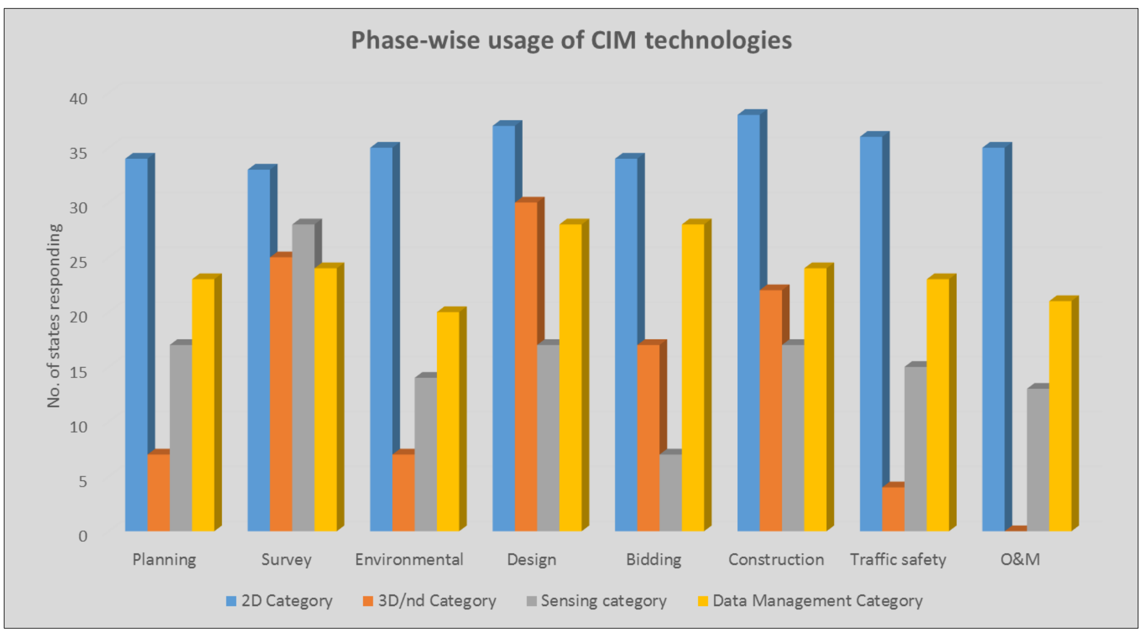


Figure 3-2 CIM usage level of agencies across technologies and phases

3.2 State-wise CIM Usage Summary

All state agencies would be better able to integrate CIM if they had a deeper understanding of the current usage of CIM by STAs and if some of the current agency leaders were identified. The cumulative CIM score of STAs recorded wide variation from 1 to 15, with a mean value of the usage being 9.14. Hence, STAs make up a broad spectrum of users;

such diversity should be taken into consideration when implementing national initiatives. Data from eight states (unavailable or incomplete) were not used in the analysis. Figure 3-3 presents a thematic map of the U.S. with the states identified in accordance with their usage score.

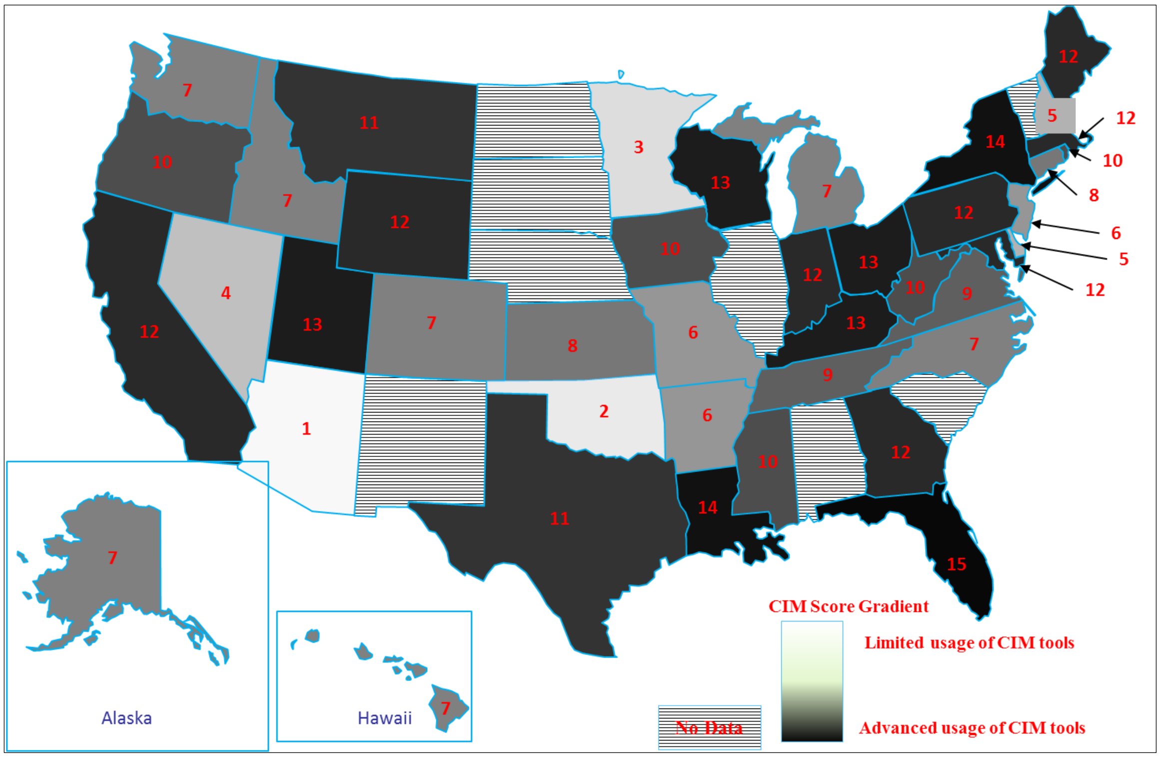


Figure 3-3 Cumulative CIM usage map

Significant points on the current state of practice for each state are discussed below.

Nine states displayed lower values of CIM usage (1-6). These states adopted a traditional and document-based workflow (2-D). They had no or limited utilization of 3D/nD modeling categories. Some states reported wide variation in their uses of sensing and data management tools. For example, Delaware used many advanced sensing tools (IC, AMG, and GPS, among others) but few data management tools. Nevada used many data management tools (such as mobile digital devices, digital signatures, and electronic as-built management) but few sensing ones.

Twenty-six states exhibited moderate levels of CIM usage (7-12). The characteristic workflow of these agencies was discernibly different from the nine states noted above. While they integrated 3D technologies in one or more of their projects (especially for design and visualization), they seldom used advanced modeling tools (4D/5D). Their increased usage of sensing and data management tools gave rise to noticeable enhancements to their CIM capabilities. For example, Iowa, Georgia, and California reported that they had adopted all the technologies in the sensing cluster and the vital ones from the data management one (e.g. electronic updating of plans, mobile digital devices, and digital signatures). Virginia and Washington reported deploying all the data management tools while having experimented with the prominent sensing tools (GPS, GIS, ITS, and AMG).

Seven states were found to have high CIM usage (score: 13-17). As expected, extensive usage of all the considered CIM tools on their projects helped these agencies reflect holistic maturity in the modeling categories. Wisconsin, New York, and Florida reported expertise in using 3D, 4D, and 5D processes for project delivery. California and Kentucky reported experience implementing all the key sensing tools, while top users of data management tools were Florida and Ohio. Overall, Wisconsin (15), Florida (15) and New York (14) emerged as the agencies having higher technological integration and process capabilities.

3.3 GENERALIZED LINEAR MODEL SPECIFICATIONS

The intent of this analysis is to identify whether managerial, organizational, and policy factors had a statistically significant impact on the usage level of CIM technologies. Table 3-3 lists the factors, covariates, and the dependent variable of interest. The predictor variables are directly collected during the survey, whereas the dependent variable (CIM score) was formalized by evaluating the responses. Design-in-house has treated a random effect as its two categories (less than equal to or more than 50%) were not fixed prior to the survey. Similarly, availability of guidelines was also treated as a random effect since the ordinal categories were not formalized (or fixed) prior to the data collection process.

Table 3-3 List of variables for statistical analysis (n=42)

Variable	Name/Description	Type
Factors (Fixed)	-Alternate Project Delivery Methods (D-B/PPP/CM/GC) - Contract specifications (Contractual) - CIM-related Federal or state regulations (FederalReg) - Investment research (ROI) - CIM Integration with project controls (CIMInt)	Ordinal Dichotomous
Factors (Random)	Design-in-house (DIH)	Ordinal Dichotomous
	Availability of guidelines (Guide)	Ordinal polytomous
Covariate	Agencies budget (Budget)	Continuous ($)
Dependent variable	CIM usage score (CIM_{UI})	Count (1-18) or Class (1-3)

The data was first screened using non-parametric correlation measures and stepwise regression measures to screen the best predictors for GLM. This step was mandatory since there were many variables for consideration with limited samples. Subsequently, GLM was estimated using Poisson regression (treating the dependent variable as count) and ordinal logistic regression (treating the dependent variable as class considering the distinctions observed in state-wise summary). The results of the analysis are presented in Appendix A, while the principal inferences are discussed next.

3.4 Principal inferences

The intent of the statistical analysis is to draw important conclusions on the key managerial and agency factors influencing the increased level of CIM utilization. Although predictive models are used, the focus is to understand the effects of the predictors rather than the goodness of fit and predictive modeling itself. The major insights from the analysis are described herein.

Descriptive statistics showed that only 3 (of 42) STAs have progressed in the direction of using CIM technologies for project controls during construction. Furthermore, document-based data still form a significant constituent of the STAs' work processes in comparison to the three CIM technology clusters. These observations show that CIM in its entirety is an emerging practice. Further research is needed to examine the various implementation issues to enhance utilization for project management.

The screening procedures for predictors gave a useful insight into the attributes that can influence CIM. The model measures of the three alternative delivery methods revealed that agencies that execute projects through PPPs display significantly greater utilization of CIM technologies (p-value <0.05). PPPs bring together a collaborative environment not only in terms of procuring funds for project delivery and maintenance but also in engendering technological innovation to deliver projects efficiently. It can be also argued that the effect of alternative delivery methods in general, and PPP in particular, on technology usage can occur due to multiple intervening factors. Enabling a State agency to execute projects through a particular Alternative Delivery Method is more of a legal and institutional challenge rather than engineering or management transformations.

Availability of guidelines under the five major categories had a statistically significant effect on the amount of CIM utilization. Agencies that have developed contract specifications and standards for digital design and construction report statistically significant higher adaptation of CIM technologies (at 90% level of confidence). This observation shows the importance of investing in these process documents for an agency to promote widespread adoption of CIM tools.

Agencies with higher budgets were expected to invest more in project delivery processes and use CIM more frequently. Although the statistical values conformed to this assumption, analysis results did not provide a significant enough difference to support the null hypothesis (p-value > 0.05 in correlation measure and the attribute did not show up in regression). Hence, it can be observed that increasing budget spending at agency-level may not necessarily lead to improved CIM usage level. This inference can also be justified considering that agencies can collaborate contractually and financially with contractors and private developers to encourage innovations in project delivery processes while optimizing the agency spending.

The final GLMs also extended the insights from the screening procedure. PPPs, availability of CIM guidelines, and formalized contractual specifications had statistically significant impacts on the overall usage level of CIM. Although procedural changes were observed between the two models, they corroborated the importance of agency-level considerations that associate with increased CIM usage. More research is needed to assess the critical managerial issues and understand the specific contract documents and guidelines influencing CIM application across the asset lifecycle.

3.5 RESEARCH GAPS

The State of Practice Survey indicates the presence of rich opportunities for detailed investigation for CIM practices. The results of the survey demonstrate the importance of investing in contractual specifications and agency strategies in supporting CIM integration in their business practices. In general, public agencies would not self-perform much of the surveying, design, or construction efforts and quite often, they contract with competent consultants or contractors to do the same. As such, they should have invested in validating and verifying their project work to ensure quality control, verification, and compliance with work by contractors. Thus, it becomes important to identify these notable process documents, deliverables by project phases from surveying to O&M.

Furthermore, performance improvements (or return on investments) of CIM technologies are perhaps claimed under project-level implementation. Little knowledge exists in the literature about specific performance benefits of CIM and an empirical analysis of the effect of CIM on the same. It is worth analyzing these topics since it can inform practitioners on in their decision-making process for technical and work process investments.

In a similar vein, the survey adopted count and classification measures for ascertaining CIM utilization at agency-level. It is reasonable to infer from the conclusions of the survey to posit the existence of a collective maturity for an agency (STA/DOT) implementing CIM. Researchers have argued for the existence of an overarching BIM maturity for organizations that correlates their technological, contractual, and legal dimensions. Perhaps several qualitative models have been proposed in the literature that provides a subjective assessment of the organizational maturity, the most common one being Bew-Richards maturity model incorporated in the U.K.'s BIM strategy ((BIM task group, UK 2014; Messner et al. 2010) as part of the development of BIM execution plan proposed a four-level model for maturity assessment of an agency along the dimensions of strategy, information, infrastructure, use cases, processes, and personnel. (Succar 2009) had also proposed a maturity model as part of developing a practical framework for BIM performance assessment qualitatively working through capability stages, maturity levels, competency levels, organization scale, and granularity levels. The major contribution of such models has been the creation of a prior knowledge for maturity evaluation, that technological integration and work process adoption play an equally important role and often they affect the functioning of each other (Xu and Liu 2014). They provide a more subjective evaluation of the maturity levels. Limited studies have attempted to create such knowledge base for CIM in highway industry and leverage existence of prior information. NCHRP Report 831 proposed a three-level maturity model for CIM that enables assessment of current CIM capability of a transportation agency. This gap in literature can open up opportunities for leveraging quantitative methods for assessing maturity. Agency's CIM potential can then be benchmarked against several constituent dimensions and its extant level of CIM utilization can be systematically evaluated.

Collectively and sequentially, these points of departure from the survey form the foundation of this research and formulate the research objectives and methodology. The research objectives and ensuing research questions are discussed next in this section.

Chapter 4 Research objectives and research questions

The points of departure identified in the literature and articulated in the motivation section demonstrate the gaps that require further research in two distinct, yet interrelated dimensions – project-level implementation and agency-level utilization. Consequently, three main research objectives have been identified in this section. Figure 4-1 illustrates the hierarchical relationship between them.

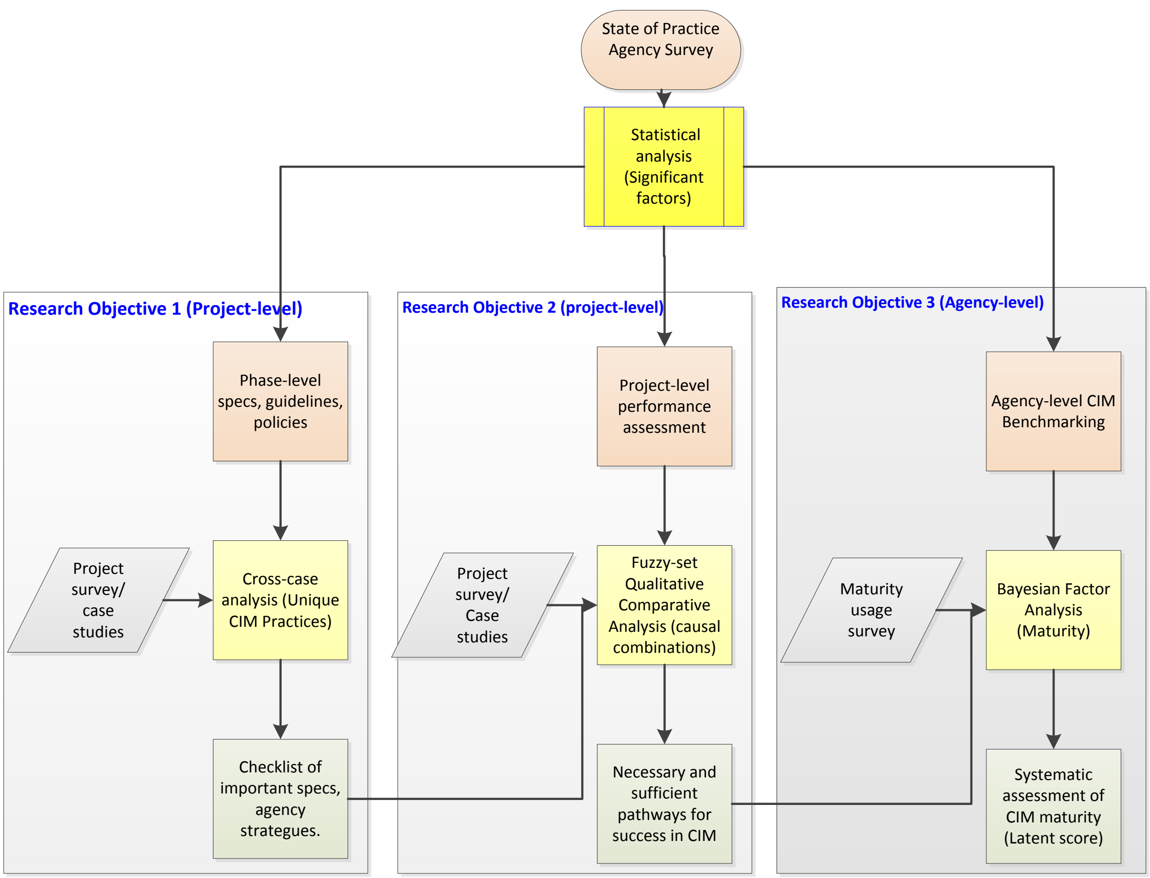


Figure 4-1 Graphical depiction of the hierarchy in the research plan

Each objective was explained further along with pertinent research questions and chosen methodologies to address the questions.

Research Objective 1: Determine the contractual specifications, bidding strategies and legal policies that enabled integration of CIM with project work processes.

RQ 1.1: What are the unique CIM practices in project work processes? Were they enabled by contract specifications and agency standards?

RQ 1.2: What are the bidding strategies and legal policy-enablers unique for CIM corresponding to each phase of project delivery?

This research objective derives its importance from the inferences and results of the state of practice survey (Chapter 3) that indicated the significance of contract specifications and agency guidelines for increased agency-level usage of CIM tools. The research questions attempt to infer, through in-depth examination, the specific requirements in technical standards, bidding strategies, and contract specifications to enable model-based design and construction. Considering the exploratory nature of the study and vast scope of CIM, the case-study design was used to address the objective. A project survey was conducted to identify candidate projects. The project survey was aimed at understanding the drivers leading to CIM implementation, level of integration with project work processes and specific performance measures for CIM tools. Case studies were chosen from this survey data to contain the lifecycle scope of CIM. The detailed discussions and results of this objective have been presented in Chapter 5. The questionnaires for project survey and case studies were displayed in Appendices B and C respectively.

Research Objective 2: Impact of CIM technologies on project performance, factoring in agency considerations and project characteristics

RQ 2.1: How can the impacts of CIM technologies be empirically tested for relevant performance improvements observed in projects?

RQ 2.2: Do the factors interact in terms of enabling performance improvements with supporting factors? Are there alternative explanations for observed benefits in practice?

This objective follows the previous ones and extensively uses the data from project survey and case studies to test the impact and interaction of CIM utilization on project performance. The first research question concerns about reformulating and using the information to extract CIM usage, supporting agency factors, and project performance. The second research question deals with understanding the level of support offered by other crucial factors apart from CIM. An augmented technique, called fuzzy-set Qualitative Comparative Analysis (fs-QCA), has been used address this objective. Further explanations on the supporting literature, the analysis, and the results are presented in chapter 6. The extracts from the results are presented in Appendix D.

Research Objective 3: Test and formally measure the existence of general maturity for CIM at highway agencies based on their technological, contractual, legal, and information management capabilities.

RQ 3.1: Is an agency's ease of technological integration in their workflow connected with *a maturity of other dimensions, namely standards and specifications, governance and policy, organizational and human resources?*

RQ 3.2: Can the hierarchy of these dimensions be tested for presence or absence of a general (holistic) maturity measure for an agency?

This research objective works with the knowledge obtained from the previous objectives and attempts to identify and evaluate a measure for benchmarking an agency's current maturity. The first research question measures all the observable variables in practice across all the four chosen (supporting) dimensions- namely technology integration with lifecycle work processes, standards and specifications, governance and policy issues, and organization and human resources. The second question tries to find the hierarchy or importance of one dimension over the other so that presence or absence of a general maturity score can be tested. This task is currently a work in progress. Data collection for this objective was made through an extensive survey of DOTs, contractors, and consultants. A multistage Bayesian factor analysis was utilized to establish a second-order maturity model for CIM benchmarking. Detailed information on questionnaire development, the methodical solution, and the demonstration of its utility are presented in Chapter 7.The questionnaire prepared for this purpose is displayed in Appendix E and the outputs from the software are presented in Appendices F and G.

Chapter 5 Civil Integrated Management for Highway Infrastructure – Case Studies and lessons learned

This chapter explores the implementation of Civil Integrated Management (CIM) practices on four case studies and documents the lessons learned to enhance CIM inclusion in project delivery processes. Through case studies of four highway projects, this study emphasizes the standards and processes that played a vital role in utilizing CIM technologies for contract documentation, design coordination, construction automation, and project management. The two small-scale projects investigated as part of this study demonstrate that pilot initiative could be successfully carried out to harvest best practices in overcoming contract and legal challenges while embracing new technologies in agencies' workflow. The two large-scale projects indicate that, with owner's participation and expertise, the role of CIM technologies can be further enhanced towards performing project management functions. The lessons learned from the case studies are organized to provide a synthesis of process and organizational considerations that would enhance the agency-wide adoption of CIM technologies.

5.1 Introduction

The State Highway Agencies (SHAs) deliver projects in a complex environment that involves the participation of many public and private entities. The need to operate in a constrained public procurement framework with coordination from many external stakeholders, such as governmental authorities and utility companies, places idiosyncratic issues on the execution of highway projects (Taylor et al. 2012). With traditional ways of project delivery, that centers on document-based workflow, stakeholders have to deal with challenges concerning availability and accessibility of quality data for project management tasks (Eastman et al. 2011). Practitioners have acknowledged that the engineering packages in 2D that generally includes plans, profiles, and cross sections, diminishes the utility of the source electronic data throughout the project lifecycle. It also reduces the effectiveness of quality control and quantity estimation processes after construction (Vonderohe et al. 2010). 2D plan sheets could pose challenges in effectively communicating the pertinent project information in the public outreach efforts as they would contain complex engineering and technical details difficult for the public to comprehend (Khwaja and Schmeits 2014). 2D design processes also pose data integration challenges for activities that require collaboration such as design reviews, conflict analysis, and constructability analysis, among others (Koo and Fischer 2000).

Technological advancements in design and in-field positioning systems are now providing opportunities to utilize digital information for project delivery and asset management processes (Hannon 2007). FHWA, AASHTO, and other State Highway Agencies (SHAs) are promoting Civil Integrated Management (CIM) to understand the opportunities for increasing the reliance on digital information for fast, efficient, and safe delivery of projects and asset management. CIM refers to the project workflow dealing with lifecycle integration of digital technologies such as advanced surveying methods, model-based design process, n-D modeling for project management, automated machine guidance (AMG) for construction, and electronic archival for asset management (FHWA 2012). These tools have the potential to enable the transition to digital project delivery and enhance the role and quality of information available for project management tasks (Parve 2012).

Model-based design (or 3-D design) process forms the central component of CIM implementation in project delivery. The usage of the model for highway projects has seen a considerable increase over the past decade (Hartmann et al. 2008a),(Dodge data & analytics 2012). 3-D models for construction provide transportation agencies, contractors, and other stakeholders a clear understanding of the design with a virtual representation of the facility. The capabilities of modeling the facility before being built had been leveraged to address several issues such as identification and resolution of spatial conflicts among design elements, constructability reviews, visualization and management of site logistics, public information and communication among stakeholders (O'Brien et al. 2012). Process benefits for integrating schedule (4-D) and cost (5-D) information are also identified in the literature towards enhancing the clarity in the communication process, construction sequencing, and quantity estimation (Hartmann et al. 2008a; Messner et al. 2010). Over the past decade, there has been an increasing trend in understanding the issues that integrate modeling practices with facility lifecycle, enabling the paradigm shift for the CIM workflow (Anderson 2012). This chapter explores the technical and process-oriented factors for CIM implementation on four case studies. It seeks to identify lessons learned for CIM integration with project work processes and agency-wide implementation consistent with current state of practice at the SHAs.

The rest of the chapter is organized as follows: the next section provides a theoretical background on the CIM literature. Subsequently, the objective of this study is explained followed by a discussion on research methodology. The chosen case studies are discussed next with emphasis on selected key CIM practices. The “Discussion” section thematically presents the implementation considerations that are deduced from the case studies. Finally, conclusions and future work are presented.

5.2 THEORETICAL BACKGROUND

CIM derives practical significance from its overall objective to better align the project workflow and delivery processes with the modern tools and technologies that have emerged in both the office (planning and design phases) and the field environments (construction and operations phases) (Parve 2014). Figure 1 represents a concise representation of the CIM workflow as described in the literature depicting the major technological adoptions (Singh 2008).

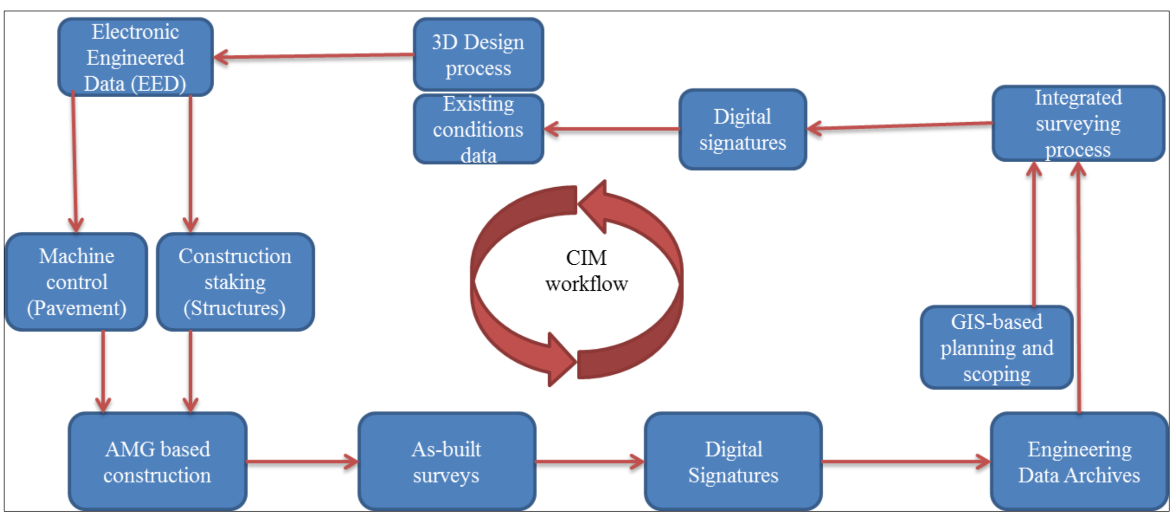


Figure 5-1 A graphical representation of CIM workflow for project delivery process (Adapted from (15)).

The CIM technology integration can be explained by analyzing the project workflow. Advanced surveying methods such as Robotic Total Stations (RTS), Mobile LiDAR, Unmanned Aerial Vehicles (UAVs) and Real-Time Network (RTN) had been utilized by many agencies for digital data collection to aid in the execution of surveying and asset management tasks (Olsen 2013). While LiDAR and UAVs assist in rapid data collection of existing conditions in a cost-effective manner for agencies, the RTS, GPS equipment, and RTN system consisting of Continuously Opiating Reference Stations (CORS) reduce the cost and time spent on project development and as-built surveys (Olsen 2013). The resources spent on enhancing the spatial quality and accuracy of survey data (for terrain, structures, and utilities) forms the foundation of the 3-D design process. Some of the agencies have now adopted specifications to help the design disciplines perform design in 3-D (e.g., roadways, bridges, and retaining walls) and use digital signatures to expedite the deliverables' approval and handover process. Availability of 3-D design models can facilitate the integration of schedule and cost information to address constructability reviews, visualization, and public information process among others. During the construction phase, the contractors can use the 3-D design deliverables and in-field positioning technologies for AMG-based pavement construction and obtain stakeout location for structural elements. Post construction, field representatives can perform Quality-Assurance/Quality Control (QA/QC) checks and quantity verification using GPS-rovers and update the design to create as-builts. Agencies can also utilize digital signatures to verify most of the survey data and archive them in its electronic archive for asset management(FHWA 2013a). The design models are updated to create accurate as-builts including subsurface utilities. Many agencies are also envisioning and developing strategies to archive the electronic data and make it usable for the infrastructure lifecycle (Vonderohe et al. 2010). FHWA (2012), AASHTO and other peer agencies had garnered such lifecycle practices for project delivery under the name “Civil Integrated Management (CIM)” (FHWA 2012).

Notably, the concept of adopting digital data remain an emerging practice in highway infrastructure projects and widespread adoption, from planning to operations and maintenance (O&M) still remains a target to be achieved by many agencies (Dodge data & analytics 2014). Several agencies have recognized the interdependencies of various technologies constituting digital project delivery process and have devised implementation plans that envision agency-wide phased implementation of the CIM tools (Vonderohe et al. 2010),(Singh 2008). However, at present, integration processes for many of the CIM technologies are primarily restricted to either a few larger projects or a particular phase of the project delivery. Furthermore, agencies also have to overcome several process challenges – organizational constraints, contractual arrangement, and legal restrictions- to enable the complete transition to CIM workflow (Thomas 2013). There are limited studies in the literature that analyzed workflows of actual projects and underlined the practical considerations that facilitate lifecycle integration of CIM technologies (Sankaran 2014). There is a need to scan the current state of practice at the SHAs regarding CIM technologies and substantiate the key practices that agencies adopt to promote the culture of CIM integration. This chapter attempts to address this gap in the literature.

5.3 RESEARCH OBJECTIVE

The objective of this research is to empirically investigate the processes that agencies utilize for successful integration of CIM technologies in project delivery. For the scope of this chapter, the focus will primarily be on the following practices of the CIM workflow: advanced surveying methods, 3-D design process, AMG-based construction and quality control, and electronic archival process. These functions are representative of key lifecycle practices that can help transitioning to digital project delivery and asset management. The major constraints that may arise due to contractual or legal issues are also considered in the scope of the study. These issues may not be directly relevant in the context of a project delivery but SHAs have to devise appropriate strategies to ensure compliance while they are considering the integration of CIM throughout the agency.

5.4 METHODOLOGY

Considering the exploratory and extensive nature of the objective, case-based research has been selected as the suitable methodology (Eisenhardt 1989). The varying level of CIM utilization across the agencies also necessitated a prior data collection process to finalize appropriate case study candidates. First, an extensive literature review was performed by examining FHWA guidelines, standards, and specifications available at various several SHAs, and academic publications. It was found that no project or agency has deployed the entire spectrum of digital technologies for project delivery. The literature review was followed by two nationwide surveys – agency survey and project survey. The agency survey was conducted to comprehend the incorporation of CIM technologies, availability of standards and guidelines, and governance and policy regulations. The project survey was conducted to understand the project characteristics that led to the deployment of specific technologies and the resulting performance benefits. The extensive data collection efforts (i.e. literature review and the national surveys) contributed in identifying the best candidate projects for case studies and narrow down the focal areas for each case study regarding CIM. Four case study projects were shortlisted based on analysis of the survey data that had responses and contacts of candidate projects from 39 SHAs across the U.S. Table 1 presents an overview of the project characteristics.

Table 5-1 An overview of project characteristics

Case study	Project type	Expected project cost ($ Million)	Project Delivery Method	Number of interviews	
				Agency	Project team
A	Rotary upgrade	1.45	D-B-B	1	1
B	Roadway relocation	26.5	D-B-B	1	1
C	Interchange reconstruction	294.4	D-B-B	1	2
D	Bridge replacement - Cable stayed bridge	550	D-B	1	2

Note: D-B-B – Design-Bid-Build; D-B – Design-Build

The selected sample of projects included projects of various types, from smaller roadway projects (case studies A and B) to projects involving both roadways and structures (case studies C and D). Between the two larger projects (C and D), a project delivered under Design-Build delivery method was also considered to examine the CIM integration process under two different, commonly used contracting mechanisms in the highway industry.

A semi-structured interview guide was developed to serve as a basis for conducting the case studies. The interview guide consisted of questions to collect information regarding organizational implications, project delivery methods, and legal concerns related to CIM. For the specific project being studied, queries regarding the CIM technologies deployed and performance benefits and challenges were incorporated. The number of interviews conducted per case study was based on the project scope and complexity, availability of the contacts and the potential opportunity for learning new practices related to CIM. It ranged from two to three with the objective to gather inputs and perspectives from both agency and project perspective, specifically from design and construction areas, with expertise in all the project work processes i.e. from planning to O&M.

5.5 Case studies

This section discusses the case studies in detail in a consistent layout. Considering the broad scope of CIM technologies, the common attributes of the implementation process observed across all the four case studies are described first in brief. The prior data collection efforts resulted in the selection of these projects that have demonstrated effective deployment of one or more technologies. Accordingly, each of them also consisted of specific, distinct focal areas for CIM implementation. These areas of interest are presented next for each case study and lessons learned documented.

5.5.1 Shared CIM Practices

The owner's current expertise, commitment, and participation in promoting CIM technologies play a major role in the successful integration of CIM tools in practice. Hence, it is important to understand the capabilities of the owner agencies to support CIM deployment on their projects. In this regard, the States of all the four case studies had RTN system (and connectivity to the network) that meets the real-time positioning and surveying needs of the equipment at the project site. Furthermore, the SHAs executing all the four projects had used electronic document management systems for managing contract documentation, daily work reports, shop drawings, submittals and correspondences and authorized usage of digital signatures for reviewing and approving contract plans and engineering reports. These CIM capabilities are consistent among the SHAs executing the four projects.

There were also similar characteristics in the CIM tools deployed in project work processes. During the planning phase, all four projects used GIS for evaluating the project impacts and obtaining spatial data. Existing information was collected using surveying equipment such as total stations and laser scanners. Photogrammetry and several other software applications were utilized to process the collected data, create Digital Terrain Models (DTMs) and calculate preliminary estimates of quantities. The design processes for all the cases occurred in 3D for terrain and roadway elements using pertinent software applications. The bidding deliverables for electronic data included both the native design files and machine-readable formats. All our projects made extensive use of AMG for dirt-work and grading activities. In general, they also adopted GPS-based inspection tools for quality control checks enabling the possibility of archiving the updated electronic data for lifecycle purposes.

5.5.2 Unique CIM Practices

Each case study involved the successful implementation of one or more CIM practices in the project delivery process. Examining the project activities from planning to construction helped identify specific areas that warranted further investigation. These topics are unique across case studies and are not adequately addressed in the literature. They provided the concerned SHAs several insights that can help them execute projects with CIM in a coordinated and efficient manner and streamline agency-wide integration. The subsequent discussions shed light on the procedures put in place for project execution, in each case study, to achieve the successful integration of the unique CIM practices (shown in Table 2).

Table 5-2 Selected CIM topics from case studies

Case study	Project phases/Interface	Key CIM practices
A	Design-Bidding	EED specifications and deliverables
B	Bidding-construction	Contract precedence to 3D models
C	Surveying - Design	Model-based design and coordination
D	Design - Construction	Model-based project monitoring

Case Study A – EED Specifications and Deliverables

The project's objective was to upgrade rotary intersection to a modern roundabout facility. This project was chosen as a case study to understand the suitability and adaptation of CIM technologies for smaller projects that are undertaken by many SHAs. Additionally, the design process involved standardized 3-D design workflows for all the major roadway components

The project, having a smaller scope and lower complexity (no major structures such as bridges), is designed in 3-D up to 95% of its elements. The design process was predominantly in-house and the Electronic Engineering Data (EED) specifications played a pivotal role in ensuring that all the specialty disciplines (such as roadway, drainage, hydraulics, geotechnical) collaborated to deliver the electronic deliverables in a timely and effective manner. The EED specifications were detailed and adapted to meet the agencies handover and deliverable requirements. It included extensive guidelines for the 3-D design of all the important project elements such as alignments, profiles, DTMs of existing ground, DTMs of proposed surface layers, survey control points, drainage, and curbs, among others. The design was performed on authorized software templates and workflows thereby reducing the time and cost while increasing quality of the data. However, it was observed that the design data was delivered in both electronic- and document-based formats (2-D) to the agency's document management systems. The paper-based plan sets continued to be the governing contract document and electronic data was provided only as supplemental information. The risk and liability of utilizing this information for AMG were transferred to the contractor. Notably, the agency ensured that they generated plan sets and supporting documents automatically from the 3-D models to prepare the bidding package. It also had procedures in place to verify and update the 3-D models depending on the deviations observed in the field during construction

As of the compilation of this study, the project had entered the construction phase. This study's major contribution is with the understanding that model-based design can be formalized across the agencies by standardizing the design workflow of all the disciplines. It also highlighted the contractual limitation in enhancing the utility of EED information for construction and lifecycle purposes. Interviewees opined that all SHAs should explore the possibilities of conducting pilot projects to understand the nuances associated with 3-D models as contract documents. Subsequently, Case study B was chosen for analysis as this unique project meets with the aforementioned objective.

Case Study B - Contract Precedence to 3-D Models

The project's objective was to relocate five miles of the rural arterial stretch, with around 60 approaches and entrances. This project was chosen as a case study because of special notes are written in the contract that the 3-D surface models supersede the (provided) plan sets as the primary contract documents. Apart from a few culverts, this pilot project (for the agency in 3-D design) did not have complicated structures thereby narrowing down the scope of work to terrain and roadway models.

The special notes in the contract were primarily intended to test and understand the policy requirements that ensure continuity in the usage of EED data (from 3-D design) for AMG. Broadly speaking, the special notes paved the way for three major process changes in project delivery. Firstly, they mandated the direct utilization of 3-D design models for construction and AMG. This rule assured that the contractors would not reverse engineer the models from plan sets, thereby avoiding redundancy and saving resources. Secondly, they necessitated that the 3-D models would supersede the plan sets in case of discrepancies between the two and the owner would use the same model to inspect contractor's work. This step was taken in order to ensure all the stakeholders were aligned with the preference for 3-D models. Finally, they included methodological guidelines to facilitate the usage of 3-D models for quantity measurements thereby obviating the need for deploying traditional methods to do the same (such as end area method). Importantly, for this project, the agency had leadership buy-in and expert assistance throughout the creation and adoption of the specifications. Collectively, these measures had created an opportunity for the agency to work around the policy regulations that can enable widespread implementation.

At the time of data collection, this project was under construction. Besides being a unique case in setting contractual precedence, the project also helped in assimilating important lessons on requirements. 3-D model should be designed with an adequate level of detail for all surface layers (existing ground, subbase, base, and top course) and close attention should be paid when modeling and detailing complex elements for roadways (e.g. gore areas, intersections, lane additions/drops). The project team also noted that it is important to include relevant specifications in contracts regarding the nature of construction activities using these 3-D models for AMG (such as excavation, grading, finished surface construction). While case studies A and B centered on applying CIM practices on comparatively smaller projects, Case studies C and D illustrate the unique strategies of utilizing CIM on projects that are larger in scope and complexity.

Case Study C – Model-based Design and Coordination

This project involves reconstruction of an interchange that had seen a large increase in vehicular traffic over years. The construction involves roadways, tunnels, bridges, retaining walls, and noise barriers and relocation of utilities. This project was chosen as a case study because of implementation of several CIM technologies including 3-D design of terrain and roadway elements, 3-D/4-D modeling of structures, and clash detection process. In this project, the return on investment (ROI) for 3-D design and clash detection were quantified and the agency had gained insightful results on empirical benefits. This project also represents the pilot effort of the agency in deploying 3-D design and clash detection.

During the planning phase, the agencies noted that existing as-builts and traditional surveying methods could not meet the data requirements for model-based design. Thus, it adopted an integrated surveying approach that involved multiple sensing technologies to assist rapid data collection with greater coverage. In the process, it systematically combined inputs from advanced sensing technologies such as mobile LiDAR, and UAVs along with the data from conventional methods (such as total stations, laser scanners). After processing the collected data, the resulting information included semantically rich and georeferenced 3-D point clouds and high-resolution images. The utility information was surveyed through subsurface investigation techniques and confirmed through digging and sampling at selected locations. The accuracy and quality of this information were vital on this project to meet the data requirements for the 3-D design process. The design of the project was shared between the agency and consultants, with the agency performing 35% of the scope in-house. The agency performed design in 3-D for terrain and roadway elements. The design consultants and the agency worked collaboratively with pertinent software tools and processes to produce 3-D models of bridges, retaining walls, drainage, utilities, lighting, and other significant structural elements. It regulated and standardized the modeling requirements for the structural entities using specifications for the Level of Detail (LOD) and accuracy of the information required in the 3-D for all the project elements (i.e. terrain, roadway, and structures).

During the construction phase, the project provided valuable insights on quantifying the return on investments for CIM. The primary benefit of 3-D design on this project manifested is its model-based design coordination and clash detection process. The

3-D design models were integrated into software applications that helped in identifying and resolving spatial conflicts among design entities such as roadways, drainage, utilities, and other structures. As such, the agency was able to quantify the benefits by designating the costs of change orders and design issues that could have arisen in the field if the conflicts are unresolved. Furthermore, 4-D modeling was also deployed to perform staging analysis and optimize the construction sequences for bridges contributing to additional benefits of the model-based design process. A design-bid-build project, this case study supported the claim that owner's leadership and involvement in 3-D design processes that can yield significant benefits through model-based clash detection. While this project demonstrated the utility of CIM technologies until pre-construction workflows, Case study D provides discussions on processes of deploying design models for project monitoring tasks during construction.

Case Study D – Model-based Project Monitoring

This project involves replacement of an existing steel truss bridge with a cable-stayed bridge that is intended to ease traffic congestion and enhance the safety and driving conditions for the travelers. The Design-Build (D-B) procurement process facilitated selection of a competent and qualified entity that used innovative CIM practices aligning with the agency's expectations. This civil project involved extensive usage of the 3-D design process and 4-D modeling for constructability reviews and public information process. Notably, it also deployed model-based progress monitoring and estimation of contractor costs (through 5-D modeling). Unlike many other instances in the literature for highway infrastructure, this project actively used 4-D/5-D models as critical deliverables for the key milestones related to project progress and payments to contractors.

The project team (owner and contractor) was able to achieve these objectives primarily through procedures in contracts. Firstly, the agency asked the Design-Builder to prepare and submit a model management plan post the contract award. This plan encapsulated all the key issues for deploying models for project management - such as model creation and maintenance strategies, software integration process between models and schedules, change management plan and quality control checks with models. The plan contained specifications on the required LOD of the 3-D model elements to ensure consistency with the details of the scheduled activities. The design-builder worked collaboratively with the department for resource loading the schedule (with all the required pay items such as materials). Emphasis was laid on defining and aligning the schedule Work Breakdown Structure (WBS) with appropriate unit costs and accounts. As per the plan, this schedule information was integrated with the 3-D models to generate 4-D and 5-D simulations to be utilized for evaluating construction sequences and quantity estimates. Secondly, the agency had updated its survey specifications to facilitate utilization of AMG for construction and GPS-based inspection tools for quality control checks. In this project, these tools allowed capturing as-built information with DTMs and this functionality enabled rapid and frequent estimation of quantities (such as earthwork) and verification of contractor payments using models. The Design-Builder also deployed mobile devices (smartphones and tablets) on this project enabling the possibility to capture real-time progress information on structural elements in the 3-D models. Thus, the models were kept updated and submitted for progress reviews and approvals

As of the compilation of this study, the project was in the construction phase and did not report any significant challenges in model-based project monitoring. Although not an agency-wide practice, this project demonstrated the applicability of models for project monitoring and control tasks. This process was facilitated through incorporating details concerning model management plan in the contract documents and its survey specifications. The next section presents the key lessons learned and practical considerations across all the four case studies on integrating CIM practices.

5.6 DISCUSSION

The case studies provided a concise and clear understanding of how the CIM tools were applied on projects in the pertinent work areas (i.e. from planning to construction). CIM technologies improve the capabilities and processes in the functional areas, which in turn enable the transition to the digital workflow for project lifecycle. This section presents the implementation considerations that are generalized across case studies regarding utilizing CIM technologies for highway projects. The lessons learned and recommendations, organized thematically in this section under five significant topics, play an integral role in widespread adoption at the agency-level.

5.6.1 CIM for Small-scale Projects

It is quite common that the projects with larger scope and complexity see greater utilization of CIM technologies and innovative practices to address the associated engineering and construction problems. Instances in the literature also concur that investments in 3-D design and modeling can be inherently suitable for larger projects as they may involve greater risks and uncertainties in design information and construction processes. However, Case studies A and B indicate that the system of CIM technologies can also be effectively used on smaller projects and provide interesting insights towards organizational acceptance and adoption. They are reflective of typical pilot projects of an agency that is beginning to embrace the 3-D design and associated processes into its projects' workflow. Case study B also indicates that smaller projects can often be potential venues for testing alternatives to overcome contract or legal challenges. There are some key lessons learned that could enhance the utility of 3D design on smaller projects. Creation and adoption of EED specifications for all the design and standards for digital deliverables are significant steps in ensuring seamless transfer of project information across all stakeholders and for downstream construction activities. Availability of good quality survey data to support the design needs can be the driving factor in these projects.

5.6.2 Level of Detail for CIM Models

With increasing adoption of model-based delivery, highway projects require specifications for Level of Detail (LOD) to be formalized to suit their modeling and reporting requirements. Incorporating detailed specifications on LOD on contracts can also help standardize the modeling and reporting practices among all the stakeholders on projects. Case studies C and D emphasized the significance of this issue especially on larger projects as they developed contract languages to communicate the requirements to the contractors. They provided a qualitative understanding of this issue that is not adequately addressed in the literature for highway projects. The terrain models should be designed with an adequate level of detail for all surface layers (existing ground, subbase, base, and top course) and close attention should be paid when modeling and detailing complex elements for roadways (e.g. gore areas, intersections, lane additions/drops). These details can directly affect the utility of the electronic data for AMG during construction. Other elements such as bridges, retaining walls and utilities can be modeled with an adequate level of detail to support intended applications of the model such as clash detection, constructability analysis, and visualization, among others. Such design elements could contain precise physical and functional attributes just enough to support the chosen applications. With many agencies showing intent in adopting 3-D design and construction processes, it has become mandatory that they develop and incorporate detailed specifications on Level of detail adapted to their project delivery practices.

5.6.3 CIM and Project Delivery Methods

Researchers and practitioners had advocated that alternative contracting methods facilitate a collaborative environment among project stakeholders for information management and allow contractors to innovate with specific means and methods for construction. Alternative methods such as Design-Build also encourage value engineering solutions and alternative technical concepts that provide the Design-Builder incentives for proposing improved ways of performing project work processes. Yet, case studies implied that it can be challenging to comprehend the effect of project delivery methods on CIM implementation. Notably, Case study C demonstrated that, even in a regulated Design-Bid-Build environment, projects can successfully deploy advanced CIM technologies provided the active involvement of the owner. In this case, the agency followed a coordinated approach by deriving the objectives of CIM implementation from the agency's strategic, high-level implementation plan. It also invested in policies and IT infrastructure that enabled the collaborative 3-D design process among all the disciplines and cloud-based tools that enable real-time data sharing with contractors on the field. Furthermore, with Design-Bid-Build projects, the SHAs can decide and have more control over the process of testing new technologies and practices on their projects and have access to the all the pertinent data; whereas with Design-Build the extent of involvement of owner in advising means and methods of project execution can be limited depending on the specifics of the contract. Nonetheless, Interviewees opined that the essential benefits of CIM tools could apply to any project delivery method since it encapsulates digital practices that cater to the entire lifecycle of a facility, including the long-spanning O&M and asset management functions. In addition, agencies have to consider the value additions and improvements in overall program costs of the future due to the availability of as-built electronic data. Although these inferences are qualitative and from a small sample of projects, they highlight the practical challenges in delineating the implications of project delivery methods on CIM integration practices. This area would require further empirical investigation in order to gather in-depth insights and ascertain detailed guidelines for agencies.

5.6.4 CIM for Asset Management

All the projects analyzed as part of this study utilized electronic data for design and construction processes for various purposes. Efforts were also made to keep the design data updated from field inspection procedures to create as-built information to be handed over to the agency. While this semantically rich data could act as valuable and supplemental resource for asset management, current archival practices at the agency level remain document-centric (2-D electronic plan sets). The agencies have to develop technical and managerial strategies for long-term retention of such digital data for future project development. Specifically, they have to develop methodologies to deal with data in different formats (2-D plans, 3-D point clouds, 3-D models). Although all the four case studies were entirely focused on project analysis, the expert interviewees from the agency emphasized the integration of O&M data needs during the detailed design processes (such as including the asset identification details in the design data). This identification number can then hold references to important documents- and data- based information (such as traffic) specific to that particular asset. The maintenance personnel can benefit from this pro-active design strategy, as they will then have access to the pertinent data as and when needed. This strategy would also help ensure alignment with the lifecycle objectives of CIM

5.6.5 CIM and Legal Issues

Case study B illustrated that it would be possible to execute projects with contractual priority to 3-D models over plan sets. However, at an organizational level, interviewees unanimously agreed that the design data in plan sets would remain contractually governing documents in the near future. The primary reason is the lack of clarity and consensus on the legal clauses (such as state's Engineering Practice Acts and agency rules) that govern the engineering activities. They have not foreseen a model-based deliverable on projects and hence currently do not have adequate specifications in this regard. A related policy issue is the usage of digital signatures. While the SHAs of all the four case studies have developed guidelines for encrypting and signing the design documents, the possibility of integrating digital signatures on model-based deliverables have not been explored adequately. These policy issues can take time and sustainable commitment from various stakeholders including SHAs, contractors, and relevant governmental agencies. As such, the agencies can try adopting managerial strategies that build up a cooperative and trustful environment to surge ahead with its CIM adoption objectives. Table 3 reorganizes and summarizes the key practices and lessons learned from the perspective of implementing CIM technologies for project execution. These issues are elicited based on findings from the case studies that can potentially act as general guidelines for agencies that are investing in CIM technologies.

Table 5-3 CIM implementation considerations for project work processes

Project work processes	Case studies*				Lessons learned	
	A	B	C	D	Process issues	Description
Planning and Surveying	✓		✓	✓	Data collection for 3-D design using integrated surveying methods	• Agencies can collect digital data of the existing conditions by using multiple data collection strategies and provide to contractors • Collaborating with other interested organizations in the state can offset costs.
Design	✓	✓	✓ ✓	✓ ✓	Standardizing 3-D design and modeling of terrain models, roadway elements, and structural entities including utilities.	• 3-D models can be provided to contractors pre-bid for design innovation and construction automation (FHWA 2013b) • Construction modeling for all surface layers to enable AMG. • Authorized software templates and workflows • Availability and implementation of EED specifications for 3-D design of all the disciplines can lead to agency-wide adoption • Methodical specifications for model-based clash detection and quantification of benefits • Agencies can consider extending current standards for managing utility conflicts on projects to include 3-D geospatial data and consider preparing agency-wide central repository for utility data.
Bidding Deliverables	✓	✓ ✓	✓	✓ ✓	3-D Design deliverables for bidding and contracting purposes	• Design data should be provided for all the surface layers in both native and machine formats to support AMG during construction • Specifications of LOD can be included in contracts along with clear instructions on how to develop and utilize 3-D/4-D/5-D models if used for actively monitoring construction progress and payments. • Contract precedence to 3D models using special notes for: ✓ Direct utilization of 3D design models for construction and AMG (grading, milling, stringless paving, concrete slipform) ✓ 3D models over plan sets for inspection and quality control ✓ Quantity measurements and contractor payments specs. using 3D models (earthwork/pavements)

Project work processes	**Case studies***				**Lessons learned**	
	A	**B**	**C**	**D**	**Process issues**	**Description**
Construction	✓		✓✓	✓✓	AMG and GPS-based quality control checks in the field	• Explore the usage of AMG beyond grading operations and implement pilot projects for using AMG for the base and top course. Having specifications and need for survey equipment with greater vertical accuracy can be the critical factors • Ensure the survey and quality control specifications are updated to facilitate agency-wide adoption of GPS-based tools
O&M and asset management			✓	✓	Electronic archival practices for as-built data	• Develop technical and managerial strategies for long-term retention of such digital data for asset management purposes to move from current archival practice - of document-based electronic data (such as plan sets with native files) • CIM Technologies Implementation Plan • Employer Information Requirements • Asset Information Management Plan • Legal support (e.g. Memos for Digital Signatures usage, Amendments to States' Engineering Practice Act) • Consider integrating O&M data and handover requirements during detailed design

* Note: A blank space indicates lessons learned "not applicable" to the case study; One tick (✓) indicates minor relevance and two ticks (✓✓) indicates major relevance.

5.7 Conclusion

CIM refers to the system of interrelated technologies and practices that can help the agencies achieve the transition to digital project delivery and asset management. This study evaluated the integration of various CIM tools for project execution processes across a facility lifecycle. Four projects were selected as case studies following a comprehensive literature review and two national surveys. These projects demonstrated successful integration of one or more CIM technologies and associated practices. The selected case studies were analyzed in detail for CIM practices related to contract documentation, design coordination, construction automation, and project management. The results of the analysis provided useful insights into the strategies that can enhance the acceptance of CIM at the organization. It is anticipated that the findings of this study will assist practitioners and decision makers within agencies and can augment their guidelines for utilizing specific CIM tools on their projects.

A limitation of this research is the size of the case study sample. However, efforts were taken in order to obtain the best possible candidate projects through preliminary literature review and nationwide surveys in order to alleviate the impact of lower sample size. Future work should include more case studies spanning across various project types and delivery methods to expound and substantiate the lessons learned and implementation considerations. Secondly, the deduced guidelines may not comprehend all the key issues encountered in practice. However, they comprise recommendations (from interviews from case studies) and principal inferences from the data collection process that included the literature review, surveys, and the case studies. They emerged as significant points considering the SHAs' current state of practice for CIM at its entirety and the level of integration in their business practices. Future research should focus on the development of objective decision support systems that can help the agencies plan, select, and prioritize the investment decisions on CIM technologies. Such tools can provide the agencies the decision-making capabilities for coordinated implementation of CIM tools.

Chapter 6 Qualitative Comparative Analysis of the impact of CIM technologies on project performance.

The digital tools and practices that facilitate the collection, organization and the use of accurate data and information throughout the life cycle of a highway infrastructure asset are referred to as Civil Integrated Management (CIM). The collective impact of CIM practices and agency policies on project and asset performance has yet to be established by data-driven research. This chapter empirically models the effect of CIM practices on the resulting reduction in change orders, savings in the schedule, improvements in quality of work, and safety benefits. The modeling framework in this study also incorporates suitable constructs to study the influence of agency approaches such as financial resources, team alignment, information management policies, standards, and contract specifications. Through case studies, CIM implementation and performance data were compiled in detail across 12 highway projects in the U.S. and a mega-project in the U.K. Cross-case comparisons were then carried out using Qualitative Comparative Analysis to extract the causal conditions for outcome measures. Results indicated the presence of multiple solution pathways for explaining performance benefits. The solution pathways that include CIM attribute sufficiently explained the reported performance benefits for the projects. However, lower necessity scores of this attribute (below 0.6) showed that CIM as an enabling ingredient is not always necessary. As such, alternate solutions that exclude CIM in causal pathways do exist and they reiterate that technology is just a supportive tool. Information management strategies and contract standards and specifications recorded high sufficiency and necessity scores (above 0.8) indicating their significance to performance. The findings from this empirical research underscore the multi-dimensional nature of CIM implementation, ascertain the associated agency factors, and demonstrate a novel performance framework for agencies investing in the integration of digital practices.

6.1 INTRODUCTION

In the U.S. highway sector, Civil Integrated Management (CIM) has been promoted as a path to improving performance and predictability of highway project delivery and asset management (Guo et al. 2017). "Civil integrated management (CIM) is a term that has come to be applied to an assortment of practices and tools entailing collection, organization, and management of information in digital formats about a highway construction project."(Sankaran et al. 2016). CIM derives its significance from and shares attributes with implementing Building Information Modeling (BIM) for highway projects. Yet what has enabled the CIM idea to gain traction are the unique aspects of infrastructure projects, including the expansive horizontal elements, associated right-of-way (ROW) acquisition, utility coordination, environmental challenges, and expanded stakeholder appraisals and inputs (Taylor et al. 2012; (Hartmann et al. 2008a). CIM also encompasses a broader scope than BIM, encapsulating digital technologies and practices that enable a data-centric and digital workflow for highway project delivery and asset management. These include advanced surveying methods, model-based design processes and project management, automated machine control for construction, and digital archives for asset management (FHWA 2012). CIM adoption has also gathered considerable significance and traction in both the national and international contexts. This is particularly true in large infrastructure projects such as Crossrail Ltd. – the £14.8 Billion UK Metrorail project that has gained recognition for its lifecycle implementation of information modeling practices and related digital technologies (Munsi 2012).

Advancements in design software, sensing equipment, and in-field positioning systems are now enabling stakeholders to use digital information for project delivery and asset management (Hannon 2007). Digital workflow can lay the groundwork to avoid redundancies, improve information quality, and ensure that data remains the focal point of project delivery (Parve 2012).

Consequently, industry observers have seen over the past decade a considerable surge in the usage of 3-D design and electronic data for design deliverables and construction (Anderson 2012). Past research on digital project delivery has emphasized that investments in 3D design and process benefits cannot be evaluated in isolation. Rather, evaluation should associate their direct and indirect effect on several connected work processes—from surveying to operation and maintenance (Sankaran et al. 2016). For instance, project managers must possess good quality survey information concerning all the design entities to support the needs of 3-D design and automating the control of construction activities. A few State Highway Agencies (SHAs), while drafting integration plans for these tools, have recognized similarly shared interdependencies and implementation challenges among several CIM technologies (Vonderohe et al. 2010; Singh 2008). In addition, NCHRP Report 831 highlighted the fact that integral to successfully implementing CIM is agency policies—project delivery strategies, standards and specifications, training requirements, the culture of innovation, and the tackling of governance and policy issues. Such findings notwithstanding, the literature has yet to adequately establish a pathway from the usage of CIM technologies to improved project performance (O'Brien et al. 2016a). With highway agencies increasingly investing in the integration of one or more of CIM technologies into their workflow, it is important to study CIM implementation based on actual projects. The reported benefits should be systematically analyzed. Analyzing CIM usage along with the related agency policies can also augment the agencies' decision-making process for beneficial CIM implementation and help agencies ascertain the policy dimensions requiring attention. This chapter compiles in-depth information from 13 highway projects across the U.S. and the U.K. The chapter extracts plausible empirical models that can better explain CIM-related causal conditions for improved project performance.

The rest of the chapter is organized as follows: The next section presents a review of the literature pertaining to CIM technologies and practices and a discussion of the current studies examining the benefits of CIM tools and of the current implementation efforts at agencies. The third section presents the research objective and the fourth section offers an explanation of the research methodology (case studies). Application of Qualitative Comparative Analysis (QCA) technique is explained next in the context of a cross-case analysis to evaluate the pathway between CIM utilization and performance benefits. Inferences and practical implications of the findings are discussed next. The final section presents our conclusions and suggestions for future work.

6.2 Background review

CIM was envisioned as a coordinated initiative of Every Day Counts-2 (EDC-2)—a state-based model promoted by Federal Highway Administration (FHWA) and American Association of State Highway Transportation Officials (AASHTO). Its aim was to study, identify and disseminate best practices for proven emerging technologies and practices for project delivery. CIM now encapsulates a set of tools and practices that can enable the transition to digital project delivery and asset management. These technologies, in turn, play a major role in enhancing the efficiency of work processes and streamlining the information flow for the lifecycle.

6.3 Overview of CIM Workflow

The objective of the CIM initiative is to reduce redundancies in information flow and create opportunities to enhance the utility of data for all stakeholders. The major transformations in the CIM workflow are described briefly below (Sankaran et al. 2016).

- During the planning and project development stages, the decision-making processes can be enhanced by well-compiled and integrated geospatial data and software. These functional improvements can benefit such activities as alternative analyses, environmental impact reviews, and visualization. It can also inform the data requirements for surveying

- To assist the modeling and quality control needs of the 3-D design process, project managers can collect digital information such as point clouds and high-resolution imagery by using such advanced sensing technologies as Mobile Light Detection and Ranging (LiDAR), Drones, Robotic Total Stations (RTS), and Subsurface Utility Engineering (SUE).
- Construction activities are supported by information-rich digital models and detailed electronic deliverables—products of collaborative 3-D Design by all the major disciplines. Contractors and operators can use this information for Automated Machine Guidance (AMG) during on-site construction. Usage of Global Positioning Systems (GPS) and Robotic Total Stations can augment the vertical accuracy of positioning while keeping in compliance with the quality control standards.
- Digital models can also be integrated with project control activities such as model-based scheduling (4-D), cost estimating (5-D), quantity estimation (such as earthwork using Digital Terrain Models), and progress monitoring.
- As-built surveys, after the construction phase, using equipment such as rovers, drones, and mobile digital devices can assist in electronic archiving of the asset data to support operations and maintenance requirements.

During design and construction, reviews can be expedited with digitally encrypted electronic signatures in conjunction with information management systems. These CIM technologies constitute the crucial stages of the digital workflow. Depending on their intended functional applications on projects, CIM technologies can be thematically clustered into three major categories—advanced sensing tools for surveying and data collection, n-D modeling and simulation tools for digital design and construction, and data management tools for managing digital workflow (such as mobile digital devices, digital signatures, materials management systems) (O'Brien et al. 2016a).

6.3.1 Review of CIM Implementation Efforts

CIM has garnered the attention of practitioners and researchers due to its overall objective—to integrate digital technologies that are connected and that offer synergistic benefits in the project delivery process. A few SHAs have foreseen the penetration of digital technologies in their office and field environments and created plans to implement them widely. In making a strong case for using digital data on projects, Oregon Departments of Transportation (DOT) laid out, in 2008, an engineering automation plan that ascertained the major technological upgrades at the agency for the ensuing 25 years. This strategic document also recognizes an inherent transition to a digital workflow paradigm (Singh 2008). Wisconsin DOT developed and approved a planning document to integrate 3-D technologies This guideline outlined the agency's vision, a vision that aligned with CIM—"Adoption of three-dimensional (3D) methods and seamless data flows throughout the initial survey, design, contracting, construction, as-built survey, and other applications included within the infrastructure lifecycle." The document identified eight major statewide initiatives (a program of projects) that promoted implementing CIM technologies and extracting best practices to update agency standards (Vonderohe 2013). Both Oregon's and Wisconsin's documents also designated specific roles and responsibilities for major stakeholders and alluded to partnerships for successful implementation.

Very recently, Utah DOT (UDOT 2015) drafted plans for lifecycle integration of digital technologies. The guideline targeted integration in three phases namely timely issuance of 3-D Computer Aided Design (CAD) files to contractors, development of special provisions for legalizing digital design deliverables, and full utilization of digital technologies in the field. Besides strategic planning, some SHAs had prepared implementation manuals for CIM technologies based on their pilot experience and expert inputs. Iowa DOT (2015) developed a manual that provides detailed guidelines for usage of advanced surveying tools for 3-D data collection, the 3-D design of engineered models, and application of 3-D models for construction (Reeder and Nelson 2015). The examples above attest to the growing interest in and significance of CIM technologies among SHAs and related stakeholders.

6.3.2 Review of Performance Evaluation studies

Decision-makers need to have an understanding of benefits of these tools to make informed judgments. CIM tools have been utilized to enhance performance in areas of cost, scheduling, productivity, quality, and safety (Dodge data & analytics 2014). After performing a cost-benefit analysis, CalTrans and Washington DOT concluded that the costs for procuring and operating a piece of advanced surveying equipment (mobile LIDAR) were recouped via benefits obtained through various asset and inventory applications (Yen et al. 2014). In coming up with a cost-benefit analysis for 3-D design, Parve (2015) observed that the tangible investments in IT infrastructure were offset by savings in the reduced number of Requests for Information (RFIs) and Change Orders (COs). It was reported that the benefits quadrupled investments from a cost standpoint (Parve 2015). MassDOT developed a strategy to evaluate the profitability of Real-Time Networks (RTN) to support positioning needs for surveying and construction activities. The savings gained regarding equipment and surveying crew costs paid for the major investments in network construction and operation (MassDOT 2013). Several other researchers have experimented with other technologies and practices in a model-based workflow and their findings outlined the value-added and lessons learned by adopting CIM on highway infrastructure projects (Barlish and Sullivan 2012; Kam et al. 2013).

These studies have focused on evaluating the benefits of a particular CIM technology. Researchers have yet to adequately explore the broader causal conditions including agency policies that aid the desired performance. The literature illustrates that to produce the desired outcomes, agencies using the new tools need to follow best practices for work processes. (Kang et al. 2013a) had evaluated the indirect impact of best practices to fully explain the observed benefits on project cost growth through the implementation of 3-D CAD. The primary work processes examined included planning and change management. Thomas et al. (2004) used statistical analysis to study the positive association between information technologies for design on the cost and schedule savings of a project. O'Connor and Yang (2004) studied technology usage at the project and phase levels, finding that project schedule realizes more benefits than project cost.

6.4 Point of departure

All the aforementioned studies focused on the benefits of design and construction technologies on industrial capital projects. Fewer efforts have been carried out analyzing the benefits of implementing technology in highway projects, especially when it comes to work-processes and the influence of agency policies (Kang et al. 2013a). Yet it is important to study the influence of such policies as training requirements, contractual requirements, and legal regulations. Since public agencies administer these projects as asset owners, their policies can influence the approaches to and protocols for designing and constructing the asset. Understanding the nuanced interplay between these dimensions and CIM technologies is paramount to realizing the benefits of integrating CIM. Research that aims for such an objective should be based on an empirical approach so as to better inform highway agency decision makers. The current chapter addresses this gap in the CIM literature.

6.5 Research objective

The trend of SHAs adopting CIM technologies calls for an evaluation of the conditions in which CIM technologies tend to produce desired outcomes. The objective of this study is to investigate CIM implementation on actual projects and to assess the impact of CIM and related agency policies on the performance of these projects. The study tries to trace the theoretically plausible pathways that could have led to the observed improvements. The scope of this study includes the following CIM technologies: n-D modeling and simulation tools for design, advanced sensing tools for surveying and data collection, and data management tools for managing digital workflow (such as mobile digital devices and digital signatures). The considered agency policies include contract specifications, legal regulations, and information management strategies.

6.6 Methodology and analysis

The methodology chosen should support the need to collect detailed information based on the actual implementation in practice. Given the exploratory and extensive nature of the objective, this work addresses it using case-based research (Eisenhardt 1989). The adoption of multiple case studies provide opportunities to study practical implementation exhaustively, decipher invariance (common patterns) cross-cases, and generate logical explanations to explain a particular phenomenon (Eisenhardt 1989). Figure 6.1 compiles the key steps involved in the research methodology. The steps are illustrated in detail.

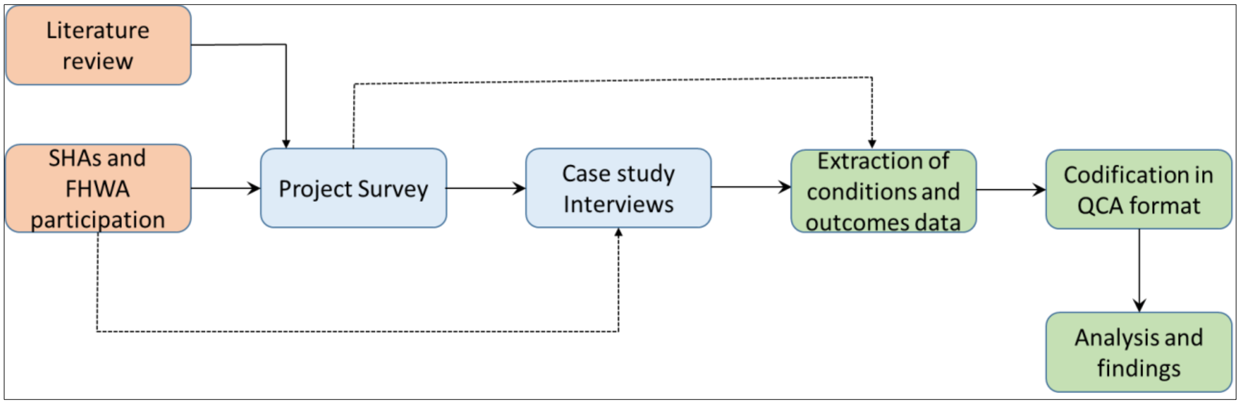


Figure 6-1 Framework for research methodology

6.6.1 Data collection

To carry out a case study, it was first necessary to collect data so as to refine and select appropriate candidate projects. After an extensive literature review of CIM practices among SHAs, a nationwide project survey was conducted to study projects and their characteristics that led to the deployment of specific technologies and the resulting performance benefits. A panel of experts across all the major SHAs and FHWA provided oversight in evaluating the questions for the survey. Panel members were drawn from U.S. SHAs and FHWA, under the auspices of National Cooperative Highway Research Program (NCHRP) of the Transportation Research Board (TRB) (Project No. 10-96). The experts included state construction engineers, pavement and material engineers, project managers, research engineers, design consultants, software service providers, and academic researchers from universities.

Besides studying technological utilization, the scope of the survey also included the support offered by project execution plans for using the selected CIM technologies. Specific questions were also included to capture the extent of the collaboration of stakeholders, contractually or officially, in promoting CIM. An assessment of performance measures of the project was also collected via a continuous Likert scale (from 1 to 10) to understand the improvements in the cost, schedule, safety, quality, and avoidance of change orders. Overall, 13 responses were selected for further case studies that would include projects of different size (budget) and complexity. Some projects that reported lower utilization levels and/or lower performance measurements were also retained for case studies to demonstrate variability and heterogeneity in the sample. While most of the candidate projects were selected for detailed investigation through interviews (case study), some projects revealed substantial information in the survey itself. Additional data needs were met through open-source documents. Table 6.1 displays an overview of key characteristics of the projects shortlisted for case studies.

Table 6-1 Characteristics of the case study projects

Project #	Title	Project Delivery Method	Expected project cost (Millions)	Investigation mode
1	Roadway relocation	D-B-B	26.5	Case Study
2	Rotary Upgrade to Modern Roundabout	D-B-B	1.45	Case Study
3	Expressway rehabilitation	D-B-B	100	Case Study
4	Roadway reconstruction	D-B-B	13	Documents
5	Interstate reconstruction	D-B	118.2	Documents
6	Ramp Metering and Traffic Operations FPI Project	D-B-B	33.1	Documents
7	Vertical steel lift bridge construction	D-B-B	300	Case Study
8	Interstate reconstruction	D-B-B	124.1	Case Study
9	Interstate reconstruction	D-B-B	1700	Case Study
10	Grading and drainage reconstruction	D-B-B	37	Documents
11	High-Speed rail project (UK)	P3	20000	Case Study
12	Interstate connector	D-B	1079	Case Study
13	Pre-stressed concrete bridge project	D-B	18	Case Study

NOTE: D-B-B – Design-Bid-Build; D-B – Design-Build; Documents – Project documents, bidding deliverables, specifications, progress report, etc.

A semi-structured interview guide was prepared to investigate projects that required further interviews for data collection (Investigation mode is “Case study” in Table 1). The number of interviews ranged from one to four for each project; the actual number varied depending on project scope, complexity, public availability of the needed data, and opportunities to learn new CIM practices. The interviews were generally conducted with representatives from the agency and the major construction contractor for the project. The framework of the guide was divided into five major thrusts to provide an in-depth understanding of CIM implementation and its supporting dimensions—CIM integration with project work processes, project characteristics and team alignment, information management strategies, and standards and specifications of agencies. These thrusts align with the queries of the project survey but were extended to capture the additional data requirements for case studies. Performance measures related to CIM that were gathered primarily from surveys were also verified during case studies. Tangible benefits related to CIM were reported on a Likert-type scale for schedule savings, quality of work, productivity improvements in the field, and cost savings due to a reduction in RFIs and Change Orders. The five thrusts related to CIM and the identified performance metrics were examined further with cross-case analysis to understand and model the impact of CIM on project performance.

6.6.2 Purpose and application of Qualitative Comparative Analysis

When using the common approaches to cross-case analyses, researchers often find it challenging to come up with mathematical configurations (models). The primary issue is twofold—a limitation in the number of cases (sample size) and the difficulty in maintaining consistency in inferences and patterns given the heterogeneity and complexity among individual cases (Rihoux and Ragin 2009). To evaluate the patterns across cases in this study, the authors have adopted Qualitative Comparative Analysis (QCA). QCA represents a powerful set of tools that work on small-to-intermediate data (ideally case study data) to extract several causal combinations that could have led to an outcome. It provides a bridge between qualitative analysis, that requires an in-depth understanding of cases, and quantitative research, that highlights significant patterns. QCA provides methodological tools to study and model "INUS configurations—causal conditions that are insufficient but Necessary part of causal recipes which are themselves Unnecessary but Sufficient"(Ragin 2012). The technique uses Boolean logic and pertinent minimization algorithms to identify complex combinations of causal conditions (or solution pathways) that explain outcomes. By employing minimization rules, it develops simplified sets that include causal conditions and the outcome.

QCA was originally conceptualized and applied extensively to model the causal complexities in comparative studies of political and social sciences. Since then, researchers have also applied this tool to areas of management, economics, organizational, and project management studies (Jordan et al. 2011; McAdam et al. 2010). It was also then adopted to study similar topics of interest in construction projects. (Santosh Kumar Delhi et al. (2012) utilized QCA to understand the combinatorial impact of economic, normative, reputational, and cognitive mechanisms on successful governance of PPP projects. Choi et al. (2016) used QCA to analyze the complex relationship between Critical Success Factors (CSFs) of modularization and associated cost and schedule benefits of industrial projects.

QCA was selected for this study for several reasons. First, QCA can theoretically incorporate the complex interactions between the essential attribute of interest (CIM usage in this study) with several pertinent attributes (process-related attributes) while analyzing the effects on outcomes. Second, the emerging nature of CIM paradigm in the highway sector and the associated constraints of collecting detailed information on project-level naturally resulted in smaller samples. Finally, QCA is one of the few methodologies that can work on generalizing patterns and infer theoretical models through cross-case analysis while still maintaining the uniqueness and heterogeneity of each case and its attributes. Further analysis of the case study data through QCA requires pre-processing and coding of variables and outcomes of interests in numerical format. The section below details that process.

6.6.3 Data processing

The primary requirement for QCA is processing the raw data obtained through the project survey and case study interviews and calibrating that data to attribute scores ranging from 0 to 1. Consequently, each of the 13 case studies was represented as a set with its attributes being variables of interest and performance outcomes. This study used the fuzzy-set QCA (fsQCA) technique, which permits membership scores anywhere in the interval from 0 to 1. A value of 0 indicates the complete absence of an attribute from the set (non-membership) and a value of 1 means complete membership (Ragin 2009). Figure 6.2 depicts the variables and outcomes considered for the fsQCA. Provided below is an explanation for the numerical coding scheme used for the attributes and associated calculations.

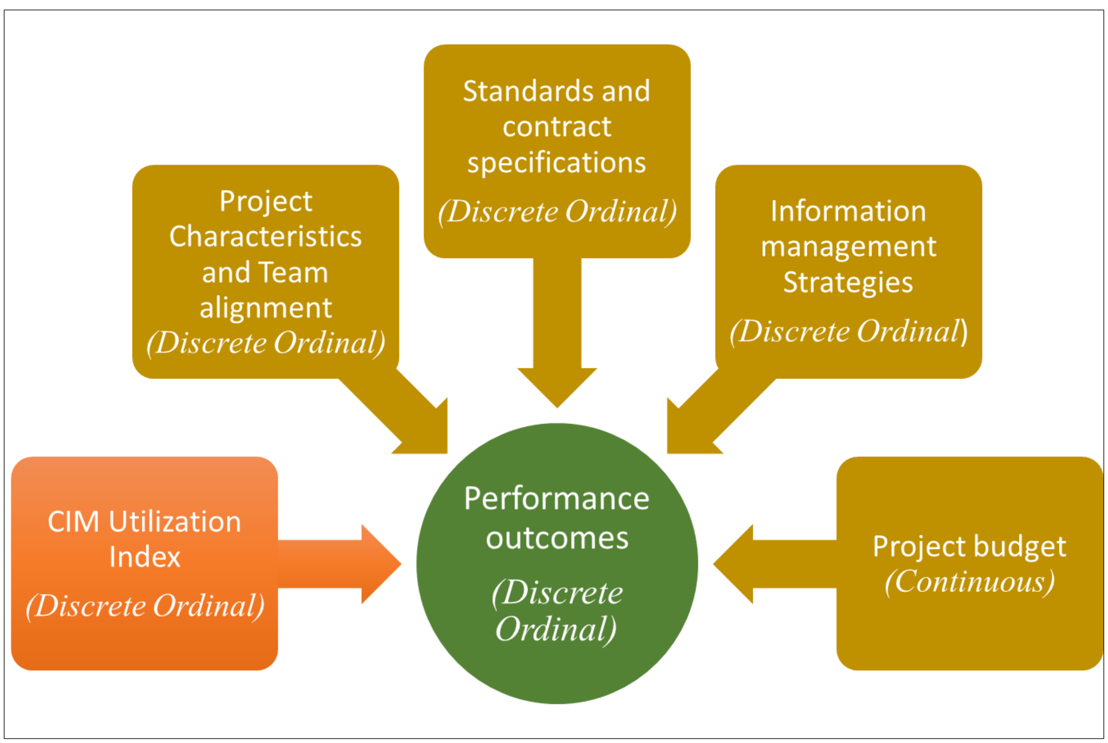


Figure 6-2 Pictorial representation of the QCA framework

CIM Utilization Index (CIM_UI)

CIM encompasses numerous technologies relevant to digital project delivery and asset management. However, to evaluate CIM implementation this study leveraged the following pre-established "clusters" based on functional application of these tools on projects: n-D modeling and simulation tools, advanced sensing tools for surveying and data collection, and data management tools for managing digital workflow (such as mobile digital devices, digital signatures, materials management systems (O'Brien et al. 2016a). Based on these three clusters, a construct for the utilization index was formulated and used for each project. Each of the studied projects used CIM tools for improving one or more of the eight project work processes—surveying and mapping, environmental assessments, design, bidding and procurement, construction, management of traffic, maintenance, and operations. A "1" was used to record usage of the particular cluster for a particular work process and a "0" indicated non-usage. The count indicators were then averaged across the eight work processes and for the three clusters, resulting in a CIM utilization index (CIM_UI) for each project. Equation 6.1 represents the mathematical representation of the construct with the three constituent elements.

$$CIM\ Utility\ Index\ (CIM\_UI) = \frac{\sum_{i=1}^{3}(\sum_{j=1}^{8} T_{ij})}{3*8} \quad \textbf{Equation 6.1}$$

Where $T_{ij} = 1$ if a technology cluster "i" has been utilized to accomplish work process "j".

The CIM_UI provides a logical order with a higher value representing the greater implementation of CIM tools with work processes.

Project characteristics and Team alignment (team alignment)

The alignment of the major project stakeholders is important to ensure the appropriate protocols are put in place for implementing CIM in work processes. In addition, project characteristics can also be an important driver in the team's selection of certain technologies and practices. The project may have incentives or unique constraints that necessitated the project team to implement CIM tools. As a representation of this attribute, this study collected the following types of information: owner requirements, contractual requirement or incentives, contractor participation/innovation, project requirements or constraints. The projects were rated for presence or absence of these four factors, encoded as “1” and “0” respectivelyThese ratings were then aggregated and standardized on a scale of 0 to 1 to arrive at an ordinal score representing the extent of team alignment and how amenable project characteristics were to CIM. A higher value of this index (closer to 1) indicates a team’s greater alignment and the project characteristics being more amenable to CIM.

Standards and contract specifications (Specs.)

Defining the contract languages for design and construction—be it prescribed or performance-based—can play an important role in improving predictability and performance of the associated project work processes. CIM encompasses several digital tools and practices for the facility lifecycle. Hence, there is a wide variety of specifications to be examined for efficient implementation in practice. Nonetheless, to keep the study scalable and practical, this study selected the most significant ones (based on the literature) that are generalizable across projects and agencies. The following list of specifications was shortlisted for further examination (Sankaran et al. 2016)

- technical manuals on software and technologies to be used on the project
- ownership and management of resulting digital data
- identification of pertinent Federal or State regulations affecting CIM usage
- contract performance specifications and prescriptions for usage of sensing technologies. 3-D design, electronic deliverables, and automated construction

- development and the contractual inclusion of level of detail (LOD) of 3-D models for project management applications
- archival plan for digital data for operations and maintenance needs
- specific training requirements to enable usage of CIM tools on the project

All the projects were examined for the presence or absence of these seven important factors. The ratings were aggregated and standardized on a scale of 0 to 1. A higher value for this index represents greater preparedness and integration capabilities of the project for CIM.

Information management Strategies (Inf_mgmt_Strategies)

While technology can provide the tools to facilitate the transition to digital project delivery, researchers have outlined the significance of devising management strategies and sharing protocols for information generated by various stakeholders throughout the project lifecycle. The contractual specifications that are technical and govern digital information were already enumerated in the "specifications" attribute. This factor gives importance to the pro-active managerial and policy considerations the SHA and the project teams put in place to utilize the available digital data efficiently. This list includes the following:

- sharing the digital data (which includes point-cloud, existing 3-D models) pre-bid to contractors to enable innovations in design,
- making initiatives to give precedence to 3-D models for project management, quality control, and verification of work during construction,
- promoting usage of interoperable software and standards for information exchange,
- encouraging data integration opportunities across various disciplines during design; most groups/processes benefit from shared data and work processes are data-centric rather than documents,

- handover plan for managing digital data beyond construction.

A scoring index based on these five factors was aggregated and standardized on a scale of 0 to 1. A higher value reflects the project team's greater intent to implement effective information management strategies for the project and the ensuing asset.

Total project cost (Budget)

Another important factor also considered was the influence of the estimated project cost on the level of utilization of CIM tools and the eventual impact on project performance. It would be intriguing to investigate this effect as projects with larger budgets (and wider scopes or greater complexity) and innovative financing schemes are able to leverage the opportunities provided by CIM technologies for project work processes. Smaller projects may, in contrast, face resource constraints and may not have the capabilities to deploy CIM. Hence, the estimated project cost (budget) for the case studies was collected and standardized as a continuous attribute on a scale of 0 to 1.

Measures for Performance outcomes

For SHAs, the key investments in CIM are related to owning or managing the technical infrastructure and absorbing the work-process disruptions to support sensing tools, 3-D design, and construction technologies. Benefits, on the other hand, are often realized through efficiency improvements or reducing uncertainties in work processes for surveying, design, utility coordination, construction, and operations and maintenance (Parve 2015; Dodge data & analytics 2012). To maintain the consistency of measurements across different projects, this work used the following performance improvement data (collected through surveys and vetted during case studies):

- reduction in design conflicts directly leading to a reduction in Requests for Information (RFIs) and Change Orders (COs) during construction,
- data quality improvements for visualization and communication during design and construction,
- schedule savings due to productivity enhancement under AMG-based construction, and
- safety improvements during construction (due to AMG and sensing technologies).

Each of these Likert-type scale measures was standardized on a 0 to 1 scale. Higher values of these five metrics are indicative of better project performance along those specific dimensions.

6.6.4 Analysis procedure

As described, the indicator variables and outcomes are coded on a consistent 0 to 1 scale. Table 6.2 displays the processed dataset of case studies ready to be used for fsQCA. Intuitively, each project, represented as a row, was transformed into a fuzzy set of values against pertinent variables and outcomes of interest. The value in each cell represents the degree of membership of the value of the variables or the outcome in the set. A greater membership value indicates a higher presence in the set. The memberships underlying these values were found to be appropriate for further analysis as they truly reflected the data from case studies. This information is used to carry out the comparative analysis using the fsQCA 2.0 tool (Rihoux and Ragin 2009). This software takes in the dataset, examines each case, and adopts Boolean logic to develop multiple combinatorial causal conditions that substantially explain the pathway to an outcome. These causal conditions are then minimized to arrive at simplified logical equations, also called "causal recipes," that explain the pattern in the dataset. Deploying the Quine-McCluskey algorithm, the software identifies all "prime implicants" (PIs). Prime Implicants are simple expressions derived by applying minimization rules of Boolean logic that explains the observed trend between variables and outcomes ("Quine–McCluskey algorithm" 2016). The Quine-McCluskey algorithm was implemented to understand the causal recipes underlying each of the four outcomes, namely improvements in the schedule, quality of communications, safety, and reduction of COs and RFIs.

Table 6-2. Processed case study dataset for fsQCA

Project #	**Variables of interest**					**Performance outcomes**			
	team_ alignment	**Inf_mgmt_ Strategies**	**Specs.**	**CIM_UI**	**Budget**	**schedule**	**safety**	**quality_ comm**	**COs_ RFIs**
1	0.25	0.73	0.43	0.65	0.1	0.7	0.6	0.7	0.7
2	0.5	0.73	0.86	0.39	0.05	0.4	0.7	0.4	0.4
3	0.5	0.60	0.86	0.71	0.5	0.8	0.9	1	0.8
4	0.25	0.07	0.00	0.40	0.07	0.2	0	0.4	0
5	0.5	0.33	0.14	0.14	0.5	0.7	0.6	0.6	0.4
6	0.25	0.07	0.00	0.22	0.12	0	0	0	0
7	0.25	0.47	0.71	0.04	0.51	0.6	0.5	0.7	0.7
8	0.25	0.53	0.29	0.43	0.5	0.4	0.4	0.6	0.1
9	0.75	0.80	0.71	0.22	0.56	0.7	0.5	0.9	0.9
10	0.5	0.47	0.14	0.88	0.13	0.2	0.1	0.1	0
11	0.25	0.80	0.86	0.17	0.95	0.8	0.5	0.7	0.6
12	0.25	0.80	0.57	0.74	0.54	0.8	0.6	1	0.6
13	0.5	0.33	0.29	0.5	0.08	0.8	0.4	0.7	0.8

It is critical to understand the contribution of individual variables of interest towards noted performance improvements. In QCA, this is usually accomplished by looking at the necessity and sufficiency scores of the individual variables. The necessity of a causal condition determines the instances of the outcome and assesses its agreement on the particular cause (variable). A higher value (generally above 0.8) reflects how necessary a particular cause is in enabling the outcome. By contrast, sufficiency works as a complementary measure and identifies cases of causal conditions and assesses their agreements on the outcome. A higher sufficiency value (generally above 0.8) reflects the sufficiency of the cause in contributing to the outcome (Ragin 2009). Theoretically, to qualify as a stand-alone factor in causing the outcome, a cause has to be both necessary and sufficient.

Table 6.3 displays the necessity and sufficiency scores of the variables of interest in this study. The values indicate that while most variables are individually sufficient and part of the set that caused improvements in outcome measures (as evident from the majority of the sufficiency scores are more than 0.8), not all of them are always necessary to explain the reported benefits. In particular, the sufficiency scores for CIM are perhaps the highest whereas its necessity scores are very low. This observation indicates that while effective utilization of CIM is sufficient to explain the realized outcomes, the presence of CIM as an enabling ingredient need not always be necessary. Perhaps there are tenable pathways involving multiple variables that could interact with CIM and augment implementation and thereby produce the intended outcomes. Interestingly, the attributes related to information management strategies and specifications displayed both high necessity and sufficiency, further supporting the need to analyze the existence of multiple pathways to the outcome. Hence, the analysis is further extended to address the causal complexity and see whether there exist multiple solutions, combining many variables.

Table 6-3. Sufficiency and Necessity scores for the variables

Outcome Variable	**RFIs_COs**	**Quality_comm**	**Schedule**	**Safety**
CIM_UI	(0.96,0.57)*	(0.98,0.45)*	(0.99,0.49)*	(0.93,0.56)*
Team alignment	(0.73,0.61)	(0.85,0.54)	(0.85,0.60)	(0.75,0.65)
Inf_mgmt_strate	(0.73,0.82)	(0.87,0.75)	(0.86,0.81)	(0.76,0.88)
Specs.	(0.81,0.79)	(0.89,0.66)	(0.88,0.72)	(0.83,0.84)
Budget	(0.74,0.57)	(0.91,0.54)	(0.92,0.60)	(0.82,0.65)

Note: * -values in the cell represents (Sufficiency, Necessity).

Table 6.4 displays the solutions of the analysis with various causal recipes for the outcome measures. Note that the absence of an input variable was also highlighted in some solutions, with "~" against their names. Interpreting them by Boolean logic, this situation implies that the outcome could have been arrived at by the absence of a condition along with the presence of other factors. The utility and the goodness of the solutions can be measured using two critical metrics:

consistency and coverage. Consistency measures the degree to which a relation of necessity or sufficiency between a causal condition (or a pathway) and an outcome is explained by a given data set. It ranges from 0 to 1, with one indicating perfect consistency (Legewie 2013). Once it has been established that a condition or combination of conditions is consistent with necessity or sufficiency, coverage provides a measure of empirical relevance. It acts as a complementary measure and calculates the proportion of memberships in the outcome that is explained by causal conditions, indicating the relevance of each pathway (Ragin 2012). Measures of consistency and coverage, working in conjunction, help delineate the combination of causal conditions that exhibited high importance and empirical relevance in the set along with performance outcomes.

Table 6-4. Summary of results from fsQCA

Performance Outcome	**Pathway/causal recipes/solutions**	**Solution Consistency**	**Solution Coverage**
Reduction in RFIs and COs	budget*stds_specs*~inf_mgmt_strate*~team_alignment budget*stds_specs*inf_mgmt_strate*team_alignment *budget*cim_ui*stds_specs*inf_mgmt_strate*	0.88	0.53
Quality_comm	budget*stds_specs*~inf_mgmt_strate*~team_alignment budget*stds_specs*inf_mgmt_strate*team_alignment ~ *budget*cim_ui*~stds_specs*inf_mgmt_strate*~team_alignment* *budget*cim_ui*stds_specs*inf_mgmt_strate*	0.91	0.58
Safety	budget*~cim_ui*stds_specs*~inf_mgmt_strate*~team_alignment ~ *~budget*cim_ui*~stds_specs*inf_mgmt_strate*~team_alignment* *budget*cim_ui*stds_specs*inf_mgmt_strate*~team_alignment* budget*~cim_ui*stds_specs*inf_mgmt_strate*team_alignmen	0.84	0.72
Schedule	budget*~cim_ui*stds_specs*~inf_mgmt_strate*~team_alignment *~budget*cim_ui*~stds_specs*inf_mgmt_strate*~team_alignment* *budget*cim_ui*stds_specs*inf_mgmt_strate*~team_alignment* budget*~cim_ui*stds_specs*inf_mgmt_strate*team_alignment	0.93	0.66

Note: * represents the logical AND; ~ represents an absence of the variable in the solution set. Each line of the solution is an eligible pathway to the outcome. Italicized rows signify the presence of CIM_UI as a necessary causal condition in the particular pathway.

Each line in the "Pathway" column (Table 6.4) represents a potential pathway that could have caused the outcome. Higher consistency scores indicate the causal recipes adequately describe the pattern in the dataset and fit the outcomes. However, lower coverage scores indicate inconsistencies as a high membership of outcomes exist in a few cases where none of the causal recipes is present (False positives). These cases can affect the causal claim and empirical relevance of the solutions (recipes or pathways). Hence, it is necessary to ascertain the deviant cases and determine the reason for their deviances from the causal solution. To do this, the solution pathways are plotted for all four outcomes of the 13 projects studied in this research (Figure 6.3). As expected, higher memberships in solutions were able to explain the noted higher degree of performance outcomes and vice versa. However, two false positives were found in the solution pathway for a reduction in RFIs and three false positives were noted for the other three performance metrics. Among these false positives, two projects were found to be common across all four metrics exhibiting greater membership in outcomes despite the lower membership in the identified causal recipes.

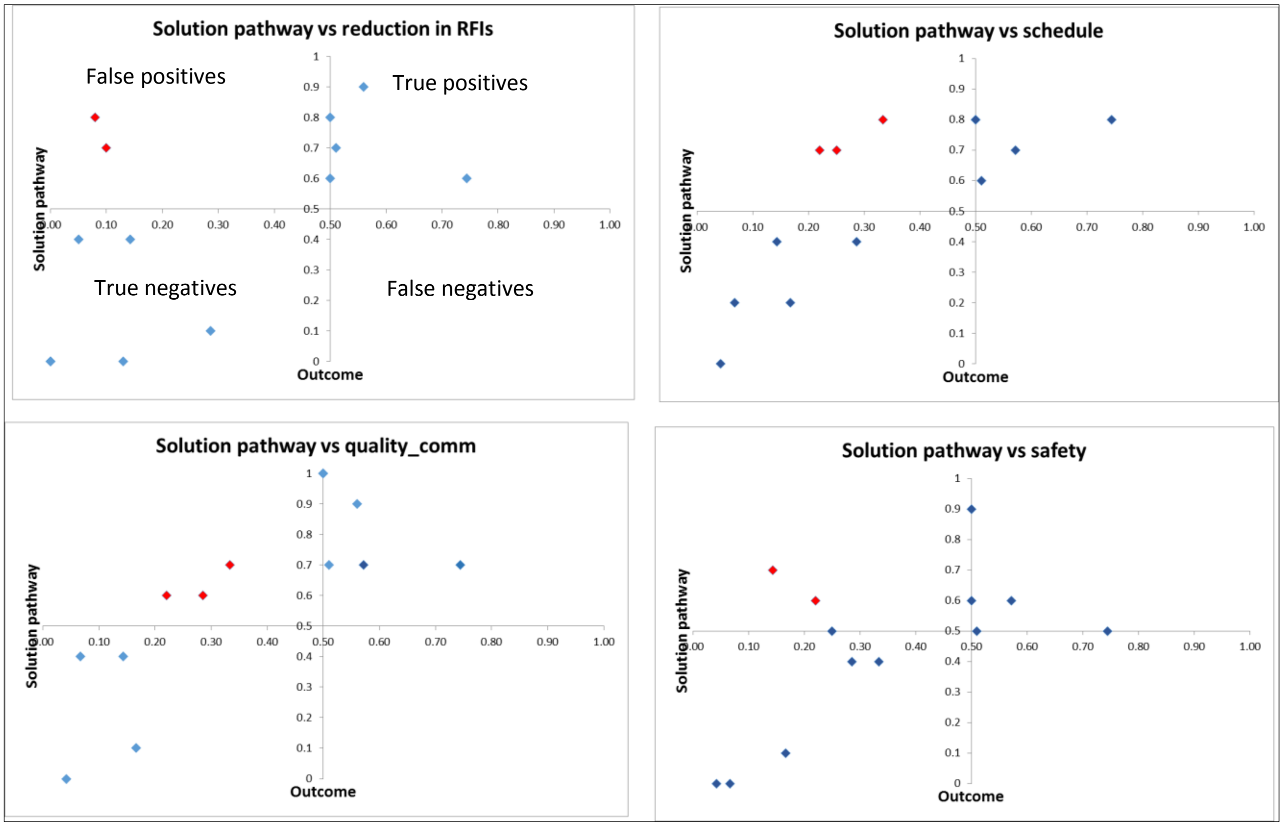


Figure 6-3 Graphical depiction of membership in solution sets vs. outcome measures

(Note: False positives are the deviant cases and represented in red. Two cases were common False positives across all the four outcomes).

The two deviant cases were identified as Case Studies 6 (ramp metering and traffic operations) and 13 (pre-stressed concrete bridge project). The authors referred back to the raw data of these projects for critical analysis and to see whether there existed possible explanations for the inconsistencies. Case Study 6 scored considerably low on CIM utilization and all the four augmenting process attributes. The project did not have adequate considerations given to formal contract specifications or information management strategies. However, the project received a dedicated grant of $2 million under a noted federal aid program to try innovative sensing and mapping technologies for 3-D design and to harvest best practices. It also had dedicated financial commitment and participatory oversight from experts at AASHTO and FHWA to monitor and guide the usage of these tools. The project team agreed that these two major issues must have played a vital role in enhancing performance despite the absence of the necessary conditions. These two unique characteristics do not necessarily suggest an exclusive pattern or systemic difference from the causal conditions resulting from fsQCA. It is not typical for all the projects to have a separate budget and expert oversight for CIM technologies implementation. Hence, this exception does not suggest any major theoretical inconsistency from the current solution. On the other hand, Case Study 13 had a reasonable contribution from team alignment, information management strategies, and standards and specifications. At the level of CIM utilization, the project scored low since the only primary tool used to assist in planning and executing the erection sequence of the bridge on site was 3-D modeling. Visualizing the bridge and erection sequences in 3-D led to the identification of a differential elevation problem between the bridge and the roadway profile. Despite the low membership from other factors, resolving this issue alone gave considerable gains across all four performance outcomes. Discussion with the project team made it clear that the benefit was rather magnified not only due to CIM utilization but also because of the diligence and timing of the designers in catching this error in pre-construction. CIM's contribution was tangible though mathematically low. Nonetheless, the team designated a high performance for the outcomes in light of the absence of logical methods to disaggregate the benefits between these two issues (CIM usage and timing of pre-construction error correction). Thus, this case does not necessitate other distinct solutions for projects in general. Future work should try to overcome this limitation by devising and incorporating subjective factors that can better capture issues such as the experience and diligence of the designers and the timing of resolving issues.

6.7 Inferences from Analysis

The analysis presents interesting insights into the influence of different variables on project performance. A graphical representation of the study's cases (Figure 3) establishes the positive influence of CIM and the necessary support of the contributing factors. The analysis also identified a few notable cases where inconsistencies between causal recipes and outcomes were observed. While the discrepancies helped identify some critical issues, they were unique to the cases and not indicative of other exclusive patterns in general.

Solution pathways (Table 4) show that, in most of the cases, causal recipes with the necessary factors in combination can better explain the pathway to the improved performance outcome. This can also be substantiated by higher consistency scores of solutions. Overall, performance outcomes displayed a positive trend from CIM implementation on all four metrics. Solutions that contributed to the presence of CIM technologies had to be augmented by other variables in the system to effectively explain the observed improvements. This observation shows that implementing suitable CIM tools for work processes had to be necessarily supported by information management strategies, standards and specifications, team alignment, and financial resources. These findings are in consensus with related studies conducted in the past to assess the impact of technology utilization on project performance (Thomas et al. 2004; O'Connor and Yang 2004). Nonetheless, this study extends their conclusions by shedding new light on and deepening our understanding of the supporting factors in the specific context of highway project delivery. Noticeably, alternative pathways (Table 4) that exclude CIM also exist and they highlight the notion that the coordinated implementation of information management strategies and standards and specifications are sufficient to explain performance benefits. These two constructs provided a reliable and separate mechanism to measure process-related requirements from the one that was intended to capture the technical utilization of CIM (CIM_UI). Another interesting observation was the absence of budget as a necessary component in some pathways. This observation could indicate that small-scale projects and projects with resource constraints can also benefit from adoption of CIM technologies when they align with other important factors. While the work considered the U.S. and the U.K. for data collection, the findings of this research are significant to highway sector worldwide considering growing interests in CIM (Dodge data & analytics 2014).

The interpretations of these results can be further strengthened by substantiating the observed results from the fsQCA analysis with the theoretical importance. In fact, this was pointed out by the CIM experts who participated in the case study. A panel of five experts was chosen from the case study interviewees based on their expertise and their experience at championing adoption of CIM technologies at their agency. The implications and conclusions from the analysis were presented and the experts were asked to comment on the practical validity of the results based on their experience in leading CIM initiatives at their respective organizations.

First, a transformative factor as per this QCA experiment is the alignment of agency personnel and contractors with CIM implementation. A case study participant strongly agreed that the barriers to widespread adoption of CIM were often as much related to organizational culture as technical challenges with the CIM tool itself. Another respondent offered the following insight into aligning the designers to adapt to the transformative and changing roles triggered by CIM integration:

> For highway projects using CIM for design and construction, designers need to be trained and equipped for construction modeling that, most commonly, entails transforming design content to 3D content suitable for machine control/machine guidance. Contractors have traditionally hired construction modelers or employed independent consultants from the cottage industry to support this need.

On the construction front, another informant pointed out the change in roles of the field personnel:

As an agency progress towards an integrated CIM workflow for construction and archival of as-built information, field staffs should be trained towards usage of GPS rovers, robotic total stations, and mobile digital devices that facilitate quality control and quantity verification in 3-D. Working from terrain modeling, the creation of as-built in digital formats had to be extended towards structural elements such as bridges, retaining walls, underground utilities etc.

Secondly, the study demonstrates that the technical standards and contract specifications also play a vital role in infusing modern CIM technologies into agency workflows. Perhaps, approaching technology implementation through formal contract specifications can create opportunities to pilot new technologies, extract best practices, and accelerate agency-wide implementation. One case study participant emphasized the importance of testing contract precedence to 3-D models and advocated the resolution it can provide for procedural challenges:

> Our past experience indicated that unless we give the Electronic Engineering Data, or EED (3-D terrain model in this case) priority over 2-D plan sets, contractors tend to always use the plans and digitize them to create their own models for various purposes (including AMG). This procedure increases the probability of errors since original design intent may be lost. It can also create redundancies since the same information is created twice.

Thirdly, this study also illustrated how project performance can be positively impacted by information management strategies. The interviewees broadly agreed that some of the issues examined under this factor are still emergent practices and hold promising results for the future. One participant noted that existing standards for model-based information exchange (such as LandXML, IFC, CityGML) represent significant initiatives, though they need to be improved to achieve full interoperability at different levels of detail for highway projects. “They are currently not adequate and self-sufficient to handle the size of files transferred in a model-based, information-rich environment, especially when using point clouds. Furthermore, not all of the civil geometry and model entities of a highway infrastructure are supported yet."

Finally, this experiment showed that budget may not be a necessary factor that aids CIM implementation and enhanced performance. All the participants broadly agreed on the finding that having financial resources available for the project could enhance the possibilities of using advanced CIM technologies. It was also noted that as an agency standardizes implementation and looks toward innovative ways of procuring and financing new practices, the contribution of the budget factor could potentially be reduced.

6.8 Conclusion

The results from the fs-QCA analysis add support to the claim that CIM is transforming the field of project delivery and asset management. CIM has garnered the attention of researchers and practitioners due to the recognition of systemic interdependencies between several connected tools. This study has empirically evaluated the impact of CIM technologies and supporting processes on improving performance outcomes. Through an extensive literature review and a national survey, 13 projects were selected to scrutinize their implementation of CIM and the observed improvements. Information collected through case study interviews and project documents were analyzed using Qualitative Comparative Analysis (QCA). QCA is an augmented cross-case analysis approach that, in this study, helped determine the likely causal conditions that led to the performance improvements. Results demonstrate the positive (though combined) effect of CIM utilization towards reducing RFIs and COs, improving schedule savings, and enhancing safety. The presence of alternative solutions also indicate the supportive nature of CIM tools and underscores the necessity to invest in work processes, build team consensus, formalize standards and specifications, and create information management strategies.

The primary contribution of this chapter is that it has demonstrated the positive association between CIM technologies and the necessary support of the agency policies to facilitate the realization of the desired outcomes. Considering the surge in the utilization of CIM technologies, empirical assessment of their impact and the associated agency policies is critical for continued and beneficial implementation efforts by the industry. The augmented QCA technique also enabled the authors to extract causal models based on detailed information from the case study data. A few deviant cases were investigated further to shed light on the inconsistencies. Future work could extend this study by including more case studies, spanning various project types, and considering more factors. The theoretical validity of the model could be improved through the diversity and heterogeneity of new cases. The performance assessment framework used in this study could also be used to develop quantitative decision support systems for studying technical and process investments and associated performance benefits from CIM technologies.

Chapter 7 Formulation of CIM maturity model for benchmarking – A Bayesian approach

The work processes for highway infrastructure projects are undergoing significant transformations due to the advent of digital technologies for project delivery and asset management. Civil Integrated Management (CIM) encompasses the digital tools and practices that facilitate the collection, organization, and use of accurate project information throughout the facility lifecycle. With the increasing reliance on CIM technologies due to their proven benefits, there is a growing need to formalize a CIM maturity model that helps agencies gauge their CIM utilization activities. Through a survey of state transportation agencies and other CIM experts, this chapter develops a quantitative approach to benchmark an agency's CIM capability. A multi-stage Bayesian factor analysis technique was used in this study. The study jointly analyzes the information from the relevant literature and the collected data on relative importance and actual implementation levels of 16 attributes related to CIM utilization. Results suggest the existence of three latent factors that adequately indicate the measurements on these attributes related to technology, processes, and organization. Furthermore, results demonstrated an overall CIM maturity score exists at second-order and can adequately summarize the measurements along the first-order latent factors. The empirical validity of the second-order model was demonstrated by applying this framework to the usage data of 6 U.S. highway agencies to benchmark their CIM maturity. The mathematical framework of this study can help highway agencies develop customized applications for maturity assessment and support decisions for prioritizing CIM investments.

7.1 INTRODUCTION

The Federal and State Transportation Agencies (STAs) in the United States are promoting Civil Integrated Management (CIM) as a path towards creating a data-centric workflow and enhancing the project outcomes for major stakeholders (Guo et al. 2017). "Civil integrated management

(CIM) is a term that has come to be applied to an assortment of practices and tools entailing collection, organization, and management of data in digital formats about a highway construction project"(O'Brien et al. 2016a). Ensuring availability and accessibility to said data for design, construction and asset management can address coordination and execution challenges unique to the highway sector, including Right-of-Way (ROW) acquisition, utility relocation, design coordination, construction quality control, public information, and mobility requirements for traffic management (O'Brien et al. 2012; Vonderohe et al. 2010). While CIM shares many attributes with implementing Building Information Modeling (BIM) for highway projects, it has its own definition in large part due to the unique challenges highlighted for this sector (Taylor et al. 2012; (Hartmann et al. 2008a). CIM encompasses a broader scope than BIM and includes advanced surveying methods, model-based design processes and project management, automated machine control for construction, and digital archival for asset management. In general, the highway sector lags behind the building industry in the integration of advanced practices such as CIM technologies. However, the adoption of CIM technologies has gained traction across several countries in the past decade, as stakeholders are exposed to and gain a broader understanding of benefits that CIM can offer. An example of this in large infrastructure projects is the Crossrail Ltd. - £14.8 Billion UK Metrorail project that has gained recognition for its life cycle implementation of information modeling practices and related digital technologies (Munsi 2012).

CIM entails multiple technologies that are interdependent in their process benefits and implementation issues. As an instance, availability of digital survey data can directly influence the ability to perform 3-D design. Similarly, the quality and completeness of 3-D design and deliverables determine the extent of deployment for automated construction technologies. Furthermore, O'Brien et al. (2016a) reiterated the need to focus on process-related factors to ensure successful CIM implementation. This study also implicitly calls for a measurement system to address the benchmarking requirements. Currently, a few highway agencies have proposed implementation plans to efficiently manage CIM integration in their workflow (Vonderohe 2013; Singh 2008), and it is expected for the use of digital technologies to increase in both office and field environments in the future.

A formalized maturity model, similar to those used in BIM implementation that measures an agency's CIM Maturity will be helpful, to both beginners and experts, to ascertain reliable and valid directions for implementation efforts. Through a survey of agencies and other highway stakeholders interested in CIM, this study formulates a general maturity model for CIM based on the relative importance and actual usage of all the pertinent factors. It adopts a quantitative approach, through factor analyses techniques, to help agencies benchmark their overall standing and delineates specific factors requiring improvements. The rest of the chapter is organized as follows: The background review section discusses the pertinent literature related to the significance of CIM practices and the need for a maturity model to assist benchmarking and future CIM implementation efforts. The next section presents the research objective and explains the methodology. Subsequently, the results of the survey are presented along with the formulation of the model. Finally, the validity of the proposed model is demonstrated using a practical case study.

7.2 REVIEW OF CIM AND MATURITY ASSESSMENT

A review of the state of practice shows that the adoption of information modeling in highway sectors lags behind the building industry (Hartmann et al. 2008a). Nonetheless, experts across the industry agreed that the work processes of the highway projects can also benefit significantly from the model-based approach for design, construction, and asset management. A study on "the Business value of BIM for infrastructure" found that around 89% of the infrastructure companies (agencies, consultants, and contractors) concurred on the positive value and returns from investing in digital technologies for design and construction (Dodge data & analytics 2012). While there are many benefits reported across the facility lifecycle, the most significant ones included a reduction in design conflicts and construction changes (58%), improvement to project quality (50%), and a reduction in uncertainties of the work processes (48%). A major study conducted to evaluate the usage of 3D engineered models for design and construction at STAs observed that agencies are at different levels of expertise; nonetheless, all the agencies agreed that the general utilization of these tools would increase in the future considering the performance and predictability benefits (FHWA 2013b).

The transformative nature of CIM technologies for the project workflow has been well recognized by leaders from both the academics and the industry (FHWA 2015a). Several research efforts conducted to advance CIM implementation recommended the need for developing a systematic framework for evaluating an agency's CIM usage and maturity (Kam et al. 2013). A synthesis on the current state of practice of CIM implementation at the Departments of Transportation (DOTs) highlighted the positive impact of agency policies on successful CIM implementation (O'Brien et al. 2016b). The study used a national survey to report the role of project delivery methods, technical standards, and contract specifications in increasing usage of CIM technologies. Similarly, Guo et al. (2014) discussed the importance of cultural shift, training requirements, and documentation of best practice guidelines towards enabling a transition in the work processes supportive of CIM integration. Thomas (2013) enumerated legal guidelines that affect the usage of digital technologies and the resulting information flow on highway projects. Synthesizing the key points from the literature, National Cooperative Highway Research Program's (NCHRP) Report 831 reported that integrating CIM technologies with work processes was perhaps a multi-dimensional issue that had to be adequately augmented through project delivery strategies, training and cultural shift, governance alignments, and legal policy up-grades (O'Brien et al. 2016a). All of these studies reiterated the need for formalizing a measurement model to assess an agency's current capabilities and judiciously plan for resources to support the adoption of new practices.

7.2.1 Review of maturity models

In theory, a maturity model for defining a capability includes all the fundamental processes and characteristics necessary for its implementation in practice (Vaidyanathan and Howell 2007). It tries to unveil the interaction among various factors driving a particular capability and provides a systematic and reliable way to benchmark an agency. Having its origins in the area of manufacturing and information technology industries, several models have been proposed to measure, control, and forecast performance measures to introduce new technologies, strategies, and principles. Some of the noteworthy developments include the Capability Maturity Model (CMM) formulated to ascertain the software capabilities of organizations (Paulk 1993) and enhance their processes and the manufacturing supply chain maturity model to determine the improvements in the supply chain. Learning from the usefulness and experience of adopting such models by other sector, researchers in the construction sector formulated maturity models for technology integration and managerial strategies. Vaidyanathan and Howell (2007) adapted the maturity model to align with complicated nature of construction supply chains and help organizations streamline their operations. (Kang et al. 2013b) proposed a three-level information integration maturity model for capital projects that assist owners and contractors evaluate their information sharing and management capabilities across an asset lifecycle.

The most popular maturity model for supporting BIM implementation was proposed as part of the U.K. government's strategic initiative to mandate usage of "level 2" BIM on public projects. This plan was towards reducing carbon emissions and achieving energy-efficient designs. The model defines four maturity levels – 0 to 3, with levels 0 and 1 outlining basic utilization of 2D/3D Computer Aided Design (CAD) models with some standard data structures and formats and level 3 deploying a fully interoperable and BIM-based information workflow for project delivery (BIM Task Group 2011). The National Institute of Building Sciences (NIBS 2015) developed a basic capability maturity for establishing the benchmarks of their BIM capabilities in 11 areas. The BIM deliverable matrix by ACE (2008) proposed a hierarchical framework that focused on capability assessment based on the extent to which agencies can integrate digital workflow and produce digital deliverables in each of the project phases. The maturity was assessed at three incremental levels. The Computer Integrated Construction (CIC) Research Program produced another five-level maturity model that was proposed as a strategy to assess an owner organization's current BIM profile to identify key areas for alignment and advancement (Messner et al. 2010). This model focused on high-level planning and evaluated an agency's profile for BIM implementation based on its vision, mission, management support, and intended BIM users from the project and operational standpoint. Giel and Issa (2015) also adopted a Delphi approach to developing an assessment tool for owner organizations across three diverse competency areas and pertinent categories. The Indiana University (IU 2015) Architect's office formulated a BIM proficiency matrix, a simple Excel-based tool that measures a user's capability across 32 areas rolled under eight categories and at 5 incremental maturity levels. Succar (2009) came up with a comprehensive process to systematically assess an agency's BIM performance based on the organizational scale and the goal of evaluation. The organization's scale had to be initiated as project team, organization or organization unit. A user can deploy this tool for various purposes such as initial discovery, evaluation, certification, or auditing. Once the competency areas have been determined based on these two criteria, maturity assessment can be analyzed based on the extent of modeling for project work processes as per the established five levels of maturity. All of these models illustrate the adoption of new or emerging technologies and strategies require a focus on issues that are complex and multi-dimensional in nature.

Most of the efforts pertaining to evaluating BIM maturity are rather qualitative and prescriptive in nature. While the models have considered both the technical and procedural issues, the interaction or hierarchy among various factors has not been adequately studied or validated in practice. The aggregate maturity score produced by these tools can be hard to interpret in the absence of such empirical validation substantiating the potential interaction among various factors. There have been some prior efforts towards addressing this challenge and developing a more robust and practical tool that quantifies the importance of these dimensions. Chen et al. (2014) conducted a national survey to understand the relative importance of twenty-seven indicators in terms of their contribution to effective BIM implementation. Factor analyses techniques were used to theorize and measure the underlying latent factors and quantify their interactions in achieving overall BIM maturity. The conceptualized factors were process definition and management, information management, training, information delivery, and technology. Chen et al. (2016) proposed an extended Structural Equation Model (SEM) that tested the causal relationship among various factors constituting the overall BIM maturity. They found empirical evidence for correlation among the factors of process management and technology management. Both of these factors had a statistically significant positive impact on information management and the overall BIM maturity. Smits et al. (2016) analyzed the impact of BIM maturity on firm performance based on strategy, BIM uses, processes, infrastructure, and personnel. It elucidated the positive, yet limited, the impact of BIM maturity on cost, schedule, and quality.

Extending research on measuring BIM maturity is justifiable considering the increasing trend of BIM integration in various industry sectors. NCHRP Report 831 proposed a qualitative maturity model for highway agencies to benchmark the capabilities of digital practices from surveying to operations and maintenance. The three-level maturity requires a consensus of agency experts knowledgeable about CIM implementation across asset lifecycle to identify the extent of CIM implementation. This maturity model is subjective in nature and oriented more towards assessing technology utilization. It is imperative to develop a maturity model that considers both technology and process-related factors to create a conducive environment for the transition to a digital workflow. This chapter integrates all the previous efforts in maturity research and proposes a formalized CIM maturity measurement suited to address the requirements for highway agencies.

7.3 RESEARCH OBJECTIVE

The objective of this chapter is to evaluate the interactions among major factors influencing the integration of CIM technologies at highway agencies and methodically formulate a unified CIM maturity model. Since CIM encompasses broader scope inclusive of digital technologies and practices pertinent to the asset lifecycle, it also necessitates consideration of attributes pertaining to agency policies and approaches that can facilitate broader implementation of these tools at agencies. Accordingly, the scope of the attributes considered in this study includes technology, contract, legal, and organizational issues. Each attribute can have different levels of implementation and associated significance in the context of CIM. Hence, this study captures both the relative importance and actual usage of these attributes at STAs. It unveils the factors underlying these attributes to developing a theoretically inclusive and quantitatively adaptable measurement model that is indicative of CIM maturity at highway agencies. This objective is achieved by conducting a national survey and analyzing the data through Bayesian factor analyses techniques. The methodology is explained next in detail.

7.4 RESEARCH METHODOLOGY

The goal of this study is to produce a useful and reliable measurement approach that can be utilized by agencies involved in integrating CIM to evaluate their current maturity. Systematic reconciliation of data about life-cycle CIM implementation and its contributing attributes is paramount towards measuring them. These attributes were observable from practice and hence, enumerated based on a review of CIM literature. The final set of attributes were corroborated based on consultation with Transportation Research Board (TRB) ABJ95 CIM sub-committee. The sub-committee comprises of representative members from several U.S. State highway agencies, contractors, academic experts, and consultants. These members have considerable expertise and experience researching and implementing CIM within their respective institutions and are involved in identifying future research needs to enhance integration of digital workflow in highway project delivery. Selection of attributes through this approach ensured that consolidation of relevant attributes remained scalable, comprehensive, and practical towards utilizing them for this study. Following the identification of CIM attributes, the authors conducted a survey to capture the importance and actual usage of the same. The collected data were analyzed using multivariate statistical methods (factor analyses) to explore the underlying latent structure and causal relationships among the recorded CIM attributes. The latent structure was scrutinized further to test for the existence of an overall maturity score indicative of the observations from practice. Figure 7.1 presents the two principal stages of the research framework. The first stage focused on data collection. It encompasses ascertaining the attributes, questionnaire design, and data collection for assessing utilization of CIM practices across STAs. The second stage includes the factor analyses of the relative importance and usage of the attributes to create a unified CIM maturity score for agencies.

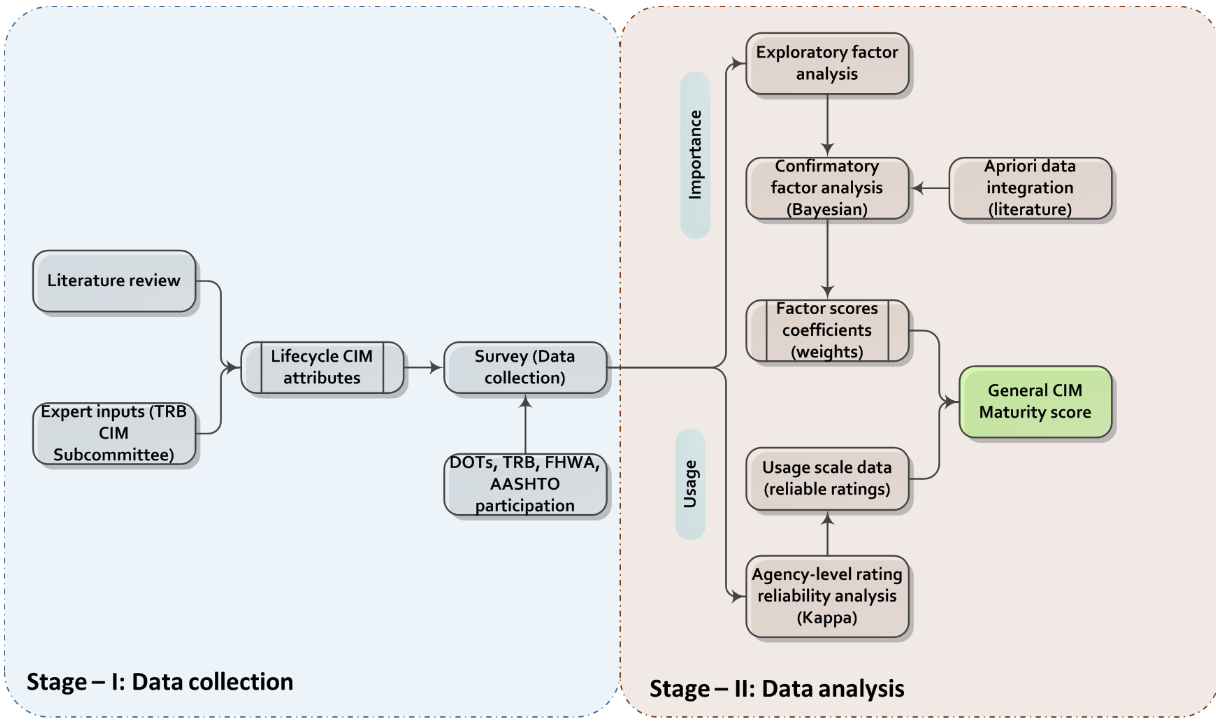


Figure 7-1 Framework of research methodology

7.4.1 Stage – I: Questionnaire Design and Data Collection

An extensive literature review was conducted to screen the list of attributes that are relevant for CIM implementation across the lifecycle. The various resources referred for this purpose include the implementation framework and the qualitative maturity model in the guidebook for CIM (O'Brien et al. 2016a), the national scan of U.S. State Highway Agencies conducted to study the advances in CIM (Jahren 2014), and other published resources from the Federal Highway Administration (FHWA) that highlights the key technical and process-related attributes for CIM integration (Parve 2015) . Considering the emerging nature of CIM and limited studies that explored the maturity assessment for highway sector, pertinent studies for BIM maturity were also considered to inform the selection of the measurement attributes for CIM. Overall, 16 attributes relevant for CIM were shortlisted for measurement. Five attributes covered technology integration relevant for digital workflow, namely advanced sensing methods (surveying), collaborative 3-D design among major design disciplines (design), automated machine control for construction, mobile digital devices, digital signatures for project management, and digital archival for asset management. The other relevant attributes were process-related that captured contractual, legal, and organizational support for CIM. The comprehensive nature of the attributes and their validity in terms of addressing the CIM maturity were further tested through discussions with the CIM sub-committee. It was concluded that the 16 attributes provided adequate coverage of all the necessary issues to objectively gauge CIM maturity.

An online survey was then administered through Qualtrics survey platform with the selected attributes for CIM maturity assessment. This survey had two sections. The first section comprised of questions that capture the demographics of respondent including the contact information, organization, area of work, and experience in the transportation industry. The second section asked the respondents to rate the CIM attributes based on their degree of importance in digital workflow and their actual level of utilization at State agencies. The importance and usage data were collected on 6-point Likert scales to ensure consistency and uniformity of responses; While importance scale varied from “not all important” to “extremely important, the usage scale was parameterized from “not at all used” to “used every time on all projects”. While respondents from agencies were requested to rate on both the importance and usage scale, non-agency experts responded to the importance scale only. The intent of this study is to produce a measurement model targeted at agencies’ usage of CIM. Furthermore, projects delivered by these agencies that own and manage these assets are also characteristics of the technologies and practices deployed by the contracted organizations and consultants. Thus, collecting usage data only at the agency-level was considered appropriate for this study. Figure 7.2 presents a snapshot of a section of the questionnaire.

2.1. **The questions in this table examine the key digital technologies in the work processes for project delivery and asset management. Please rate the following questions on two levels:**

I. Relative importance to implementing CIM on capital projects (digital project delivery and asset management)

II. Frequency of actual implementation at your agency on capital projects

	Level of Importance						Frequency of usage					
	Not at all important	Low Importance	Moderately important	Important	Very Important	Extremely Important	No plans to use	Planned	Piloted	Occasionally used	Frequently	Everytime
Usage of advanced sensing techologies (i.e. LiDAR/UAVs) to support digital data collection	○	○	○	○	○	○	○	○	○	○	○	○
Usage of collaborative 3-D design among major design disciplines and advanced construction planning (4-D/5-d)	○	○	○	○	○	○	○	○	○	○	○	○
Usage of Automated Machine Guidance (AMG) technology for construction, digital practices for QA/QC and as-builts verification	○	○	○	○	○	○	○	○	○	○	○	○
Usage of Mobile digital devices , Electronic Information Management systems, digital signatures for document management	○	○	○	○	○	○	○	○	○	○	○	○
Usage of electronic and/or digital archival practices for asset management.	○	○	○	○	○	○	○	○	○	○	○	○

Figure 7-2 Sample survey questions

A pilot questionnaire was served to the experts at the TRB CIM sub-committee to test for the robustness and the consistency of the survey objectives with the included questions. The experts responded to the queries and concurred that the questionnaire adequately covers the subject area with respect to the chosen goal. Minor suggestions regarding semantics and grouping of questions were given and the authors implemented them as recommended. The revised questionnaire was then officially used for data collection. The outreach efforts involved distribution to experts from academia and industry that are involved in studying and promoting CIM integration in practice. The list of potential respondents contacted includes serving members of the following committees:

- TRB ABJ95 Visualization for Transportation Committee and CIM sub-committee
- FHWA Office of design and construction
- American Association of State Highway and Transportation Officials (AASHTO) subcommittees on design and construction
- State Departments of Transportation

- American Society of Civil Engineers' Visualization, Information Modeling and Simulation (VIMS) Committee (Computing in Civil Engineering)

7.4.2 Stage – II: Data Analysis

The survey gathered 206 responses in total spanning over a period of four months. Survey responses with more than fifty percent of missing data were not considered further for the analysis. As such, 128 qualified responses were considered for examination. The sampled respondents covered all the major area of work experience ranging from surveying to design and operations and maintenance (Figure 7.3). There was also a reasonable response from academicians and researchers interested in CIM. Meeting this pre-requisite was significant as the scope of CIM encompasses issues relevant for asset lifecycle and it is crucial to gather diverse perspectives of experts across various domains. All the participants had considerable work experience in the highway sector (Mean = 23 and Standard Deviation = 9.11), enhancing the validity and coverage of the recorded responses. 91 responses are from experts at state Departments of Transportation who had provided both the importance and usage data at their agencies, while the remaining 37 are non-agency experts who rated the importance of the attributes.

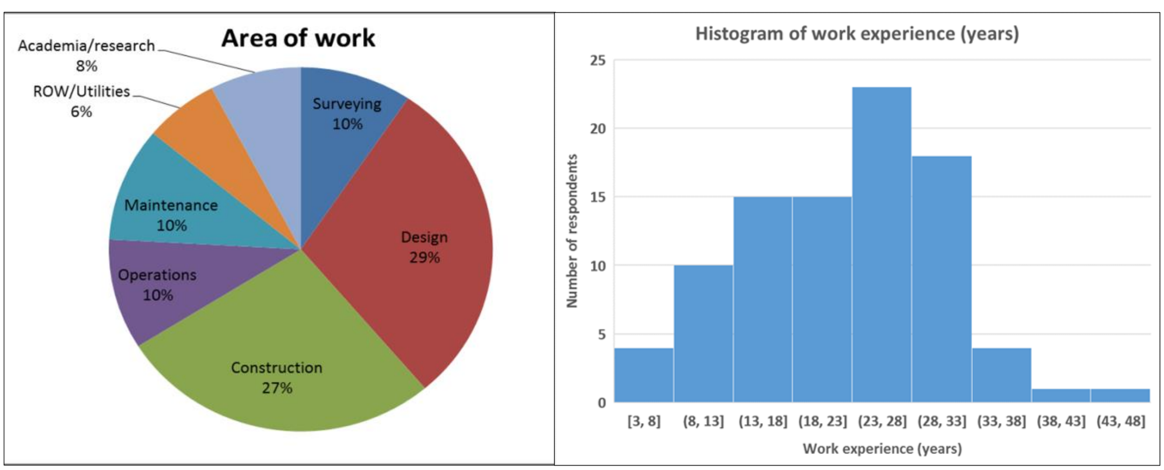


Figure 7-3 Respondent demographics – (left) area of work and (right) experience in highway sector

Evaluation of the responses corresponding to importance scale is considered next as it is of common interest to both agency and non-agency experts. They provide empirical evidence of the relative contribution of each attribute towards measuring CIM maturity. The sampled responses were further tested for patterned relationships among the CIM attributes by examining their pairwise correlation. From a statistical standpoint, correlation values between 0.3 and 0.8 are considered appropriate for conducting factor analysis. The minimum correlation threshold suggests the existence of patterned relationships among attributes favoring factor analyses. The maximum limit ensures avoidance of multicollinearity that could lead to estimation problems and false interpretations of results when multivariate statistical methods are used (Yong and Pearce 2013). Nonetheless, the correlation between any pair of attributes, among the 16 attributes, were found to be compliant with the recommended limits (table presented in Appendix F). Thus, 128 responses on importance scale were considered to be valid for factor analysis

The correlation analysis indicates the existence of a simplified latent structure that could possibly explain the variability in the data in reduced dimensions. It is sequential and statistically appropriate to conduct an exploratory factor analysis and empirically establish the causal structure from the given dataset.

7.5 ANALYSIS PROCEDURE

7.5.1 Exploratory Factor Analysis of CIM Attributes (Importance scale)

Performing Exploratory Factor Analysis (EFA) requires conducting several screening checks on the dataset to demonstrate its suitability. Table 7.1 presents the results of the EFA. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was found to be 0.917 (minimum theoretical threshold is 0.5) indicating the current sample size for the analysis was justifiable. The Bartlett's test of sphericity was significant (p-value <0.001) implying that there are considerable patterned relationships and inter-correlations among the attributes and applying factor analysis technique was indeed appropriate (Hair et al. 2010). The convergent validity of the attributes was tested using Cronbach's alpha which worked out to be 0.94 demonstrating the high internal consistency of the attributes and reliability of the scales as a group. Finally, the diagonal elements of the anti-correlation matrix are greater than 0.5 showing that distinct and reliable factors can be extracted. EFA was performed in IBM SPSS® using Principal Axis Factoring extraction and Varimax rotation methods. These techniques are useful when conducting factor extraction studies that are exploratory in nature (Yong and Pearce 2013). The analysis indicated the presence of three latent factors that explain around 60 percent of the total variance of the original data. All of the 16 attributes contributed significantly to the three latent factors as observed their communality values, all of which are higher than the theoretical cut-off of 0.2 (Yong and Pearce 2013). The factor loadings of the attributes that are higher than 0.4 are retained. Cross-loadings less than 0.3 are not retained to obtain an elegant and simple representation of the factor model that explains the variance observed in practice (Hair et al. 2010).

Table 7-1 Consolidated summary of results (EFA)

CIM Attributes (Importance)	Factor 1*	Factor 2*	Factor 3*	Communality
	CGP	**TWP**	**OHR**	
Formalization of technical standards/specs.	0.644			0.628
Contract precedence for CIM practices	0.672	.		0.756
Alternative Delivery Methods and ATCs support	0.426			0.417
State or federal laws and agency rules pro-CIM	0.654			0.581
Interoperable software for data integration	0.751			0.666
Strategic changes to bidding policies	0.785			0.777
Digital handover plan for O&M	0.563			0.491
Sensing practices for digital data collection		0.421		0.363
Collaborative 3D design		0.516		0.539
AMG for construction and digital QA/QC practices		0.53		0.588
Digital hardware and software for Project Management		0.609		0.534
Electronic and digital archival practices for assets		0.698		0.562
Agency-level Implementation plan for CIM			0.58	0.667
Training for design, construction, and field staffs			0.518	0.529
Culture of innovation and leadership buy-in		.	0.611	0.634
Budget availability and financial commitment (CIM)			0.71	0.736
Eigen Value	**8.55**	**1.28**	**1.05**	
Total Variance Explained (%)	**27.024**	**43.94**	**59.17**	
Cronbach's α				**0.94**
KMO Measure of sampling adequacy				**0.917**
Barlett's test of sphericity (p-value <0.000)				**1282.9**

Note: Factor -1: Contract and Governance Policies (CGP), Factor – 2: Technology Integration with Work Processes (TWP), Factor 3 – Organizational and Human Resources (OHR). Factor * - all the loadings are significant at 0.05 level of confidence. Cross loadings are not shown

It is vital to examine the nature and type of attributes loading onto a particular factor and ascertain its nomenclature to facilitate logical interpretation of results and inferences. Factor 1 essentially consists of attributes pertaining to contractual and governance policies of an agency (CGP). They include transforming bidding policies, software solutions, technical standards, specifications, and legal implications for integrating CIM in their workflows. Factor 2 comprises of attributes related to technology integration with project work processes (TWP). The attributes span the lifecycle of the facility from surveying to digital archival for asset management. Factor 3 addresses the attributes pertaining to the organization and human resources alignment (OHR). In summary, the factor analysis supports the existence of three latent factors that can be leveraged to formally measure CIM maturity. Nonetheless, the factors identified at this stage had to be evaluated for their validity and adequacy towards explaining the variability of the data and the inherent causal relationships. Thus, Confirmatory Factor Analysis (CFA) was carried next.

7.5.2 Confirmatory Factor Analysis (CFA) of the Factors: Assumptions and Model Testing

While EFA provided insights into fundamental factors that can reasonably determine the observed attributes, the nuanced interactions, and dependencies between these constructs had to be validated through CFA (Hair et al. 2010). CFA provides opportunities to test multiple plausible and competing hypotheses that relate the three theorized factors –CGP, TWP, and OHR - and verify and establish a unified measure of CIM maturity. The various hypotheses consistent with the theory are evaluated next.

Hypothesis 1 (First-order measurement model)

This hypothesis states that the three reflective constructs (CGP, TWP, and OHR) identified through EFA are statistically reliable and sufficient to adequately represent the measured data from the 16 CIM attributes. Figure 7.4 shows the mathematical model that corresponds to the assumptions of the hypothesis. The CFA was conducted in Mplus© (Muthen and Muthen 2012) software with the hypothesized factor model and the raw data corresponding to the values of the CIM attributes. Concisely put, the method estimates the model parameters and goodness-of-fit by ensuring the reproduced correlation matrix closely resembles observed correlation matrix from the CIM attributes.

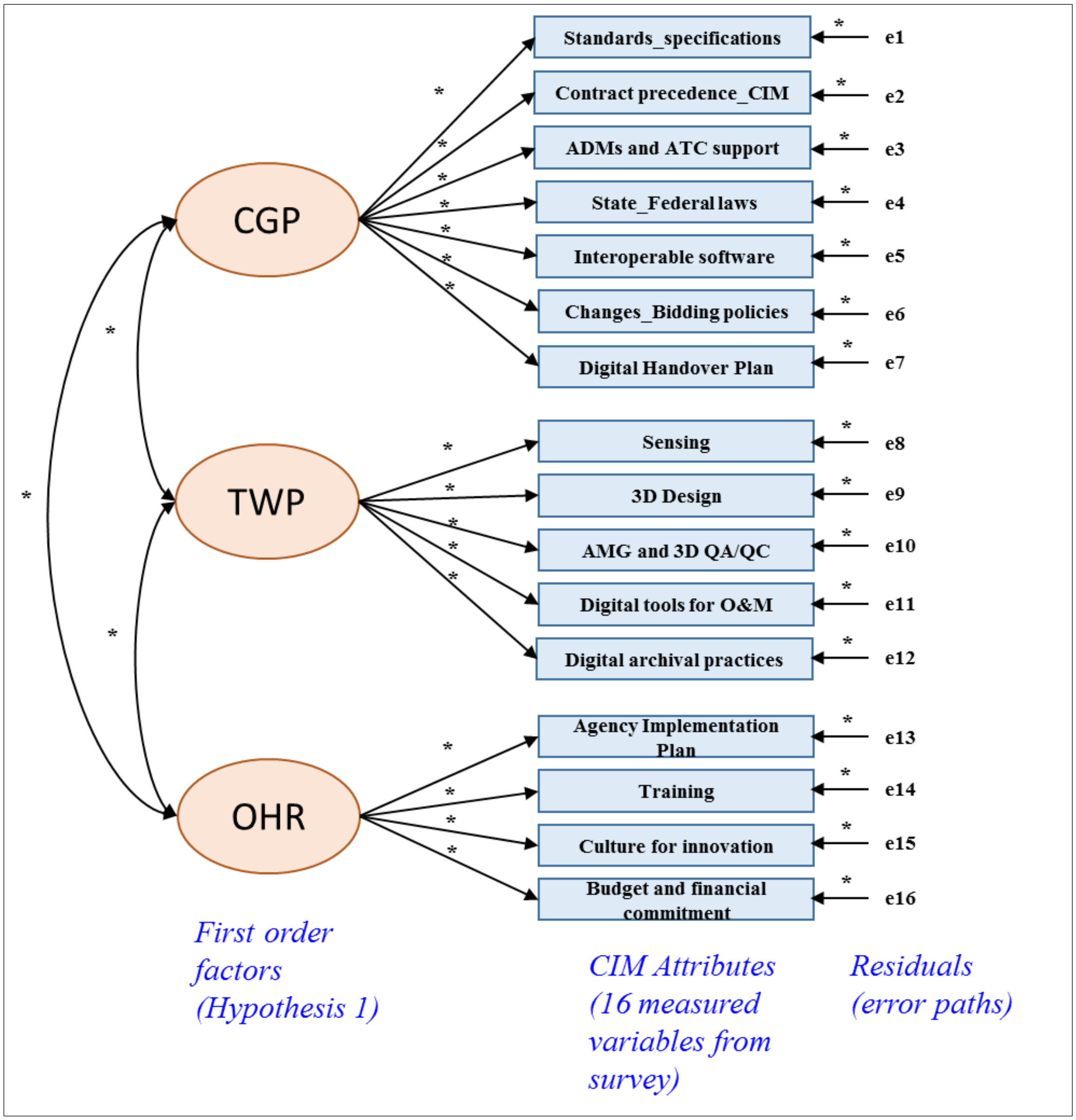


Figure 7-4 First-order measurement model

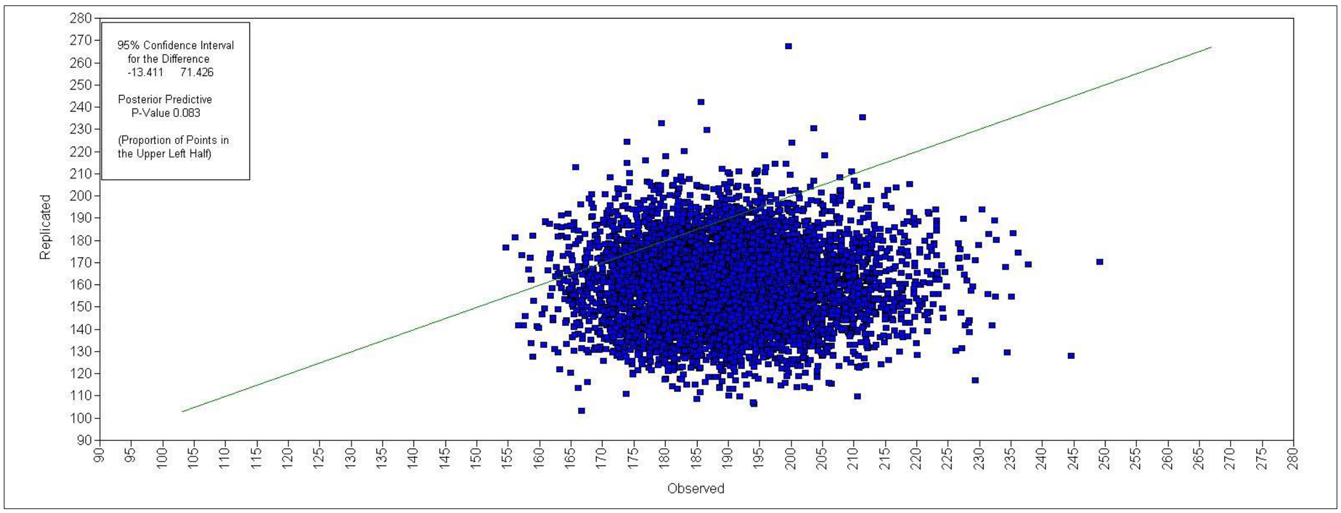
Note: * represents model parameters namely factor loadings, covariance, and error paths, to be estimated in CFA; CGP – Contract Governance and Policies; TWP – Technology Integration with Work Processes; OHR – Organization and Human Resource Alignment

The analysis was conducted using Bayesian estimation to identify the model parameters. Bayesian paradigm presents a robust and reliable approach to systematically integrate the knowledge from the CIM literature in the form of a priori probability distributions for model parameters (Kaplan and Depaoli 2013). It gives due weight to both the established prior beliefs and the likelihood of the data. The Bayesian approach also performs considerably well for lower sample size. Furthermore, it does not require asymptotic normal distribution for data unlike the conventional Maximum Likelihood estimation for the classical approach.

Bayesian estimation was implemented using Monte-Carlo Markov Chain (MCMC) sampling that works on the principle of intelligently sampling the posterior distributions of the model parameters to determine the parameter estimates and calculating the model fit statistics (Hoyle 2012). Qualitatively, all the three factors CGP, TWP, and OHR have been identified as key enablers contributing to efficient CIM implementation at agencies and could influence each other in an affirmative way (O'Brien et al. 2016a). Furthermore, the strong positive association between the CIM attributes was anticipated based on findings from similar research in the area of BIM maturity (Chen et al. 2014). Since first-level factor loadings are reflective of the strength and direction of inter-correlation between multiple variables, they are all designated as a normal distribution with a mean hyper-parameter of 0.7, and variance of 0.35. No prior knowledge was incorporated into the factor means by specifying prior distributions with little precision – a mean value of 0 and a variance of 10^{10}. The factor and unique variances were also given non-informative and diffuse Inverse-Wishart (IW) priors since variance constitute real-valued positive definite matrices (Hoyle 2012). Finally, MCMC technique was implemented using Gibbs sampler with two chains to scan the posterior search space and 60,000 iterations were performed for each chain.

After incorporating various assumptions, the model was estimated in Mplus. The accuracy of the hypothesized model was further improved by identifying and including covariance between the errors among the observed variables (i.e. covariance between e1-e16 as shown in Figure 7.4). It has to be noted that error paths do not entail a deviation from the statement of hypothesis 1. Covariance can be included among a pair of residuals and they rather indicate that the observed

CIM attributes have residuals that are positively associated beyond the variability explained by the significant loadings from its parent factor (Hoyle 2012). This process was accomplished by performing chi-square difference test for each of the incorporated additional covariance between error paths. Overall 9 error paths were added. Figure 7.5 displays the model fit results from the CFA for the first-order measurement model (Hypothesis – 1). The scatter plot indicate a pair of observed and replicated observations.



Note: PPC – Posterior Predictive checking. The scatters indicate a pair of observed and replicated observations. (Model choice parameter DIC = 5003)

Figure 7-5 Summary of model fit statistics for PPC - Hypothesis 1

Results provided empirical evidence towards the support in the favor of hypothesis – 1 with the p-value for posterior predictive checking working out to be 0.083 (>0.05). This indicates that there is no significant difference between the observed data and the replicated data generated from the posterior distributions of the model parameters. Secondly, the maximum Potential Scale Reduction Factor (PSRF) for any parameter came closer to 1 indicating strong convergence between the two Markov chains. The model took less than a minute to converge. Furthermore, all the factor loadings were found to be statistically significant and greater than 0.5 and associated with their respective parent factors indicating the construct validity. The Deviance Information Criterion (DIC) was observed to be 5003; it is a relative metric and generally used for comparing competing hypothesis (to be later explained in comparison with Hypothesis 2). The CFA of the first-order model arguably indicates that the three latent factors CGP, TWP, and OHR can freely indicate the measurements of the 16 CIM attributes from a modeling perspective. Nonetheless, there is considerable evidence in the CIM literature and pertinent studies from the building sector which suggests the presence of an overall CIM maturity unifying all the process factors (O'Brien et al. 2016a); (Chen et al. 2014). Conceptually, an overall CIM maturity could be indicated by multiple factors spanning technical, contractual, and legal standpoint. Hence, the analysis was extended to hypothesis – 2.

Hypothesis 2 (Second-order measurement model)

This hypothesis is stated as follows: A general CIM maturity (CIMM) indicates the variability information conveyed by the three reflective constructs CGP, TWP, and OHR and is representative of the relative importance of the observed CIM attributes (second-order measurement model). Figure 7.6 shows the graphical representation of the model.

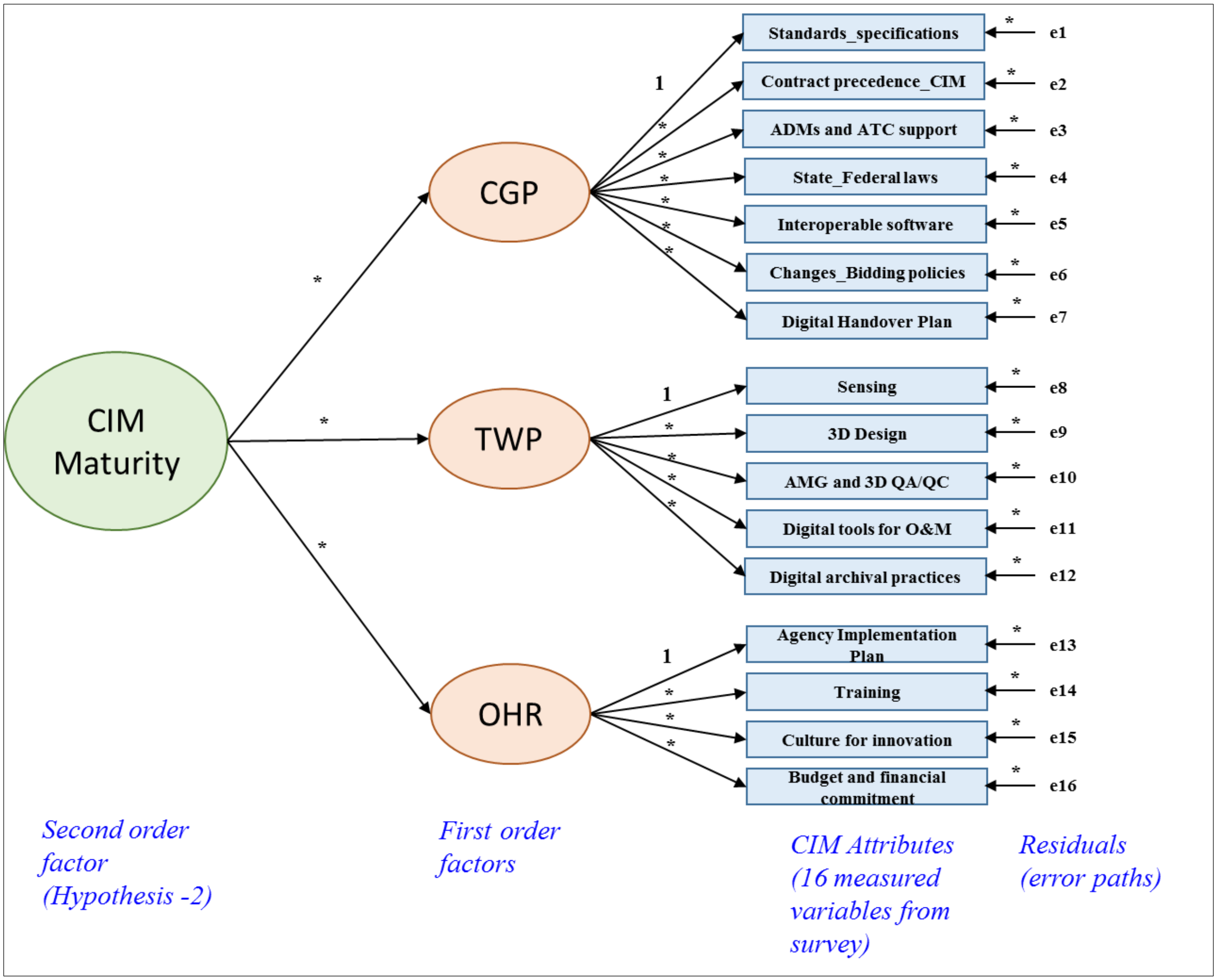
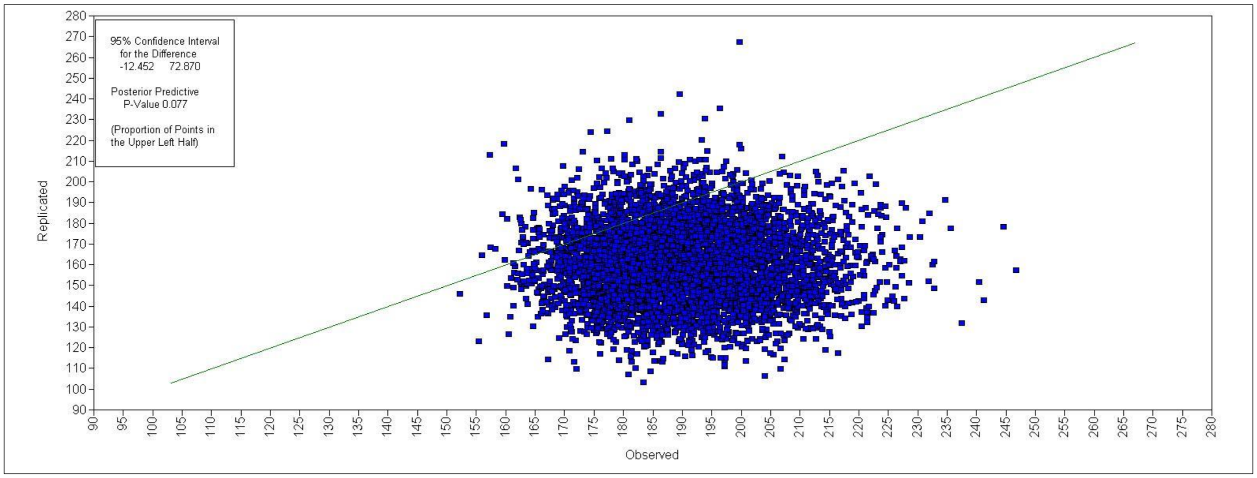


Figure 7-6 CFA of the second order measurement model

Note: * represents model parameters, factor loadings and error paths to be estimated in CFA; CGP – Contract Governance and Policies; TWP – Technology Integration with Work Processes; OHR – Organization and Human Resource Alignment

From a mathematical standpoint, the only difference between this model and hypothesis 1 is the inclusion of a second-order construct that indicates the three first-order factors of CGP, TWP, and OHR. As a result, additional prior distributions needed to be considered for the three second-order factor loadings. Since the second-order loadings are comparably less certain to predict than that of the first order loadings, they are initiated with the normal distribution of mean 0.6 and larger variance of 1.0. Other specifications remained the same and estimation process was conducted for the second-order model using the Bayesian approach in the Mplus software. Two Markov chains were used along with 60,000 iterations. Figure 7.7 presents the summary of results from the Bayesian CFA.



Note PPC – Posterior Predictive checking. The scatters indicate a pair of observed and replicated observations. (Model choice parameter DIC = 4756)

Figure 7-7 Summary of model fit statistics for PPC - Hypothesis 2

The analysis from Bayesian standpoint gave credible, empirical evidence to the formulation of a second-order construct as the PPC p-value came out to be 0.077 indicating that model fit was adequate. Moreover, the two Markov chains also converged since PSRF was close to 1. Both the first order and second order factor loadings were significant and above 0.5. As such, the results demonstrate that hypothesis 2 is valid and cannot be rejected. It can be inferred that inclusion of a second-order construct analogous to a CIM maturity explains the multi-dimensional nature of CIM implementation across CGP, TWP, and OHR dimensions, as postulated in some qualitative studies on CIM literature. The DIC of the model, which is a relative metric used for model comparison, was observed to be 4756.

In the presence of two competing hypothesis and two different estimation approaches, it becomes necessary to perform model selection for identifying the model that best represents the data. This step is necessary to also extract the factor loadings that can be used to ascertain the relative importance of the 16 CIM attributes. This procedure is explained next.

7.5.3 Model Identification and Importance Scale Determination

Both the first-order and second-order measurement models were estimated using Bayesian approaches. These two hypotheses were both statistically valid and support the assumptions in the literature about the multidimensional nature of CIM maturity. Hence, these models were compared using Deviance Information Criterion (DIC) to select the model that is a better alternative. DIC remains the commonly accepted metric for comparing the goodness of multiple models estimated using the Bayesian approach (Muthen and Muthen 2012). The first-order model had a DIC of 5003 while the second order model had DIC of 4756. While absolute value of DIC holds little relevance, the model with smaller DIC is preferred among a set of competing models. Thus, the second-order measurement model was selected as it also complies with the theory of a general, unifying CIM maturity underlying the three major dimensions, namely technology, contract, and organization. Table 7.2 shows a detailed summary of the factor loadings and the posterior estimates for the second-order measurement model.

Table 7-2 Final CFA model - Posterior estimates of the standardized factor loadings

Factor loadings	EAP**	S.D.	95% C.I.		Factor Score Coefficient
			2.50%	97.50%	
CGP	BY				
Formalization of technical standards/specs.	0.773	0.04	0.686	0.844	1.114
Contract precedence for CIM practices	0.889	0.027	0.83	0.934	0.740
Alternative Delivery Methods and ATCs support	0.642	0.057	0.521	0.744	0.723
State or federal laws and agency rules pro-CIM	0.736	0.046	0.635	0.817	0.005
Interoperable software for data integration	0.692	0.053	0.58	0.785	0.356
Strategic changes to bidding policies	0.795	0.038	0.714	0.86	0.904
Digital handover plan for O&M	0.705	0.049	0.599	0.792	0.386
TWP	BY				
Sensing practices for digital data collection	0.622	0.063	0.488	0.734	0.293
Collaborative 3D design	0.745	0.049	0.638	0.832	0.771
AMG for construction and digital QA/QC practices	0.8	0.044	0.704	0.875	1.214
Digital hardware and software for Project Management	0.531	0.072	0.382	0.662	0.574
Electronic and digital archival practices for assets	0.578	0.067	0.436	0.699	0.127
OHR	BY				
Agency-level Implementation plan for CIM	0.802	0.042	0.712	0.874	1.343
Training for design, construction, and field staffs	0.705	0.052	0.593	0.798	0.875
Culture of innovation and leadership buy-in	0.739	0.051	0.628	0.829	0.502
Budget availability and financial commitment (CIM)	0.791	0.045	0.693	0.868	0.656
CIM Maturity	BY				
CGP	0.884	0.044	0.791	0.962	0.452
TWP	0.953	0.03	0.886	0.996	0.415
OHR	0.898	0.04	0.811	0.967	0.271

Note: ** EAP – Expected Aposteriori estimate. The loadings had a one-sided p-value of 0.00. S.D. – Standard Deviation; C.I. – Credible Intervals

The analysis results provide interesting insights from an empirical standpoint. First, The 95% credible intervals are positive and do not include zero suggesting that there is a significant positive association between the loadings and the factor. The impact and the direction of the relationship between CIM attributes and their parent factors are consistent with the assumptions. Secondly, The TWP factor had the highest second-order loading of 0.953, closely followed by both the OHR (0.898) and the CGP(0.884). This suggests that while the overall CIM maturity has the highest impact on technology integration, processes and people dimensions are also equally significant and strongly associated with the former. Finally, the posterior standard deviations of the model parameters were quite small in comparison with the Expected Aposteriori Estimates (EAPs). It demonstrates the validity of the prior distributions assumed for factor loadings and also substantiates less uncertainty of the final results (as also seen from the convergence of the Markov chains).

The final goal of conducting the EFA and CFA is to produce methodical values for the relative contribution of the CIM attributes towards measuring the foundational CIM maturity. Noticeably, factor loadings are interpreted as regression coefficients for the factor in predicting the attributes. Hence, they cannot be used as a representative measure of the item in determining the factor. To address this issue, factor score coefficients are obtained since they statistically mimic relative weights of attributes or their contributions towards parent factors (Hair et al. 2010). These coefficients (**B**) are calculated by multiplying the inverse of the correlation matrix (**R**) and the loadings matrix (**A**). Equations 7.1 and 7.2 presents the mathematical foundation to obtain these coefficients.

$$\boldsymbol{B}_{first-order} = \boldsymbol{R}_{attributes}{}^{-1}.\boldsymbol{A}_{first-order} \qquad \textbf{Equation 7.1}$$

$$\boldsymbol{B}_{second-order} = \boldsymbol{R}_{first-order}{}^{-1}.\boldsymbol{A}_{second-order} \qquad \textbf{Equation 7.2}$$

At first, the coefficients are calculated at the first-order level using the correlations of the CIM attributes and their respective loadings to CGP, TWP or OHR. Subsequently, the second-order coefficients are obtained using the correlation of the first-order factor scores and their respective loadings to CIMM. It is important to note that the factor score coefficients would not necessarily add up to 1 as they imply a regression equation of attributes in determining their parent factor scores. Table 7.2 displays the coefficients obtained as per this method.

7.5.4 Usage Scale Determination

The original survey provided information on the measured CIM attributes on two scales – Relative importance to CIM workflow and actual usage level at agencies. All the 128 valid responses were utilized to evaluate the relative weights of each of the contributing attributes (using Factor Score Coefficients). This section presents the analysis of actual usage data. 91 responses were collected from agency experts pertaining to the usage levels from 41 state agencies in the U.S. 21 agencies had multiple respondents for the survey. Agencies with multiple raters were only used for usage assessment. The presence of multiple raters provide opportunities to systematically test the consensus on usage levels beyond chances or biases among raters. When analyzing responses of multiple raters on the same subjects (16 CIM attributes), the consensus is quintessential on the extent of CIM implementation since it represents the frequency of actual usage.

The reliability of usage scale ratings has been tested using Cohen's kappa statistic to infer on the level of agreement between two raters responding from the same agency (Fleiss and Cohen 1973). The statistic was later extended to test the cases that involved more than two raters using the generalized kappa statistic. Table 7.3 summarizes the results of the analysis for the six agencies that had statistically significant and reasonable consensus beyond chance. Hence, usage data reported from experts at these agencies were only considered for further analysis for maturity assessment. The usage ratings of these six agencies were averaged across raters to produce final values for all the 16 attributes under consideration.

Table 7-3 Inter-rater reliability test results for CIM attributes usage levels at agencies

State	No. of raters	Generalized Kappa	T-statistic	p-value
AZ	2	0.204	1.689	0.091
MI	2	0.431	3.477	0.001
OH	2	0.464	3.441	0.001
IA	3	0.195	2.7	0.007
MT	4	0.151	2.75	0.0059
VT	4	0.139	2.31	0.0209

7.5.5 Demonstration of Maturity Calculation

The CIM maturity should encompass both the technological expertise of an agency and process-related support implemented to promote its widespread implementation. Thus, a general CIM maturity score was calculated for an agency by weighing the usage levels of attributes with their relative contribution towards CIM workflow. The calculation is hierarchically carried out at the two levels as described by the CIM maturity model. First, weighted usage scores are obtained for the three factors TWP, CGP, and OHR based on factor score coefficients (first-order) and usage level of 16 attributes. Subsequently, the overall CIM maturity was calculated based on the second-order factor coefficients and the calculated usage score of the first-order dimensions. Equation 7.3 provides a mathematical description of the calculation of the CIM maturity score.

$$CIM\ Maturity\ score_{agency} = \underbrace{\sum_{i=1}^{3}(R.I.)_i}_{\text{Second-order aggregation for overall CIM maturity}} * \underbrace{\sum_{j=1}^{n_i}(R.I.)_j * U_j}_{\text{First order aggregation for TWP, CGP, and OHR factors}}$$ **Equation 7.3**

Where, j represents the CIM attributes; i represents the three first-order factors; n_i denotes the number of attributes under the factor i; $(R.I.)_j$ represents the relative importance of the CIM attribute j towards the parent factor; U_j represents the average actual usage of the attribute j; $(R.I.)_i$ symbolizes the relative importance of the factors to the CIM maturity.

Table 7.4 provides the scores of the selected agencies along the three factors and also the overall CIM score of the agencies. The maximum and minimum usage are pre-defined Likert scale inputs (1 to 6) and are included for comparative reference. Aggregation at the first-order level can provide important insights and provide opportunities to visualize and interpret the utilization across the major dimensions. Reconciling at the second-order was aimed at creating a unidimensional construct that can both comprehensively represent the utilization of all the major dimensions and at the same time act as a summary reporting measure for an agency's CIM implementation practices. These scores are calculated for the six agencies that reported consistent responses on usage scale based on Kappa test. It is conceptually possible to extend this approach towards benchmarking CIM practices of any agency.

Table 7-4 Component scores and CIM maturity calculations for the selected States

Relative Importance (FS Coefficients)	Average Usage scales (U_i)						Limits from survey Likert scale	
	AZ	**MI**	**OH**	**IA**	**MT**	**VT**	**Max scale**	**Min scale**
0.293	4	4.5	2	4.33	3.75	3	6	1
0.771	3	4.5	3	4	3	1.5	6	1
1.214	4	5	3	4	2.75	3.25	6	1
0.574	4.5	5	5	5	2.75	3.5	6	1
0.127	5	4.5	3	3.33	2.5	3	6	1
TWP score =R.I * usage	**11.56**	**14.30**	**9.79**	**12.50**	**8.65**	**8.37**	**17.87**	**2.98**
1.114	2	3.5	3	4.67	2.25	1.75	6	1
0.74	1.5	2	1	4	1.5	1	6	1
0.723	1.5	2.5	1	2.33	1.75	1.5	6	1
0.005	1.5	3.5	3.5	5.33	2	1.25	6	1
0.356	2	2	1	5	2.75	1.5	6	1
0.904	2.5	2	1	4.33	2	1	6	1
0.386	1	1	1	1.33	1.25	1	6	1
CGP score = R.I *usage	**7.79**	**10.11**	**6.45**	**16.08**	**8.16**	**5.60**	**25.37**	**4.23**
1.343	2.5	4	1.5	3	2.75	1.25	6	1
0.875	2	4	2	4	3	2	6	1
0.502	2.5	4	2.5	4.33	4.5	2	6	1
0.656	1.5	4	2	4	2.5	2.5	6	1
OHR score = R.I.*usage	**7.35**	**13.50**	**6.33**	**12.33**	**10.22**	**6.07**	**20.26**	**3.38**
CIM Maturity (Rounded)	**10**	**14**	**9**	**16**	**10**	**8**	**24**	**4**

Note: CIM maturity score = TWP score x0.415 + CGP score x 0.452 + OHR score x 0.27

The component scores for the three factors and the overall CIM maturity scores provides critical insights into the major CIM implementation opportunities at the six agencies. Overall, Iowa DOT emerged as the agency with the highest maturity score owing to its strong emphasis on both technology integration and streamlined implementation of process issues. Noticeably, Michigan DOT came second although it had scored the highest for technology integration. The individual component scores indicate the scope for improvements in contract and governance factors to regularize their CIM practices. Vermont DOT displayed lower usage of CIM among all the three major dimensions indicating many potential attributes for further improvements. The scores are also visualized for making further interpretations (Figure 7.8). Since the scales are composed of different limits, they are transformed to a 0 to 1 scale to ensure uniformity and consistency for visualization.

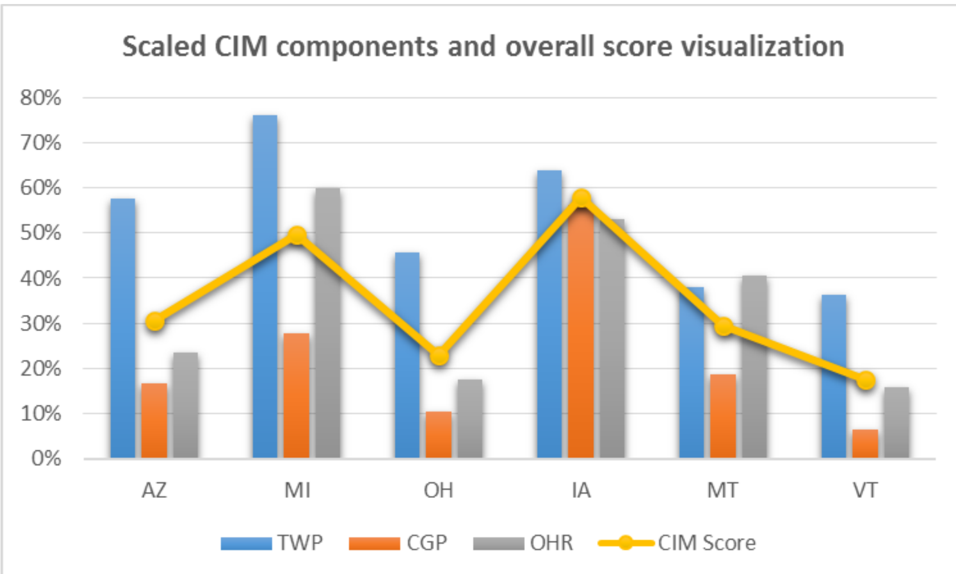


Figure 7-8 Visual representation of CIM components and maturity

Visual demonstration further augments the empirical validity and practical utility of the model. The model indicates that CIM initiative is primarily driven by the TWP factor as the agencies had comparatively scored more on it than CGP or OHR. This is a tenable implication since the long-term transformation in the agencies' processes and policies are preceded first by testing new CIM tools and deciding on the continued use of it. The model also shows that ensuring a good overall CIM score is also contingent on significant scorings on the process-related factors, as seen in the case of Iowa DOT. Arizona DOT and Michigan DOT scored less due to the lower level of implementation of the attributes pertaining to the CGP factor. The visual output and maturity assessment were presented to the CIM experts and the CIM champions of the respective agencies and they concurred with the interpretations of the results.

7.6 DISCUSSION OF THE MATURITY FRAMEWORK

This section further elaborates on the validity of the model based on how it supports and extends the current studies and deepens the understanding of measuring CIM maturity. It also demonstrates the model's applicability by providing guidelines for agencies trying to benchmark their current CIM practices and working towards identifying areas for improvement.

Theoretically, the CIM model was regarded consistent and comprehensive as it complies with key factors identified for technology integration across different subject areas (such as Information Technology, BIM, sensing technologies). The maturity framework essentially comprises of three major factors. The TWP factor deals with implementing transformative digital products across the asset lifecycle. The CGP factor covers the process goals and objectives that enable coordinated implementation of the technical practices. The OHR factor includes the people and the organizational requirements. In summary, the maturity model of this study aligns with the vetted people, process, and product (PPP) model for evaluating new practices across many industries. The multidimensional nature of CIM maturity can further be supported by comparing similar studies in BIM. For instance, Succar's BIM maturity matrix assessment was evaluated across three major constructs – technology, process, and policy (Succar 2009). The Smart market report on BIM for infrastructure in North America also provided evidence to substantiate the major factors that influence digital technology for highway sector (Dodge data & analytics 2012). The major issues requiring investments were reported to be "Interoperable software", "Upgraded hardware". "Collaborative CIM processes", and "Training". The first two issues directly align with the Technology (TWP) factor of this study while the others cater to process (CGP) and people

(OHR) dimensions respectively. Chen et al. (2014) developed measurement model for BIM maturity that identified similar factorial structure underlying the key attributes. The constructs of this study are also consistent with the primary factors impacting BIM implementation enlisted in international BIM standards and the state of practice of major countries including Canada, U.S., Europe, U.K, and Singapore (Bernstein et al. 2010; BCA 2014; Cheng et al. 2016). In summary, the maturity model proposed in this study uniquely contributes by formalizing a measurement adapted to meet the requirements of the highway sector. The study also leveraged the capability of a Bayesian approach to integrate the prior beliefs in CIM literature and the knowledge from the CIM experts who participated in this study.

The framework also has considerable practical utility for public agencies in the highway sector. The model rated Iowa DOT with the highest maturity owing to its holistic adoption of both technological and process-related practices. This inference augurs well with other studies and guidelines that demonstrate the capability and the commitment of the agency in standardizing the integration of digital workflow (Iowa DOT 2014; Guo et al. 2014; Jahren 2014). The need for other examined DOTs such as Arizona, Ohio, and Vermont to enhance their process capabilities are also well documented in the literature (FHWA 2015b). The current state of practice indicates that the agencies are at different levels of implementation and need quantitative guidelines to benchmark CIM practices. This tool provides a blueprint for any agency to evaluate their usage of these 16 CIM attributes to arrive at an overall maturity score. This numerical summary can further be visualized along with the component scores aiding the agencies to ascertain the dimensions requiring further attention for enhancing CIM implementation. Subject to data available from multiple agencies, it is also possible to conduct comparative studies to ascertain agencies excelling in particular dimensions and foster knowledge sharing among the participating organizations.

This study illustrated the framework's implementation by six agencies that provided reliable inputs on CIM usage. Nonetheless, any interested highway asset owner can use a team of CIM experts and leverage the maturity framework to benchmark their CIM capabilities. Additional attributes can also be incorporated depending on the requirements of the agencies and their weighted importance and usage levels can be ascertained following the approach presented in this study. Such extensions can lead to the development of a comprehensive and robust tool for maturity assessment for highway asset owners.

7.7 Conclusion

The delivery of highway projects is undergoing major transformation due to the advent of digital technologies that positively impact the project and asset lifecycle. With the asset owners increasing their reliance on the CIM technologies for work processes, it calls for a need to develop a formalized framework to benchmark their current maturity to guide the industry's implementation requirements. It is also critical to quantify and model the interactions among the technology implementation and various agency factors that influence widespread usage of these tools. The primary contribution of this chapter is the development of a methodical approach to benchmark an agency's CIM maturity. This approach considers both the technological and process-related dimensions in formulating an overall CIM maturity score of an agency. The collective opinion of the subject matter experts across the industry (academics, engineers, highway agencies, contractors) was utilized to determine the relative importance of the key 16 CIM-related attributes. A multi-stage factor analysis technique was adopted to formulate the model and to validate the factorial structure of CIM maturity. Overall, a second-order factor model adequately described the relative contribution of the attributes and hence, was used to construct a general maturity score representative of all the dimensions.

The work presented in this study can be extended further as it presents opportunities for further improvements. First, the proposed survey design for maturity assessment saw participation from respondents across all the work areas (from surveying to operations and maintenance) and key professions (academics and industry experts). Nonetheless, the usage was benchmarked only for six STAs from the U.S. Since the factorial structure for maturity was established from both a theoretical standpoint and empirical data from this study, usage information from asset owners worldwide can be collected to extend the benchmarking processes. Secondly, the differences in the importance of attributes between experts from different professions and from different countries can be examined. Extending research on this aspect would help understand perspectives of global organizations and provide useful insights on their respective priorities for technology implementation. Finally, it would also be interesting to study the impact of the overall CIM maturity score on performance benefits. Further exploration of this topic would augment the capability and statistical sufficiency of a single score to represent the overall efficiency improvements caused by CIM at the organization level.

Chapter 8 Conclusion

This research formally incorporated and analyzed the system of digital technologies under "Civil Integrated Management". It extended the current understanding of the fundamental and emerging technologies by performing a detailed investigation of project-work processes and agency considerations. This section enumerates the major contributions of this research towards the body of literature and practice.

8.1 Intellectual Contribution

Chapter 5 scoped the principal technologies for digital practices for project delivery and asset management. This step played a major role in formalizing the workflow for CIM for researching implementation issues and challenges. The case studies examined in this study were chosen based on their successful integration of multiple CIM technologies and practices. In semi-structured interview of case study participants, this study determined major contract documents, bidding strategies, and enabling practices by phases. These unique practices were identified as vital catalysts for seamless usage of advanced CIM technologies. This step was crucial to enhance the understanding of supporting dimensions for successful integration of

Chapter 6 of the dissertation also analyzed the necessary and sufficient conditions under which CIM technologies can improve project performance. Through the implementation of Qualitative Comparative Analysis (QCA), the detailed case study data were codified to study the complex relationship between various CIM attributes and performance outcomes. The analysis supportive demonstrated the nuanced interplay between utilization of CIM technologies and the INUS (**i**nsufficient but **n**on-redundant parts of a condition which is itself **u**nnecessary but **s**ufficient for the occurrence of the effect) nature of the supportive dimensions for explaining the reported performance measures. The study also makes a unique contribution to the adoption of a novel methodical approach to delineate the affirmative impact of technology implementation on project performance.

Finally, Chapter 7 study proposes a framework for measurement model of CIM maturity. This chapter integrates the lessons learned and implications from previous chapters of this dissertation and tackles an important issue for assisting widespread implementation of CIM. The study conceptualizes a factorial structure for benchmarking CIM maturity and leverages advanced statistical models to validate and quantify the relationship between measured CIM attributes and a holistic maturity measure. The study makes an incremental contribution to the body of knowledge by establishing a second-order maturity model for CIM benchmarking, a repeatable and reusable tool to assist agencies in systematically measuring their CIM capabilities. From a methodical standpoint, it integrated the knowledge in the literature using a reliable Bayesian framework for model estimation and maturity calculations.

8.2 CONTRIBUTIONS TO PRACTICE

The unique CIM practices and enumeration of specifications can provide owner-agencies and contractors a checklist of key implementation resources. It can serve as a comprehensive reference for various stakeholders interested in using one or more CIM practices. Furthermore, the findings included innovative bidding policies, enabling contract specifications, and a reconciliation of key CIM standards. Investing in these resources and practices, an agency can increase the level of utilization of CIM technologies.

Factorial interactions in the CIM pathways and Presence of non-CIM causal pathways confirms that CIM is neither always necessary nor individually sufficient. The findings that reduction in RFIs, design and construction changes needs to be augmented with process-related factors emphasize the need to focus on CIM integration with work process for realizing the expected performance. More specifically, technical standards, contract specifications, and agency's managerial strategies have to be favorably and intrinsically aligned with CIM technologies usage on projects. This implication is of particular interest to project management professionals who should be key participants in creating necessary changes in work practices for CIM integration.

The attempt to quantify and measure CIM maturity can yield a latent CIM maturity score that can benchmark an agency's current capabilities. This measure can help various decision-makers, dealing with technology investments and project management, select appropriate dimensions/attributes to focus on enhancing the opportunities for integrating CIM technologies and practices in their agency.

8.3 FUTURE RESEARCH

CIM entails a system of digital technologies and practices that enhance work processes across the facility lifecycle. The studies presented in this dissertation analyze some of the key questions involved in the beneficial implementation of CIM. It will be intriguing to formulate a system-of-systems (SoS) framework interconnecting various phases of an asset lifecycle and hierarchically classifying the implementation levels at agencies (such as State, District, Area, Projects). Each phase/discipline of project delivery can be justifiably modeled as a system since they are managed by different offices and workforce. Nonetheless, they are inter-connected and functionally dependent on each other for various information for managing the asset. Hence, theorizing CIM as a SoS would give broad consideration to implementation benefits and challenges at different levels (technology, processes, people, office, field work, etc.). It can produce a realistic assessment of workflow impacts and return-on-investment for intervention using a particular technology.

This dissertation established the latent and multi-dimensional nature of a CIM maturity measure. The proposed metric has been validated in the context of its theoretical relevance and the practical utility. It would be interesting to evaluate the reliability of this unifying metric based on its ability to capture and determine the performance measures at the agency-level. The CIM experts, who responded to the maturity survey, provided their assessment on the perceived benefits of CIM using a Likert Scale (evaluated metrics include a reduction in RFIs and Contract Change Orders, quality improvements, cost savings due to a reduction in design conflicts, schedule savings due to productivity improvement etc.). The future goal is to develop a latent regression model that directly relates the CIM maturity and performance improvements. Testing this hypothesis would provide interesting insights on the statistical adequacy of the metric and the extent to which it explains the variability in reported performance measures. Furthermore, representatives from senior management and executives often make crucial decisions on technology or workflow investments depending on their collective perception of the significance of the tools or practices under consideration and the likelihood of the success of proposed measures. As such, it would be intriguing to evaluate how stakeholders at various organizations (agencies, contractors, and consultants) perceive differently the relative importance of the CIM attributes. Evaluation of differences in perceptions of various stakeholders can reveal interesting trends in terms of priorities of participating entities. It will then be possible to research and propose policy measures that are targeted and valuable for specific organizations (such as owner agencies, regulatory

The CIM maturity model proposes significant stride in an emerging paradigm (CIM) for highway project delivery and asset management. It also advances the body of knowledge in the area of maturity assessment by methodically accounting for prioritization of technical and process-related factors. In its current state of development, this maturity model can specifically identify the critical CIM attribute measurable at the organizational level that requires attention to improve overall CIM maturity. Devising specific policy-measures to work upon the identified attributes will be a significant extension that can further enhance the value and the utility of the maturity model presented in this study. Agencies can then utilize this tool to benchmark, identify, and delineate policy measures to enhance their overall CIM score. Addressing the holistic CIM maturity help agencies overcome vital process- and people-related challenges and maximize the anticipated performance benefits, in a predictable manner, on their projects.

Another interesting proposition is to expand the implementation of the maturity framework with the reliable usage data from all the 50 State agencies in the U.S. While this study demonstrated the maturity assessment with six agencies, collecting and reconciling information from more DOTs would enable systematic benchmarking of CIM across all the transportation agencies. A thematic CIM maturity map can then be developed (similar to Figure 3-3) to identify expert agencies by specific attributes, first-order factor level maturity for the three dimensions, and the second-order CIM score. This step would promote sharing of best practices and implementation strategies across agencies and evolve as a mutually beneficial measure for all the participating agencies in the long term.

Selection of technologies for widespread usage at an organization level should also be based on the business case and added value for all viable alternatives. While it is often challenging to accurately quantify the benefits of CIM tools, there is still a broader consensus, among both the academic experts and the practitioners, on the need to investigate the Return-on-investment (ROI) for CIM. It will be beneficial to conduct research on ROI using Multi-Criteria Decision Making (MCDM) methods that integrate both subjective (such as usability, standardization, etc.) and objective metrics (cost-benefit assessment for the technology) with appropriate consideration for other economical parameters relevant at the organization level.

List of Appendices

Appendix A GENERALIZED LINEAR MODEL SPECIFICATIONS

The surveys included questions intended to capture the extent to which CIM utilization was impacted by technical, managerial, and legal factors. Several managerial, organizational, and policy factors were identified to see whether they had a statistically significant impact on the usage level of CIM technologies. Table A-1 lists the factors, covariates, and dependent variable considered for the analysis. The predictor variables are collected during the survey, whereas the dependent variable (CIM score) was formalized by evaluating the responses. Design-in-house was treated a random effect as its two categories (less than equal to or more than 50%) were not fixed prior to the survey. Similarly, availability of guidelines was also treated as a random effect since the ordinal categories were not formalized (or fixed) prior to the data collection process.

Table A-1 List of variables for statistical analysis

Variable	Name/Description	Type
Factors (Fixed)	-Alternate Project Delivery Methods (D-B/PPP/CM/GC) - Contract specifications (Contractual) - CIM-related Federal or state regulations (FederalReg) - Investment research (ROIr) - CIM Integration with project controls (CIMInt)	Ordinal Dichotomous
Factors (Random)	Design-in-house (DIH)	Ordinal Dichotomous
	Availability of guidelines (Guide)	Ordinal polytomous
Covariate	Agencies budget (Budget)	Continuous ($)
Dependent variable	CIM usage score (CIM_{UI})	Count (1-18) or Class (1-3)

The response variable is an aggregated ordinal measure and represents the cumulative number of CIM technologies an agency has used on one or more of its project. Thus, it can be interpreted as count measure. Hence, Generalized Linear Model (GLM) is used to understand the effects of factors and covariates on the usage level in this case. The general mixed model for this specification is as follows:

$$g(CIM_{UI}) = \alpha + \beta_1 * Budget + \beta_2 * DIH + \sum_{i=3}^{7} \beta_i * Guide_i + \sum_{i=8}^{n} \beta_i * Fixed_i$$

Equation A-1

Where, α represents the intercept of the model.

β_i's represent the coefficients of the covariate, random effect, and fixed effects respectively

$g(CIM_{UI})$ represents the appropriate link function for the dependent variable representing expected CIM usage

Preliminary analysis of data revealed that including as many predictors of interest may cause issues with respect to parameter estimation process due to less sample size of the study. Thus, non-parametric association measures and stepwise regression procedures were used to identify the final predictors for the study. Stepwise regression can be used to screen for predictors to be included in the final mixed models, dropping statistically insignificant predictors While stepwise regression is not completely appropriate for GLMs, it provides a methodical framework to identify simpler and efficient models that explain considerable variability in the dependent variable given the limitations of sample size and dimensionality issues. Table A-2 summarizes the numerical results of the screening process.

Table A-2 Summary of results - screening tests for predictors for GLM

Correlation with CIM_UI		Multiple linear regression for CIM_UI(Stepwise_final)			
Attribute	**Spearman r**	**Attribute**	**Estimate**	**p-value**	**VIF**
Budget	0.346*	PPP	2.785	0.013**	1.136
DIH	-0.131	Guide	0.834	0.016**	1.136
Guide	0.547**	**Model fit summary**			
ROIr	0.236	**R**	**Adjusted R^2**	**F-Value (ANOVA)**	**p-value**
Contract	0.345*	0.678	0.459	10.615	0.000**
D-B	0.036				
PPP	0.590**				
Federal reg	0.207				
CIMInt	0.225				

** - Significant at 0.05 level; *- Significant at 0.1 level

The screening process suggests that the major attributes that can be included in the GLM as predictors are: agency budget ($), Availability of Guidelines, and Contract specifications. The final model specifications for GLM is

$$g(CIM_{UI}) = \alpha + \beta_1 * Budget + \beta_2 * PPP + \beta_3 * Contract + \sum_{i=4}^{8} \beta_4 * Guide_i$$

Equation 2

1. **Link functions for GLM**

The form of functional transformation that the dependent variable can assume is called link function. In this study, the CIM usage can be interpreted as an aggregated ordinal measure obtained by summing up different technologies used by a STA. Thus, the log-linear link can be used for the variable, and the GLM becomes a Poisson log-linear regression. Furthermore, as seen in the state-wise CIM summary, it is also reasonable to classify the score into three ordinal categories – low (1-6), medium (7-12), and high (13-18). Agencies appear to exhibit a clear distinction in the average usage of CIM clusters for work processes as defined by the three levels. Thus, the effects model can also be investigated with a "class" based dependent variable. Accordingly, ordinal logit link can be used to study the influence of different predictors on CIM. Equation 2 takes in specific forms with the link functions substituted as shown in Table 4.

Table A-3 Link functions for the GLM

Link function	Final Model Description
Poisson log-linear model	log $(CIM_{UI}) = \alpha + \beta_1 * Budget + \beta_2 * PPP + \beta_3 * Contract + \sum_{i=4}^{8} \beta_4 * Guide_i$
Ordinal logistic regression	log $(\frac{p_j}{1-p_j}) = \alpha + \beta_1 * Budget + \beta_2 * PPP + \beta_3 * Contract + \sum_{i=4}^{8} \beta_4 * Guide_i$

Where p_j is the probability of observing the class j or above;
α_j represent the intercept threshold for the three classes. For this model there will be two thresholds, one separating class 1 and 2, and the other class 2 and 3.
β_i's represent the coefficents of the covariate, random effect, and fixed effects respectively.

2. Model estimation and results

The model specifications were estimated in SPSS software to study the effects of the predictors and the model fit. The set of predictors tried in the model include only those listed in Equation 2. Several trials were conducted to test both the main effects and interactions. Some predictors were either statistically insignificant or tend to inflate the Standard errors in the estimate of significant estimates. These attributes were dropped and the results of the final, parsimonious model were presented in Table A-4. As can be seen, the overall model is statistically significant, implying that the predictors were able to explain considerable amount of variability on the level of CIM

Table A-4 Summary of results – Poisson log-linear formulation

Poisson log-linear model - Parameter estimation results			
Variable	**Coefficient (β)**	**Wald Chi-square**	**p-value**
PPP	0.231	3.780	0.050**
Guidelines =1	0.377	5.239	0.022**
Guidelines =2	0.304	4.204	0.040**
Guidelines =3	0.310	2.374	0.123
Guidelines =4	0.056	0.092	0.762
Model – Goodness of fit results			
Likelihood ratio-chi square		17.891	
p-value		0.007**	
Over-dispersion measures			
Deviance (value/df)		1.271	
Pearson chi square (value/df)		1.141	

**- statistically significant effect at 0.05 level;

The predictor for PPP and guidelines, until a maximum of two, produced statistically significant impact at 0.05 level of confidence. Over-dispersion metrics closer to one indicate the conformity to the assumptions of Poisson regression. This simpler model also resulted in significant estimates, better model fit, and lower values of comparative model measures such as Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) in comparison to the other models. Thus, this model was retained as appropriate.

A similar procedure was followed for the logistic regression model. The initial model formulated with the screened predictors suffered from "quasi-completion" effect, where the outcome variable separated one or combination of predictor variables to a considerable degree. Thus, the MLE parameter estimates for the models were not obtained. Considering the sample size and the complexity of the issue, it was considered appropriate to drop the statistically insignificant predictors to obtain a simpler, effective model. The final model, thus obtained, had PPP, contract, and interactions between them (Table A-5).

Table A-5 Summary of results – ordinal logistic regression

Ordinal logistic regression model - Parameter estimation results			
Variable	**Coefficient (β)**	**Wald Chi-square**	**p-value**
PPP	2.087	3.810	0.055*
PPP=0*Contract=1	1.952	4.490	0.034**
PPP=1*Contract=0	1.794	1.719	0.190
Model – Goodness of fit results			
Likelihood ratio-chi square		19.624	
p-value		0.000**	

** - Statistically Significant results at 0.05 level. ; *- statistically significant at 0.1 level.

Interestingly, ordinal logistic formulation produced a slightly different model than Poisson regression. PPP usage still had statistically significant effect on CIM usage. Formalization of contract clauses could not produce a stand-alone impact on CIM usage; rather it had a significant impact through interaction with PPP, in cases where the latter is absent. One possible statistical reason for this anomaly is plausible multicollinearity issue of this attribute with the major predictor (PPP).

Appendix B PROJECT SURVEY QUESTIONNAIRE

The purpose of this survey is to document the methods and lessons learned from projects and agencies that implement digital project delivery and asset management methods in order to incorporate them as part of the NCHRP project 10-96 a *Guide for Civil Integrated Management (CIM) in the Departments of Transportation*.

Definition of Civil Integrated Management (CIM)

Although there are several terms that are used to describe the overall concept of digital project delivery and asset management such as CIM and building information modeling (BIM) for infrastructure, for the purpose of this survey we will define CIM as the term for transportation infrastructure projects that encompasses a wide range of practices, methods, and technologies that entail the collection, organization, and management of information in a digital format. This broad definition is broken down into 4 main categories with *examples that include, but are not limited to*:

- **2D**
    - 2D Plan sets in the field during construction

- **3D / nD**
    - 3D Visualization during construction (e.g., isometric drawings, physical models, etc.)
    - 3D CADD
    - 4D Modeling Analysis (3D + schedule)
    - 5D/nD Modeling Analysis (model-based quantity takeoff/model-based cost estimating)
    - Work Packaging Software / Advanced Scheduling

- **Sensing3D / nD**
    - 3D Imaging (e.g., LiDAR, photogrammetry)
    - Geographical Information Systems (GIS)
    - Global Positioning Systems (GPS)
    - Intelligent Transportation Systems (ITS)
    - Field Sensors (e.g., RFID, ground penetrating radar, ultrasonics)
    - Intelligent Compaction
    - Automated Machine Guidance and Control (AMG)
    - Utility Engineering / Clash Detection / Coordination

- **Data Management**
    - Electronic archival and updating of plans

- Digital Asset Management
- Materials Management System (e.g., Spreadsheets and RFIDs)
- Mobile Digital Devices for onsite applications (tablets, smart phones, etc.)
- Data Connectivity Other than Cellular Towers
- Digital Signature

Are there any additional projects within your agency, or the agency you work with, that you recommend we contact regarding their use of CIM?

Project Name: Click here to enter text.
Contact (Name/Email/Phone): Click here to enter text.

Project Name: Click here to enter text.
Contact (Name/Email/Phone): Click here to enter text.

Project Name: Click here to enter text.
Contact (Name/Email/Phone): Click here to enter text.

Project Name: Click here to enter text.
Contact (Name/Email/Phone): Click here to enter text.

I. Respondent Specific Questions

Name: Click here to enter text.

Title: Click here to enter text.

Agency/Company Name: Click here to enter text.

Address: Click here to enter text.

City: Click here to enter text. State: Click here to enter text. Zip: Click here to enter text.

Phone: Click here to enter text. Fax: Click here to enter text.

E-mail: Click here to enter text.

1. What is your primary area of work (check all that apply)?
   - ☐ Design
   - ☐ Construction
   - ☐ Operations
   - ☐ Maintenance
   - ☐ Other, please describe: Click here to enter text.

2. What discipline do you work in (check all that apply)?
   - ☐ Construction
   - ☐ Planning and Programing
   - ☐ Roadway
   - ☐ Structures
   - ☐ Utilities
   - ☐ ROW
   - ☐ Materials
   - ☐ Drainage / Hydraulics
   - ☐ Geology/Geotechnical
   - ☐ Environmental
   - ☐ Contracts & Estimates
   - ☐ District / Region field personnel
   - ☐ Executive
   - ☐ Other, please describe: Click here to enter text.

3. How many years of experience do you have in the industry? Click here to enter text.

II. Project Characteristics

If you are unsure or a specific question does not apply, please skip.

a. Project Overview

Project Title: Click here to enter text.

Project Location: Click here to enter text.

Project and/or contract ID: Click here to enter text.

4. What was the project delivery method?
   - ☐ Design Bid Build
   - ☐ CM/GC
   - ☐ Design Build
   - ☐ Design Build Operate Maintain (agency retains ownership)
   - ☐ Public Private Partnerships (P3)/Concession (outside party owns/operates for concession period)
   - ☐ Other, please describe: Click here to enter text.

5. What is the type of project site?
   - ☐ New Construction –Road Surface (e.g., lane expansion, new route, realignment)
   - ☐ New Construction – Structure (e.g., bridge)
   - ☐ Maintenance – (e.g., repaving and guardrail repair)
   - ☐ Other, please describe: Click here to enter text.

6. What is the construction contract payment type?
   - ☐ Lump sum
   - ☐ Unit Price
   - ☐ Time and Materials
   - ☐ Other, please describe: Click here to enter text.

7. What is the size of the project in terms of contact value (Note: This excludes ROW acquisition and O&M cost)? Click here to enter text.

8. Approximately what percentage of the project (as it relates to construction cost only) are the design costs? Click here to enter text.

9. What was the primary driver(s) behind the deployment of CIM on this project?
   - ☐ Owner/agency requirements
   - ☐ Contractual requirement/incentives
   - ☐ Contractor participation/innovation
   - ☐ Project requirements/constraints
   - ☐ Other, please describe: Click here to enter text.

10. Was CIM required in the procurement and/or contract documents?
    - ☐ Yes
    - ☐ No

11. If CIM was utilized during design, was this information shared with the contractor?
    - ☐ Yes

☐ No

12. What project phases were CIM technologies deployed (include future planned uses and check all that apply)?
    ☐ Planning
    ☐ Design
    ☐ Procurement
    ☐ Construction
    ☐ Operations
    ☐ Maintenance

13. Was there a specific requirement for data handover at the end of the project or at specific milestones?
    ☐ Yes
    ☐ No

14. Were guidelines and specs for implementing CIM techniques incorporated in the Project Execution Plan?
    ☐ Yes
    Check all that apply:

    ☐ Defining what software/technologies will be used
    ☐ Defining who will own/manage the data
    ☐ Describing how the technologies will be deployed
    ☐ Developing specifications for level of detail
    ☐ Determining how the data will be archived
    ☐ Determining what training will be provided if any
    ☐ Other, please describe: Click here to enter text.
    ☐ No

b. TECHNOLOGIES USED

15. Was model information (e.g., existing model/LiDAR point cloud data) provided to contractor pre-bid?
    ☐ Yes
    ☐ No
    a. If yes was it provided "for information only?"
       ☐ Yes

       ☐ No

16. Please characterize the level of data integration implemented on the project:
    ☐ limited use of data integration; most work performed in traditional silos; work processes are document centric (paper or electronic)

☐ moderate use of data integration; certain groups/processes benefit from data sharing; work processes are a mix of document and digital based
☐ extensive use of data integration; most groups/processes benefit from shared data; work processes are data centric

17. Which technologies were utilized throughout the project (check all that apply)?
    - **2D**
      ☐ 2D Plan sets in the field during construction
      ☐ Other, please describe: Click here to enter text.
    - **3D / nD**
      ☐ 3D Visualization during construction (e.g., isometric drawings, physical models, etc.)
      ☐ 3D CADD
      ☐ 4D Modeling Analysis (3D + schedule)
      ☐ 5D/nD Modeling Analysis (model-based quantity takeoff/model-based cost estimating)
      ☐ Work Packaging Software / Advanced Scheduling
      ☐ Other, please describe: Click here to enter text.
    - **Sensing**
      ☐ 3D Imaging (e.g., LiDAR, photogrammetry)
      ☐ Geographical Information Systems (GIS)
      ☐ Global Positioning Systems (GPS)
      ☐ Intelligent Transportation Systems (ITS)
      ☐ Field Sensors (e.g., RFID, ground penetrating radar, ultrasonics)
      ☐ Intelligent Compaction
      ☐ Automated Machine Guidance and Control (AMG)
      ☐ Utility Engineering / Clash Detection / Coordination
      ☐ Other, please describe: Click here to enter text.
    - **Data Management**
      ☐ Electronic archival and updating of plans
      ☐ Digital Asset Management
      ☐ Materials Management System (e.g., Spreadsheets and RFIDs)
      ☐ Mobile Digital Devices for onsite applications (tablets, smart phones, etc.)
      ☐ Data Connectivity Other than Cellular Towers
      ☐ Digital Signatures
      ☐ Other, please describe: Click here to enter text.

18. For the technologies used based on the previous question please check the box under the specified categories, for each stage of the project work process they are utilized (check all that apply):

	Planning and Programming	Survey and Mapping	Environmental Assessments	Design	Bidding & Procurement	Construction	Management of Traffic / Traffic Safety	Maintenance and Operations
2D	☐	☐	☐	☐	☐	☐	☐	☐
3D/nD	☐	☐	☐	☐	☐	☐	☐	☐
Sensing	☐	☐	☐	☐	☐	☐	☐	☐
Data Management	☐	☐	☐	☐	☐	☐	☐	☐

For Design, please list disciplines: Click here to enter text.

c. PROJECT PERFORMANCE MEASURES

19. Project Qualitative Assessments – For each of the following categories, rank 1 through 10 (1 no change from traditional project methods, 10 being great with no improvement possible) regarding how much CIM improved the quality of this area on your project.

    a. Project Costs: Choose an item.

    b. Project Schedule: Choose an item.

    c. Construction Safety: Choose an item.

    d. Quality and Frequency of Communication: Choose an item.

    e. Avoidance of change orders and/or RFIs: Choose an item.

    f. Other performance goals (Please name goals): Choose an item.

20. Have you ever done an internal analysis of the benefits/ROI of using any of the technologies previously discussed?

    ☐ Yes

    Please describe: Click here to enter text.

    ☐ No

III. IMPLEMENTATION AND BEST PRACTICES

21. What are lessons learned (if any) with respect to contractual requirements related to CIM? Click here to enter text.

22. In your view, what are the primary benefits derived from the utilization of CIM related technologies and methods? Click here to enter text.

23. What are the primary challenges to the utilization and implementation of CIM? Click here to enter text.

24. If there was a guide for implementation, what do you think should be included? Click here to enter text.

Appendix C CASE STUDY QUESTIONNAIRE

I. INTERVIEW AGENDA

Topic 1: Organization

In this section, we would like to discuss the implementation initiatives for CIM at your organization. Specifically, we would like to know about the availability of standards and guidelines for various CIM technologies, the kind of technologies that are used on a typical project at your organization, workforce training programs and any performance objectives for CIM at organizational level.

Topic 2: Contracts and governance

Utilizing CIM technologies on projects can impact the contractual provisions and can be subjected to legal restrictions. In this section, we would like to hear about any issues relating Project Delivery Methods and CIM. We would also like to understand the legal implications on a model-based project (issues such as ownership and copyright of models, federal/state laws, usability of digital signatures, strategies for Public Information and disclosure, responsibilities for maintaining and updating the model)

Topic 3: CIM integration with the Project Work Processes (PWPs)

Literature suggests that CIM technology implementation leads to better project performance through improving the associated work processes. In this context, we would like to understand how CIM tools are used in the project by several disciplines. (Please describe the process wherever applicable – Input, Process, deliverables, significant benefits and challenges)

- Planning and surveying process
- Identifying project scope and objectives
- Bidding and contracting process
- 3-D technology for design of roadways, bridges and other structures – specs. for Level of Detail
- Reviews (design and constructability reviews), Fabrication and approval
- Utility coordination and management – clash detection
- 4-D/5-D modeling to plan for construction - work zone traffic modeling (simulation and other tools)
- Materials and equipment procurement for construction
- Construction of roadways, bridges and other structures (AMG, IC, Stringless Concrete/Asphalt Paving)
- Functions of project controls – estimating, budgeting, change management, BOQs and payments
- Asset management

Topic- 4: CIM Lessons learned and best practices

Documenting the lessons learned and best practices and sharing them with the stakeholders will lead to effective and profitable implementation of CIM technologies in the long run. In this section, we would like to discuss the means and methods through which such practices are performed at your agency and at the project-level.

Topic – 5: CIM Performance goals and measurements

Agencies and projects using CIM have reported to be deploying a wide range of performance measures/objectives for tracking the benefits over investments. Also, the maturity level of an agency varies with different technologies and is not uniform across all available CIM tools. In this final section, we would like to know about the various project-level performance measures for CIM and the expertise of your agency with different technologies.

II. A CATALOG OF CIM TECHNOLOGIES

CIM is the terminology meant for transportation infrastructure projects and it encompasses a wide range of practices, methods, and technologies that assist in digital project delivery and asset management. This broad definition is broken down into 3 main categories with examples that include, but are not limited to:

n-D modeling: 3-Dimensional (3D) Computer Aided Drafting and Design, 3D model for visualization, 4D/5D modeling, Advanced scheduling

Sensing applications
Surveying: LiDAR (static/mobile/terrestrial), aerial survey, Radio Frequency Identification (RFID) / Ground Penetrating Radar (GPR) based mapping for utilities/other materials
Construction applications – 3D controls: GPS and model-based Automated Machine Guidance (AMG) for the construction cycle of pavements – clearing and grubbing, excavating, grading operations, paving, compacting and inspection. Specifically for CIM, this includes (but not limited to) techniques such as Intelligent Compaction (IC), Stringless Paving for Concrete/asphalt
Mobile devices for onsite applications: Technologies that include (but not limited to) smartphones, tablets and other devices
Intelligent Transportation Systems: Applications that were deployed for traffic management and work-zone traffic control

Information and data management
Stakeholder collaboration /Project Team integration: Usage of communication tools and processes that assist in efficient transaction of required information at the right time (Ex: Weekly meetings through video-conferencing, Using Bentley ProjectWise)
Digital Signatures: Usage of electronic signatures for various purposes throughout project lifecycle
Digital/Electronic Asset management: Includes practices for archival, update and maintenance of as-builts information
Material Management systems: Usage of advanced technologies and online tools to track and manage materials and equipment to the site
Document management and quality management: Using ProjectWise, AASHTOware SiteManager and other online tools for elements of project controls
This project is sponsored by the TRB and supported by FHWA and various other state DOTs. The research team appreciates your participation in this process. Further details on the project, its objectives and deliverable can be found at the project website.

Appendix D FUZZY QUALITATIVE COMPARATIVE ANALYSIS RESULTS

```
Analysis of Necessary Conditions

Outcome variable: cos_rfis

Conditions tested:
                      Consistency          Coverage
cim_ui                0.568717             0.962880


Analysis of Necessary Conditions

Outcome variable: cos_rfis

Conditions tested:
                      Consistency          Coverage
team_alignment        0.608333             0.730000


Analysis of Necessary Conditions

Outcome variable: cos_rfis

Conditions tested:
                      Consistency          Coverage
inf_mgmt_strate       0.822222             0.732673


Analysis of Necessary Conditions

Outcome variable: cos_rfis

Conditions tested:
                      Consistency          Coverage
stds_specs            0.790476             0.809756
delete variable: costs_a
delete variable: schedule_a
delete variable: safety_a
delete variable: quality_comm_a
delete variable: cos_rfis_a


Analysis of Necessary Conditions

Outcome variable: cos_rfis

Conditions tested:
                      Consistency          Coverage
```

```
fuzzy_budget          0.573333              0.746204

Analysis of Necessary Conditions

Outcome variable: quality_comm

Conditions tested:
                      Consistency           Coverage
cim_ui                0.449532              0.989418

Analysis of Necessary Conditions

Outcome variable: quality_comm

Conditions tested:
                      Consistency           Coverage
team_alignment        0.544872              0.850000

Analysis of Necessary Conditions

Outcome variable: quality_comm

Conditions tested:
                      Consistency           Coverage
inf_mgmt_strate       0.747863              0.866337

Analysis of Necessary Conditions

Outcome variable: quality_comm

Conditions tested:
                      Consistency           Coverage
stds_specs            0.664835              0.885366

Analysis of Necessary Conditions

Outcome variable: quality_comm

Conditions tested:
                      Consistency           Coverage
fuzzy_budget          0.539744              0.913232

Analysis of Necessary Conditions
```

Outcome variable: schedule

Conditions tested:

	Consistency	Coverage
cim_ui	0.493852	0.989418

Analysis of Necessary Conditions

Outcome variable: schedule

Conditions tested:

	Consistency	Coverage
team_alignment	0.598592	0.850000

Analysis of Necessary Conditions

Outcome variable: schedule

Conditions tested:

	Consistency	Coverage
inf_mgmt_strate	0.816901	0.861386

Analysis of Necessary Conditions

Outcome variable: schedule

Conditions tested:

	Consistency	Coverage
stds_specs	0.726358	0.880488

Analysis of Necessary Conditions

Outcome variable: schedule

Conditions tested:

	Consistency	Coverage
fuzzy_budget	0.597183	0.919740

Analysis of Necessary Conditions

Outcome variable: safety

Conditions tested:

	Consistency	Coverage
cim_ui	0.569239	0.931639

Analysis of Necessary Conditions

Outcome variable: safety

Conditions tested:

	Consistency	Coverage
team_alignment	0.646552	0.750000

Analysis of Necessary Conditions

Outcome variable: safety

Conditions tested:

	Consistency	Coverage
inf_mgmt_strate	0.885058	0.762376

Analysis of Necessary Conditions

Outcome variable: safety

Conditions tested:

	Consistency	Coverage
stds_specs	0.839902	0.831707

Analysis of Necessary Conditions

Outcome variable: safety

Conditions tested:

	Consistency	Coverage
fuzzy_budget	0.650000	0.817787

****

```
*TRUTH TABLE ANALYSIS*
**********************

File:  C:/Users/bs28343/Documents/Box Sync/NCHRP 10-96 Data
Analysis/QCA/QCA_dataset_v3_0831.dat
Model:  cos_rfis  =  f(fuzzy_budget,  cim_ui,  stds_specs,
inf_mgmt_strate, team_alignment)

 Rows:       3



 Algorithm: Quine-McCluskey
      True: 1
  0 Matrix: 0L
Don't Care: -

--- INTERMEDIATE SOLUTION ---
frequency cutoff: 1.000000
consistency cutoff: 0.835478
Assumptions:


                         Raw         unique
                         coverage    coverage   Consistency

----------  ----------  ----------
fuzzy_budget*~cim_ui*stds_specs*~inf_mgmt_strate*~team_alig
nment                    0.312421    0.043333    0.857812
fuzzy_budget*cim_ui*stds_specs*inf_mgmt_strate*~team_alignm
ent                      0.389127    0.134722    0.835478
fuzzy_budget*~cim_ui*stds_specs*inf_mgmt_strate*team_alignm
ent                      0.345754    0.056627    0.882955

solution coverage: 0.523809
solution consistency: 0.872381





**********************
```

```
*TRUTH TABLE ANALYSIS*
**********************

File:  C:/Users/bs28343/Documents/Box Sync/NCHRP 10-96 Data
Analysis/QCA/QCA_dataset_v3_0831.dat

Model: quality_comm = f(fuzzy_budget, cim_ui, stds_specs,
inf_mgmt_strate, team_alignment)

 Rows:      7

Algorithm: Quine-McCluskey

      True: 1

  0 Matrix: 0L

Don't Care: -


--- INTERMEDIATE SOLUTION ---
frequency cutoff: 1.000000
consistency cutoff: 0.860322
Assumptions:
cim_ui (present)


                         raw            unique
                         coverage    coverage   consistency

----------  ----------  ----------
fuzzy_budget*stds_specs*~inf_mgmt_strate*~team_alignment
                         0.290842    0.033333    0.986948
fuzzy_budget*stds_specs*inf_mgmt_strate*team_alignment
                         0.324725    0.043559    0.988294
~fuzzy_budget*cim_ui*~stds_specs*inf_mgmt_strate*~team_alig
nment                    0.342186    0.131685    0.860322
fuzzy_budget*cim_ui*stds_specs*inf_mgmt_strate
                         0.348779    0.066850    0.973503

solution coverage: 0.584066
solution consistency: 0.905151




**********************
```

```
*TRUTH TABLE ANALYSIS*
**********************

File:  C:/Users/bs28343/Documents/Box Sync/NCHRP 10-96 Data
Analysis/QCA/QCA_dataset_v3_0831.dat
Model:  safety  =  f(fuzzy_budget,  cim_ui,  stds_specs,
inf_mgmt_strate, team_alignment)

 Rows:       4



 Algorithm: Quine-McCluskey
      True: 1
  0 Matrix: 0L
Don't Care: -

--- INTERMEDIATE SOLUTION ---
frequency cutoff: 1.000000
consistency cutoff: 0.829624
Assumptions:


                         Raw         unique
                         coverage    coverage   consistency

----------  ----------  ----------
fuzzy_budget*~cim_ui*stds_specs*~inf_mgmt_strate*~team_alig
nment                    0.370731    0.043103    0.983983
~fuzzy_budget*cim_ui*~stds_specs*inf_mgmt_strate*~team_alig
nment                    0.443760    0.160673    0.829624
fuzzy_budget*cim_ui*stds_specs*inf_mgmt_strate*~team_alignm
ent                      0.434565    0.091338    0.901934
fuzzy_budget*~cim_ui*stds_specs*inf_mgmt_strate*team_alignm
ent                      0.390435    0.048235    0.963823

solution coverage: 0.722496
solution consistency: 0.832584




**********************
```

```
*TRUTH TABLE ANALYSIS*
**********************

File:  C:/Users/bs28343/Documents/Box Sync/NCHRP 10-96 Data
Analysis/QCA/QCA_dataset_v3_0831.dat
Model:  schedule  =  f(fuzzy_budget,  cim_ui,  stds_specs,
inf_mgmt_strate, team_alignment)

 Rows:       4



 Algorithm: Quine-McCluskey
      True: 1
  0 Matrix: 0L
Don't Care: -

--- INTERMEDIATE SOLUTION ---
frequency cutoff: 1.000000
consistency cutoff: 0.883346
Assumptions:


                         Raw         unique
                         coverage    coverage   consistency

----------  ----------  ----------
fuzzy_budget*~cim_ui*stds_specs*~inf_mgmt_strate*~team_alig
nment                    0.307780    0.036620    1.000000
~fuzzy_budget*cim_ui*~stds_specs*inf_mgmt_strate*~team_alig
nment                    0.385983    0.150503    0.883346
fuzzy_budget*cim_ui*stds_specs*inf_mgmt_strate*~team_alignm
ent                      0.393595    0.108987    1.000000
fuzzy_budget*~cim_ui*stds_specs*inf_mgmt_strate*team_alignm
ent                      0.330919    0.047854    1.000000

solution coverage: 0.657914
solution consistency: 0.928095
```

Appendix E QUESTIONNAIRE OF CIM MATURITY SURVEY

SURVEY - INTRODUCTION

The survey is conducted by the NCHRP 10-96 Research Team and supported by the ABJ95: CIM Subcommittee of the Transportation Research Board (TRB).

i. **Objective**

This survey is based on insights and research outputs from the NCHRP 10-96 project that resulted in an implementation Guide for CIM at DOTs (to be published shortly as NCHRP Report 831).

The objective of this survey is to capture the relativeimportance and the levelofusage of CIM practices at agencies along four dimensions - technology integration with work processes, technical standards and contract specifications, legal and policy issues, organizational and human resource alignment. Results will be used to devise a strategy to assess an agency's CIM usage and maturity.

Your participation will help assimilate interesting insights and useful guidelines for advancing CIM implementation in practice. Your responses will remain confidential. The results from aggregated analysis will be shared with all the participants.

0. PRELIMINARY QUESTION FOR QUESTIONNAIRE GENERATION

Do you work at a State Highway Agency (e.g. Departments of Transportation)?

Yes

No

Confidentiality note: Respondent's identity will be kept anonymous. The inputs will be treated as confidential data and will only be used for aggregated analysis.

1. Respondent-Specific Questions

1.1. Name

1.2. Email

1.3. Phone

1.4. Title

1.5. Organization name

1.6. What is your primary area of work (check all that apply)?

Surveying Maintenance

Design

ROW/Utilities Construction Academia/research

Operations

1.7. How many years of experience do you have in the transportation industry?

1.8. Please rate your knowledge (or expertise) with CIM technologies

Not knowledgeable at all Slightly knowledgeable Moderately knowledgeable Very knowledgeable

Extremely knowledgeable

2. CIM Maturity Assessment (DOT staffs and executives)

2.1. The questions in this table examine the key <u>digital technologies in the work processes</u> for project delivery and asset management. Please rate the following questions on two levels:

I. Relative importance to implementing CIM on capital projects (digital project delivery and asset management)

II. Frequency of actual implementation at your agency on capital projects

	Level of Importance					Frequency of usage				
	Not at all Important	Low Importance	Moderately Important	Important	Very Important	Extremely Important	No plans to use	Planned	Piloted	Occasionally Used	Frequently Every time
Usage of advanced sensing technologies (i.e. LiDAR/UAVs) to support digital data collection											
Usage of collaborative 3-D design among major design disciplines and advanced construction planning (4-D/5-d)											
Usage of Automated Machine Guidance (AMG) technology for construction, digital practices for QA/QC and as-builts verification											
Usage of Mobile digital devices , Electronic Information Management systems, digital											

signatures for document management

Usage of electronic and/or digital archival practices for asset management.

2.2. **The questions in this table address the major <u>technical standards and contract specifications</u> in enabling an agency's transition to CIM. Please rate the following questions on two levels:**

i. Relative importance to implementing CIM on capital projects (digital project delivery and asset management)
ii. Extent of availability and usage at your agency on capital projects

Updates or formalization of major technical standards and specifications (e.g. Surveying guidelines for LiDAR, 3-D design, machine-readable electronic deliverable for AMG in pavements and structures, GNSS Surveying for QA/QC and quantity checks, LOD for 3-D/4-D/5-D)

Contract precedence to CIM technologies and practices (e.g. 3-D design over 2-D plan sets, DTMs over end-area method, 3-D as builts over redlining)

Technological innovation through Alternative Technical Concepts and alternative delivery methods to support CIM

2.3. **The questions in this table address the <u>legal and policy issues</u> and their impact on planning and utilization of CIM technologies at your agency. Please rate the following questions on two levels:**

I .Relative importance to implementing CIM on capital projects (digital project delivery and asset management)

II. Extent of availability and usage at your agency on capital projects

Support to digital practices from state or federal laws, agency rules (e.g. rules on digital signatures, Ownership and copyright issues of 3D models, Conflicts and dispute resolution mechanisms)

Interoperable Software for 3-D design across disciplines and data integration across design and construction

Strategic changes to bidding policies (such as Pre-bid support/provisions for 3-D models; request utility data through contract specs.)

Handover plan for digital (3-D) data for O&M

2.4. **The questions in this table evaluate the impact of <u>organizational and human resource alignment</u> in the effort towards transitioning to CIM workflow. Please rate the following questions on two levels:**

I . Relative importance to implementing CIM on capital projects (digital project delivery and asset management)

II. Extent of implementation at your agency on capital projects

Implementation Plan for CIM technologies at organizational level with mission statements, responsibilities, initiatives, ROIs.
Training for Surveyors (GIS, sensing tools), Designers (3-D reviews and approvals, construction modeling for AMG) and field staffs (QA/QC)
Culture of innovation and leadership buy-in; learning curve recognition
Budget availability or financial commitment for CIM implementation

2.5. **From your experience at the agency and your perception, based on implementing CIM on projects, how would you assess the overall CIM maturity of your agency ?**

Baseline level (CIM completely non-existent from surveying to O&M; Agency follows traditional workflow and practices)

3.

Initial level (Beginning stage; Most of the functions and deliverable are non-CIM with limited/no utilization of CIM technologies; information integration across phases is limited)

Intermediate level (Usage of model-based tools for performing certain functions. information deliverables are matured with points of integration across phases)

Advanced level (A matured approach for project delivery where CIM-based functions dominate the project workflow with full information integration across phases)

Full effectiveness (Complete digital workflow for project delivery and asset management)

2.6. **Please rate the performance benefits that you had realized over CIM implementation. Representative benefits in literature are identified below to ensure consistency and uniformity in responses.**

Rate each metric on a scale of 1 to 7, corresponding to labels shown below

Impact on reduction in RFIs and Change orders for design and construction

Schedule savings due to improved design and onsite productivity (AMG operations)

Impact on communication and visualization for design and construction

Improved quality of work and information flow across lifecycle

Other benefits (if any)

Appendix F SPSS RESULTS FOR EXPLORATORY FACTOR ANALYSIS

Pairwise-correlation among 16 attributes

	a1	a2	a3	a4	a5	a6	a7	a8	a9	a10	a11	a12	a13	a14	a15	a16
a1	1	0.493	0.517	0.404	0.427	0.519	0.419	0.326	0.329	0.431	0.42	0.267	0.428	0.443	0.39	0.417
a2	0.493	1	0.618	0.356	0.465	0.492	0.609	0.414	0.422	0.519	0.485	0.483	0.489	0.421	0.427	0.428
a3	0.517	0.618	1	0.375	0.464	0.563	0.655	0.492	0.47	0.542	0.577	0.478	0.509	0.446	0.535	0.476
a4	0.404	0.356	0.375	1	0.606	0.401	0.468	0.392	0.371	0.256	0.346	0.357	0.389	0.369	0.49	0.459
a5	0.427	0.465	0.464	0.606	1	0.334	0.467	0.398	0.378	0.422	0.359	0.394	0.358	0.303	0.412	0.45
a6	0.519	0.492	0.563	0.401	0.334	1	0.701	0.441	0.603	0.656	0.643	0.466	0.638	0.619	0.454	0.578
a7	0.419	0.609	0.655	0.468	0.467	0.701	1	0.597	0.673	0.622	0.703	0.667	0.557	0.494	0.586	0.572
a8	0.326	0.414	0.492	0.392	0.398	0.441	0.597	1	0.46	0.383	0.452	0.498	0.518	0.335	0.494	0.52
a9	0.329	0.422	0.47	0.371	0.378	0.603	0.673	0.46	1	0.578	0.763	0.533	0.559	0.504	0.439	0.52
a10	0.431	0.519	0.542	0.256	0.422	0.656	0.622	0.383	0.578	1	0.721	0.607	0.6	0.556	0.442	0.482
a11	0.42	0.485	0.577	0.346	0.359	0.643	0.703	0.452	0.763	0.721	1	0.587	0.645	0.606	0.55	0.544
a12	0.267	0.483	0.478	0.357	0.394	0.466	0.667	0.498	0.533	0.607	0.587	1	0.506	0.421	0.441	0.523
a13	0.428	0.489	0.509	0.389	0.358	0.638	0.557	0.518	0.559	0.6	0.645	0.506	1	0.577	0.587	0.662
a14	0.443	0.421	0.446	0.369	0.303	0.619	0.494	0.335	0.504	0.556	0.606	0.421	0.577	1	0.541	0.588
a15	0.39	0.427	0.535	0.49	0.412	0.454	0.586	0.494	0.439	0.442	0.55	0.441	0.587	0.541	1	0.701
a16	0.417	0.428	0.476	0.459	0.45	0.578	0.572	0.52	0.52	0.482	0.544	0.523	0.662	0.588	0.701	1

Communalities

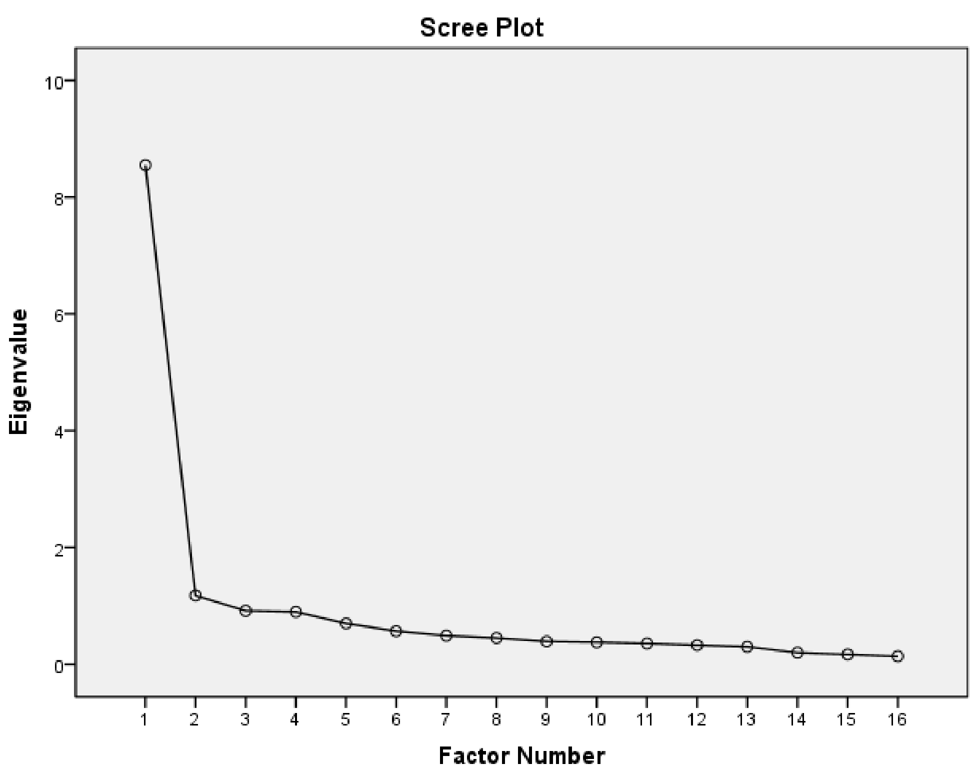
	Initial	Extraction
Importance_Sensing	.447	.363
Importance_3D_design	.532	.539
Importance_AMG_3D_QA_QC	.581	.588
Importance_digital_devices_Information_systems_DS	.530	.534
Importance_digital_archival_practices_AM	.531	.562
Importance_standards_specifications	.703	.628
Importance_contract_precedence_CIM	.774	.756
Importance_Contractual_innovation	.464	.417
Importance_state_federal_laws_impact	.653	.581
Importance_Interoperable_Software_data_integration	.674	.666
Importance_Strategic_changes_policies	.757	.777
Importance_Handover_plan	.575	.491
Importance_Agency_Implementation_Plan_CIM	.641	.667
Importance_Training	.540	.529
Importance_Culture_leadership	.640	.634
Importance_Budget_financial_commitment_CIM	.654	.736

Extraction Method: Principal Axis Factoring.

Total Variance Explained

F	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	8.550	53.437	53.437	8.161	51.004	51.004	4.324	27.024	27.024
2	1.275	7.356	60.792	.773	4.833	55.837	2.707	16.918	43.942
3	1.048	5.724	66.516	.534	3.336	59.173	2.437	15.231	59.173
4	.897	5.605	72.121						
5	.700	4.374	76.495						
6	.566	3.536	80.031						
7	.490	3.061	83.092						
8	.450	2.810	85.903						
9	.392	2.448	88.351						
10	.376	2.352	90.703						
11	.357	2.229	92.931						
12	.327	2.046	94.977						
13	.300	1.873	96.849						
14	.199	1.242	98.092						
15	.168	1.051	99.143						
16	.137	.857	100.000						

Extraction Method: Principal Axis Factoring.



Rotated Factor Matrix[a]			
	Factor		
	1	2	3
Importance_Strategic_changes_policies	.785		
Importance_Interoperable_Software_data_integration	.751		
Importance_contract_precedence_CIM	.672	.487	
Importance_state_federal_laws_impact	.654		
Importance_standards_specifications	.644		
Importance_Handover_plan	.563		
Importance_3D_design	.298	.516	
Importance_digital_archival_practices_AM		.698	
Importance_digital_devices_Information_systems_DS		.609	
Importance_AMG_3D_QA_QC	.325	.530	
Importance_Contractual_innovation	426	.	
Importance_Sensing		.421	
Importance_Budget_financial_commitment_CIM			.710
Importance_Culture_leadership		.427	.611
Importance_Agency_Implementation_Plan_CIM	.229		.580
Importance_Training	.279		.518

Extraction Method: Principal Axis Factoring.
Rotation Method: Varimax with Kaiser Normalization.

a. Rotation converged in 13 iterations.

Appendix G MPLUS CODES AND RESULTS – 2ND ORDER CIM MATURITY MODEL

```
Mplus VERSION 7.4
MUTHEN & MUTHEN
03/21/2017   5:43 PM

INPUT INSTRUCTIONS

  TITLE: INITIAL SEM MODEL - CIM MATURITY

  DATA:    FILE    IS    C:\Users\bs28343\Desktop\Mplus
project\CMAS_Indicators.txt;
        TYPE IS INDIVIDUAL;
        NOBSERVATIONS ARE 205;

  VARIABLE: NAMES ARE Y1-Y40;
            USEVARIABLES ARE Y3-Y7, Y13-Y15, Y19-Y22,
Y27-Y30;
            MISSING ARE all (9999);

  ANALYSIS: ESTIMATOR = BAYES;
            ALGORITHM = GIBBS (RW);
            CHAINS = 2;
            FBITER = 60000;
            POINT = MEAN;


  MODEL: F1 BY Y3-Y7*0.7(A3-A7);
         F2 BY Y13-Y15*0.7(A13-A15)
               Y19-Y22*0.7(A19-A22);
         F3 BY Y27-Y30*0.7(A27-A30);
         F4 BY F1-F3*0.6(B1-B3);

         Y3 WITH Y13;
         Y6 WITH Y7;
         Y7 WITH Y20;
         Y13 WITH Y20 Y28;
         Y19 WITH Y21;
         Y20 WITH Y21 Y22;
         Y29 WITH Y30;


  MODEL PRIORS:
            A3-A7 ~ N(0.7,0.35);
            A13-A15 ~ N(0.7,0.35);
            A19-A22 ~ N(0.7,0.35);
            A27-A30 ~ N(0.7,0.35);
```

```
            B1-B3 ~ N(0.6,1);

  OUTPUT:  TECH1 TECH8 STDYX;

  PLOT: TYPE = PLOT2;

  SAVEDATA: FILE IS bayesian.xlsx;
            SAVE = FSCORES(20);



*** WARNING in OUTPUT command
  TECH1 option is the default for multiple imputation.
*** WARNING
  Data set contains cases with missing on all variables.
  These cases were not included in the analysis.
  Number of cases with missing on all variables:  77
   2 WARNING(S) FOUND IN THE INPUT INSTRUCTIONS



INITIAL SEM MODEL - CIM MATURITY

SUMMARY OF ANALYSIS

Number of groups                                         1
Number                  of                    observations
128
Number  of  draws  for  Bayes  factor  score  estimation
20

Number          of          dependent          variables
16
Number          of          independent        variables
0
Number     of     continuous     latent      variables
4

Observed dependent variables

  Continuous
   Y3          Y4          Y5          Y6          Y7
Y13
   Y14         Y15         Y19         Y20         Y21
Y22
   Y27         Y28         Y29         Y30
```

```
     Continuous latent variables
        F1          F2          F3          F4


     Estimator                                                    BAYES
     Specifications for Bayesian Estimation
       Point estimate                                              MEAN
       Number  of  Markov  chain  Monte  Carlo  (MCMC)  chains
2
       Random     seed     for     the     first     chain
0
       Starting            value            information
UNPERTURBED
       Treatment       of       categorical       mediator
LATENT
       Algorithm   used   for   Markov   chain   Monte   Carlo
GIBBS(RW)
       Fixed         number         of         iterations
60000
       K-th      iteration      used      for      thinning
1
     Specifications for Data Imputation
       Number       of       imputed       data       sets
20
       Iteration       intervals       for       thinning
100

     Input data file(s)
       C:\Users\bs28343\Desktop\Mplus
project\CMAS_Indicators.txt
     Input data format  FREE


     SUMMARY OF DATA



     SUMMARY OF MISSING DATA PATTERNS

          Number of missing data patterns             5


          MISSING DATA PATTERNS (x = not missing)

                1  2  3  4  5
      Y3        x  x  x  x  x
      Y4        x  x  x  x  x
      Y5        x  x  x  x
      Y6        x  x  x  x  x
```

```
     Y7          x  x  x  x  x
     Y13         x     x  x
     Y14         x     x  x
     Y15         x     x
     Y19         x        x  x
     Y20         x        x  x
     Y21         x     x  x  x
     Y22         x     x  x  x
     Y27         x     x  x  x
     Y28         x     x  x  x
     Y29         x     x  x  x
     Y30         x     x  x  x


         MISSING DATA PATTERN FREQUENCIES

         Pattern     Frequency         Pattern     Frequency
Pattern   Frequency
              1         124          3           1          5
1
              2            1           4           1


     COVARIANCE COVERAGE OF DATA

     Minimum covariance coverage value   0.100


          PROPORTION OF DATA PRESENT


                Covariance Coverage
                   Y3            Y4            Y5            Y6
Y7
                   __________    __________    __________
__________      __________
     Y3              1.000
     Y4              1.000         1.000
     Y5              0.992         0.992         0.992
     Y6                1.000          1.000          0.992
1.000
     Y7                1.000          1.000          0.992
1.000         1.000
     Y13               0.984          0.984          0.984
0.984         0.984
     Y14               0.984          0.984          0.984
0.984         0.984
     Y15               0.977          0.977          0.977
0.977         0.977
```

Y19	0.984	0.984	0.977	0.984	0.984
Y20	0.984	0.984	0.977	0.984	0.984
Y21	0.992	0.992	0.984	0.992	0.992
Y22	0.992	0.992	0.984	0.992	0.992
Y27	0.992	0.992	0.984	0.992	0.992
Y28	0.992	0.992	0.984	0.992	0.992
Y29	0.992	0.992	0.984	0.992	0.992
Y30	0.992	0.992	0.984	0.992	0.992

Covariance Coverage

	Y13	Y14	Y15	Y19	Y20
Y13	0.984				
Y14	0.984	0.984			
Y15	0.977	0.977	0.977		
Y19	0.977	0.977	0.969	0.984	
Y20	0.977	0.977	0.969	0.984	0.984
Y21	0.984	0.984	0.977	0.984	0.984
Y22	0.984	0.984	0.977	0.984	0.984
Y27	0.984	0.984	0.977	0.984	0.984
Y28	0.984	0.984	0.977	0.984	0.984
Y29	0.984	0.984	0.977	0.984	0.984
Y30	0.984	0.984	0.977	0.984	0.984

Covariance Coverage

	Y21	Y22	Y27	Y28	Y29

```
     Y21              0.992
     Y22              0.992         0.992
     Y27              0.992         0.992         0.992
     Y28                0.992           0.992           0.992
0.992
     Y29                0.992           0.992           0.992
0.992         0.992
     Y30                0.992           0.992           0.992
0.992         0.992


               Covariance Coverage
                  Y30
                ________
     Y30          0.992


THE MODEL ESTIMATION TERMINATED NORMALLY



MODEL FIT INFORMATION

Number of Free Parameters                              64

Bayesian Posterior Predictive Checking using Chi-Square

          95% Confidence Interval for the Difference
Between
          the Observed and the Replicated Chi-Square
Values

                              -12.452          72.870

          Posterior Predictive P-Value            0.077

Information Criteria

          Deviance (DIC)                       4756.096
          Estimated Number of Parameters (pD)        -
204.161
          Bayesian (BIC)                       5474.948


MODEL RESULTS
```

		Estimate	Posterior S.D.	One-Tailed P-Value	95% C.I. Lower 2.5%	Upper 2.5%	Significance
F1 BY							
	Y3	0.748	0.231	0.000	0.355	1.237	*
	Y4	0.946	0.278	0.000	0.461	1.528	*
	Y5	1.034	0.301	0.000	0.507	1.659	*
	Y6	0.584	0.189	0.000	0.267	0.994	*
	Y7	0.643	0.202	0.000	0.300	1.073	*
F2 BY							
	Y13	0.816	0.186	0.000	0.466	1.200	*
	Y14	1.057	0.235	0.000	0.610	1.535	*
	Y15	0.817	0.197	0.000	0.456	1.228	*
	Y19	0.846	0.194	0.000	0.480	1.245	*
	Y20	0.800	0.186	0.000	0.451	1.183	*
	Y21	1.009	0.226	0.000	0.578	1.470	*
	Y22	0.929	0.215	0.000	0.526	1.373	*
F3 BY							
	Y27	0.873	0.291	0.000	0.356	1.475	*
	Y28	0.652	0.222	0.000	0.263	1.115	*
	Y29	0.777	0.260	0.000	0.317	1.320	*
	Y30	0.808	0.269	0.000	0.331	1.370	*
F4 BY							
	F1	0.701	0.459	0.000	0.051	1.757	*
	F2	0.790	0.492	0.000	0.067	1.958	*

```
         F3                         0.865         0.542         0.000
0.068       2.146         *

      Y3        WITH
         Y13                        0.113         0.055         0.015
0.011       0.227         *

      Y6        WITH
         Y7                         0.302         0.074         0.000
0.171       0.462         *

      Y7        WITH
         Y20                        0.131         0.051         0.003
0.039       0.238         *

      Y13       WITH
         Y20                        0.124         0.049         0.004
0.031       0.225         *
         Y28                        0.091         0.048         0.025
0.000       0.189         *

      Y19       WITH
         Y21                        0.221         0.062         0.000
0.110       0.354         *

      Y20       WITH
         Y21                        0.193         0.055         0.000
0.094       0.308         *
         Y22                        0.150         0.067         0.009
0.024       0.290         *

      Y29       WITH
         Y30                        0.141         0.072         0.018
0.009       0.297         *

      Intercepts
         Y3                         4.445         0.096         0.000
4.258       4.635         *
         Y4                         4.445         0.102         0.000
4.247       4.646         *
         Y5                         4.584         0.104         0.000
4.381       4.788         *
         Y6                         4.851         0.088         0.000
4.679       5.024         *
         Y7                         4.883         0.088         0.000
4.710       5.057         *
         Y13                        4.745         0.093         0.000
4.562       4.927         *
```

Y14	4.452	0.105	0.000	4.246	4.655	*
Y15	4.151	0.112	0.000	3.933	4.370	*
Y19	4.457	0.101	0.000	4.260	4.655	*
Y20	4.719	0.101	0.000	4.521	4.917	*
Y21	4.443	0.111	0.000	4.225	4.661	*
Y22	4.254	0.116	0.000	4.027	4.482	*
Y27	4.317	0.108	0.000	4.103	4.529	*
Y28	4.734	0.091	0.000	4.555	4.913	*
Y29	4.892	0.104	0.000	4.689	5.098	*
Y30	4.727	0.101	0.000	4.528	4.923	*
Variances						
F4	28.030	184.686	0.000	0.229	234.442	*
Residual Variances						
Y3	0.704	0.105	0.000	0.525	0.935	*
Y4	0.571	0.093	0.000	0.409	0.772	*
Y5	0.479	0.088	0.000	0.325	0.670	*
Y6	0.689	0.098	0.000	0.520	0.903	*
Y7	0.656	0.094	0.000	0.491	0.862	*
Y13	0.423	0.061	0.000	0.316	0.559	*
Y14	0.280	0.057	0.000	0.180	0.402	*
Y15	0.899	0.125	0.000	0.685	1.176	*
Y19	0.572	0.085	0.000	0.427	0.765	*
Y20	0.658	0.098	0.000	0.489	0.873	*
Y21	0.561	0.083	0.000	0.415	0.739	*

Y22	0.827	0.117	0.000	0.628	1.084	*
Y27	0.511	0.090	0.000	0.354	0.704	*
Y28	0.520	0.078	0.000	0.385	0.689	*
Y29	0.610	0.102	0.000	0.433	0.834	*
Y30	0.474	0.086	0.000	0.323	0.663	*
F1	0.229	0.194	0.000	0.042	0.763	*
F2	0.101	0.092	0.000	0.006	0.337	*
F3	0.365	0.457	0.000	0.051	1.559	*

STANDARDIZED MODEL RESULTS

STDYX Standardization

	Estimate	Posterior S.D.	One-Tailed P-Value	95% C.I. Lower 2.5%	Upper 2.5%	Significance
F1 BY						
Y3	0.622	0.063	0.000	0.488	0.734	*
Y4	0.745	0.049	0.000	0.638	0.832	*
Y5	0.800	0.044	0.000	0.704	0.875	*
Y6	0.531	0.072	0.000	0.382	0.662	*
Y7	0.578	0.067	0.000	0.436	0.699	*
F2 BY						
Y13	0.773	0.040	0.000	0.686	0.844	*
Y14	0.889	0.027	0.000	0.830	0.934	*
Y15	0.642	0.057	0.000	0.521	0.744	*
Y19	0.736	0.046	0.000	0.635	0.817	*

```
    Y20                    0.692      0.053      0.000
0.580    0.785    *
    Y21                    0.795      0.038      0.000
0.714    0.860    *
    Y22                    0.705      0.049      0.000
0.599    0.792    *

 F3      BY
    Y27                    0.802      0.042      0.000
0.712    0.874    *
    Y28                    0.705      0.052      0.000
0.593    0.798    *
    Y29                    0.739      0.051      0.000
0.628    0.829    *
    Y30                    0.791      0.045      0.000
0.693    0.868    *

 F4      BY
    F1                     0.884      0.044      0.000
0.791    0.962    *
    F2                     0.953      0.030      0.000
0.886    0.996    *
    F3                     0.898      0.040      0.000
0.811    0.967    *

 Y3      WITH
    Y13                    0.206      0.094      0.015
0.021    0.385    *

 Y6      WITH
    Y7                     0.447      0.075      0.000
0.289    0.583    *

 Y7      WITH
    Y20                    0.198      0.069      0.003
0.062    0.333    *

 Y13     WITH
    Y20                    0.233      0.082      0.004
0.063    0.386    *
    Y28                    0.193      0.096      0.025
0.000    0.375    *

 Y19     WITH
    Y21                    0.387      0.080      0.000
0.221    0.535    *

 Y20     WITH
```

```
          Y21                        0.317          0.074          0.000
0.169         0.457       *
          Y22                        0.202          0.082          0.009
0.035         0.358       *

       Y29       WITH
          Y30                        0.255          0.111          0.018
0.020         0.457       *

       Intercepts
          Y3                         4.148          0.281          0.000
3.602         4.703       *
          Y4                         3.921          0.263          0.000
3.411         4.442       *
          Y5                         3.972          0.267          0.000
3.455         4.503       *
          Y6                         4.954          0.332          0.000
4.315         5.613       *
          Y7                         4.922          0.325          0.000
4.297         5.568       *
          Y13                        4.621          0.305          0.000
4.030         5.224       *
          Y14                        3.849          0.260          0.000
3.348         4.369       *
          Y15                        3.357          0.233          0.000
2.907         3.820       *
          Y19                        3.987          0.269          0.000
3.467         4.521       *
          Y20                        4.198          0.282          0.000
3.656         4.760       *
          Y21                        3.596          0.244          0.000
3.119         4.084       *
          Y22                        3.317          0.228          0.000
2.880         3.768       *
          Y27                        3.601          0.245          0.000
3.123         4.087       *
          Y28                        4.652          0.307          0.000
4.059         5.262       *
          Y29                        4.219          0.281          0.000
3.678         4.779       *
          Y30                        4.199          0.281          0.000
3.654         4.757       *

       Variances
          F4                         1.000          0.000          0.000
1.000         1.000

       Residual Variances
```

Variable	Estimate	S.D.	P-Value	Lower 2.5%	Upper 2.5%	
Y3	0.609	0.077	0.000	0.461	0.761	*
Y4	0.443	0.073	0.000	0.309	0.593	*
Y5	0.359	0.069	0.000	0.234	0.504	*
Y6	0.713	0.075	0.000	0.562	0.854	*
Y7	0.662	0.076	0.000	0.512	0.810	*
Y13	0.401	0.062	0.000	0.288	0.529	*
Y14	0.209	0.047	0.000	0.128	0.311	*
Y15	0.585	0.072	0.000	0.447	0.728	*
Y19	0.456	0.067	0.000	0.332	0.596	*
Y20	0.518	0.072	0.000	0.384	0.664	*
Y21	0.367	0.059	0.000	0.260	0.490	*
Y22	0.501	0.069	0.000	0.373	0.641	*
Y27	0.355	0.066	0.000	0.236	0.493	*
Y28	0.500	0.073	0.000	0.364	0.649	*
Y29	0.452	0.075	0.000	0.313	0.606	*
Y30	0.373	0.070	0.000	0.246	0.520	*
F1	0.216	0.077	0.000	0.074	0.375	*
F2	0.090	0.056	0.000	0.007	0.215	*
F3	0.193	0.071	0.000	0.065	0.342	*

R-SQUARE

Variable	Estimate	Posterior S.D.	One-Tailed P-Value	95% C.I. Lower 2.5%	Upper 2.5%
Y3	0.391	0.077	0.000	0.239	0.539

Y4	0.557	0.073	0.000	0.407	0.691
Y5	0.641	0.069	0.000	0.496	0.766
Y6	0.287	0.075	0.000	0.146	0.438
Y7	0.338	0.076	0.000	0.190	0.488
Y13	0.599	0.062	0.000	0.471	0.712
Y14	0.791	0.047	0.000	0.689	0.872
Y15	0.415	0.072	0.000	0.272	0.553
Y19	0.544	0.067	0.000	0.404	0.668
Y20	0.482	0.072	0.000	0.336	0.616
Y21	0.633	0.059	0.000	0.510	0.740
Y22	0.499	0.069	0.000	0.359	0.627
Y27	0.645	0.066	0.000	0.507	0.764
Y28	0.500	0.073	0.000	0.351	0.636
Y29	0.548	0.075	0.000	0.394	0.687
Y30	0.627	0.070	0.000	0.480	0.754

Variable	Estimate	Posterior S.D.	One-Tailed P-Value	95% C.I. Lower 2.5%	Upper 2.5%
F1	0.784	0.077	0.000	0.625	0.926
F2	0.910	0.056	0.000	0.785	0.993
F3	0.807	0.071	0.000	0.658	0.935

TECHNICAL 1 OUTPUT

PARAMETER SPECIFICATION

NU

	Y3	Y4	Y5	Y6	Y7
1	1	2	3	4	5

NU

	Y13	Y14	Y15	Y19	Y20
1	6	7	8	9	10

NU

	Y21	Y22	Y27	Y28	Y29
1	11	12	13	14	15

NU

	Y30
1	16

LAMBDA

	F1	F2	F3	F4	
Y3	17	0	0	0	0
Y4	18	0	0	0	0
Y5	19	0	0	0	0
Y6	20	0	0	0	0
Y7	21	0	0	0	0

Y13	0	22	0	0
Y14	0	23	0	0
Y15	0	24	0	0
Y19	0	25	0	0
Y20	0	26	0	0
Y21	0	27	0	0
Y22	0	28	0	0
Y27	0	0	29	0
Y28	0	0	30	0
Y29	0	0	31	0
Y30	0	0	32	0

THETA

	Y3	Y4	Y5	Y6	Y7
Y3	33				
Y4	0	34			
Y5	0	0	35		
Y6	0	0	0	36	
Y7	0	0	0	37	38
Y13	39	0	0	0	0
Y14	0	0	0	0	0
Y15	0	0	0	0	0
Y19	0	0	0	0	0
Y20	0	0	0	0	44
Y21	0	0	0	0	0

Y22	0	0	0	0	0
Y27	0	0	0	0	0
Y28	0	0	0	0	0
Y29	0	0	0	0	0
Y30	0	0	0	0	0

THETA

	Y13	Y14	Y15	Y19	Y20
Y13	40				
Y14	0	41			
Y15	0	0	42		
Y19	0	0	0	43	
Y20	45	0	0	0	46
Y21	0	0	0	47	48
Y22	0	0	0	0	50
Y27	0	0	0	0	0
Y28	53	0	0	0	0
Y29	0	0	0	0	0
Y30	0	0	0	0	0

THETA

	Y21	Y22	Y27	Y28	Y29
Y21	49				
Y22	0	51			
Y27	0	0	52		
Y28	0	0	0	54	

Y29 0 0 0
0 55
Y30 0 0 0
0 56

THETA
Y30

	Y30
Y30	57

ALPHA

	F1	F2	F3	F4
1	0	0	0	

0

BETA

	F1	F2	F3	F4
F1	0	0	0	

58

F2	0	0	0

59

F3	0	0	0

60

F4	0	0	0

0

PSI

	F1	F2	F3	F4
F1	61			
F2	0	62		
F3	0	0	63	
F4	0	0	0	

64

STARTING VALUES

NU

	Y3	Y4	Y5	Y6	Y7
1	4.445	4.445	4.591	4.852	4.883

NU

	Y13	Y14	Y15	Y19	Y20
1	4.746	4.452	4.160	4.452	4.714

NU

	Y21	Y22	Y27	Y28	Y29
1	4.441	4.252	4.315	4.732	4.890

NU

	Y30
1	4.724

LAMBDA

	F1	F2	F3	F4
Y3	0.700	0.000	0.000	0.000
Y4	0.700	0.000	0.000	0.000
Y5	0.700	0.000	0.000	0.000
Y6	0.700	0.000	0.000	0.000
Y7	0.700	0.000	0.000	0.000
Y13	0.000	0.700	0.000	0.000

Y14	0.000	0.700	0.000	0.000
Y15	0.000	0.700	0.000	0.000
Y19	0.000	0.700	0.000	0.000
Y20	0.000	0.700	0.000	0.000
Y21	0.000	0.700	0.000	0.000
Y22	0.000	0.700	0.000	0.000
Y27	0.000	0.000	0.700	0.000
Y28	0.000	0.000	0.700	0.000
Y29	0.000	0.000	0.700	0.000
Y30	0.000	0.000	0.700	0.000

THETA

	Y3	Y4	Y5	Y6	Y7
Y3	0.545				
Y4	0.000	0.624			
Y5	0.000	0.000	0.648		
Y6	0.000	0.000	0.000	0.454	
Y7	0.000	0.000	0.000	0.000	0.458
Y13	0.000	0.000	0.000	0.000	0.000
Y14	0.000	0.000	0.000	0.000	0.000
Y15	0.000	0.000	0.000	0.000	0.000
Y19	0.000	0.000	0.000	0.000	0.000
Y20	0.000	0.000	0.000	0.000	0.000
Y21	0.000	0.000	0.000	0.000	0.000
Y22	0.000	0.000	0.000	0.000	0.000

Y27	0.000	0.000	0.000	0.000	0.000
Y28	0.000	0.000	0.000	0.000	0.000
Y29	0.000	0.000	0.000	0.000	0.000
Y30	0.000	0.000	0.000	0.000	0.000

THETA

	Y13	Y14	Y15	Y19	Y20
Y13	0.507				
Y14	0.000	0.656			
Y15	0.000	0.000	0.739		
Y19	0.000	0.000	0.000	0.608	
Y20	0.000	0.000	0.000	0.000	0.586
Y21	0.000	0.000	0.000	0.000	0.000
Y22	0.000	0.000	0.000	0.000	0.000
Y27	0.000	0.000	0.000	0.000	0.000
Y28	0.000	0.000	0.000	0.000	0.000
Y29	0.000	0.000	0.000	0.000	0.000
Y30	0.000	0.000	0.000	0.000	0.000

THETA

	Y21	Y22	Y27	Y28	Y29
Y21	0.745				
Y22	0.000	0.795			
Y27	0.000	0.000	0.698		
Y28	0.000	0.000	0.000	0.500	
Y29	0.000	0.000	0.000	0.000	0.647

```
        Y30                 0.000           0.000           0.000
0.000          0.000

                  THETA
                     Y30
                     ________
        Y30            0.612

                  ALPHA
                     F1             F2             F3             F4
                     ________       ________       ________       ________
        1                0.000          0.000          0.000
0.000

                  BETA
                     F1             F2             F3             F4
                     ________       ________       ________       ________
        F1               0.000          0.000          0.000
0.600
        F2               0.000          0.000          0.000
0.600
        F3               0.000          0.000          0.000
0.600
        F4               0.000          0.000          0.000
0.000

                  PSI
                     F1             F2             F3             F4
                     ________       ________       ________       ________
        F1             1.000
        F2             0.000          1.000
        F3             0.000          0.000          1.000
        F4               0.000          0.000          0.000
1.000

          PRIORS FOR ALL PARAMETERS                  PRIOR MEAN
PRIOR VARIANCE     PRIOR STD. DEV.

          Parameter 1~N(0.000,infinity)                 0.0000
infinity              infinity
```

```
           Parameter  2~N(0.000,infinity)                 0.0000
infinity              infinity
           Parameter  3~N(0.000,infinity)                 0.0000
infinity              infinity
           Parameter  4~N(0.000,infinity)                 0.0000
infinity              infinity
           Parameter  5~N(0.000,infinity)                 0.0000
infinity              infinity
           Parameter  6~N(0.000,infinity)                 0.0000
infinity              infinity
           Parameter  7~N(0.000,infinity)                 0.0000
infinity              infinity
           Parameter  8~N(0.000,infinity)                 0.0000
infinity              infinity
           Parameter  9~N(0.000,infinity)                 0.0000
infinity              infinity
           Parameter  10~N(0.000,infinity)                0.0000
infinity              infinity
           Parameter  11~N(0.000,infinity)                0.0000
infinity              infinity
           Parameter  12~N(0.000,infinity)                0.0000
infinity              infinity
           Parameter  13~N(0.000,infinity)                0.0000
infinity              infinity
           Parameter  14~N(0.000,infinity)                0.0000
infinity              infinity
           Parameter  15~N(0.000,infinity)                0.0000
infinity              infinity
           Parameter  16~N(0.000,infinity)                0.0000
infinity              infinity
           Parameter  17~N(0.700,0.350)                   0.7000
0.3500                0.5916
           Parameter  18~N(0.700,0.350)                   0.7000
0.3500                0.5916
           Parameter  19~N(0.700,0.350)                   0.7000
0.3500                0.5916
           Parameter  20~N(0.700,0.350)                   0.7000
0.3500                0.5916
           Parameter  21~N(0.700,0.350)                   0.7000
0.3500                0.5916
           Parameter  22~N(0.700,0.350)                   0.7000
0.3500                0.5916
           Parameter  23~N(0.700,0.350)                   0.7000
0.3500                0.5916
           Parameter  24~N(0.700,0.350)                   0.7000
0.3500                0.5916
           Parameter  25~N(0.700,0.350)                   0.7000
0.3500                0.5916
```

```
          Parameter 26~N(0.700,0.350)                0.7000
0.3500              0.5916
          Parameter 27~N(0.700,0.350)                0.7000
0.3500              0.5916
          Parameter 28~N(0.700,0.350)                0.7000
0.3500              0.5916
          Parameter 29~N(0.700,0.350)                0.7000
0.3500              0.5916
          Parameter 30~N(0.700,0.350)                0.7000
0.3500              0.5916
          Parameter 31~N(0.700,0.350)                0.7000
0.3500              0.5916
          Parameter 32~N(0.700,0.350)                0.7000
0.3500              0.5916
          Parameter 33~N(0.000,infinity)             0.0000
infinity            infinity
          Parameter 34~IG(-1.000,0.000)            infinity
infinity            infinity
          Parameter 35~IG(-1.000,0.000)            infinity
infinity            infinity
          Parameter 36~N(0.000,infinity)             0.0000
infinity            infinity
          Parameter 37~N(0.000,infinity)             0.0000
infinity            infinity
          Parameter 38~N(0.000,infinity)             0.0000
infinity            infinity
          Parameter 39~N(0.000,infinity)             0.0000
infinity            infinity
          Parameter 40~N(0.000,infinity)             0.0000
infinity            infinity
          Parameter 41~IG(-1.000,0.000)            infinity
infinity            infinity
          Parameter 42~IG(-1.000,0.000)            infinity
infinity            infinity
          Parameter 43~N(0.000,infinity)             0.0000
infinity            infinity
          Parameter 44~N(0.000,infinity)             0.0000
infinity            infinity
          Parameter 45~N(0.000,infinity)             0.0000
infinity            infinity
          Parameter 46~N(0.000,infinity)             0.0000
infinity            infinity
          Parameter 47~N(0.000,infinity)             0.0000
infinity            infinity
          Parameter 48~N(0.000,infinity)             0.0000
infinity            infinity
          Parameter 49~N(0.000,infinity)             0.0000
infinity            infinity
```

```
          Parameter  50~N(0.000,infinity)              0.0000
infinity             infinity
          Parameter  51~N(0.000,infinity)              0.0000
infinity             infinity
          Parameter  52~IG(-1.000,0.000)             infinity
infinity             infinity
          Parameter  53~N(0.000,infinity)              0.0000
infinity             infinity
          Parameter  54~N(0.000,infinity)              0.0000
infinity             infinity
          Parameter  55~N(0.000,infinity)              0.0000
infinity             infinity
          Parameter  56~N(0.000,infinity)              0.0000
infinity             infinity
          Parameter  57~N(0.000,infinity)              0.0000
infinity             infinity
          Parameter  58~N(0.600,1.000)                 0.6000
1.0000               1.0000
          Parameter  59~N(0.600,1.000)                 0.6000
1.0000               1.0000
          Parameter  60~N(0.600,1.000)                 0.6000
1.0000               1.0000
          Parameter  61~IG(-1.000,0.000)             infinity
infinity             infinity
          Parameter  62~IG(-1.000,0.000)             infinity
infinity             infinity
          Parameter  63~IG(-1.000,0.000)             infinity
infinity             infinity
          Parameter  64~IG(-1.000,0.000)             infinity
infinity             infinity
```

TECHNICAL 8 OUTPUT

Kolmogorov-Smirnov comparing posterior distributions across chains 1 and 2 using 100 draws.

```
          Parameter   KS Statistic P-value
          Parameter 58    0.3200    0.0000

          Parameter 60    0.2600    0.0018
          Parameter 64    0.2500    0.0030
          Parameter 59    0.2500    0.0030
```

Parameter 10	0.1700	0.0994
Parameter 39	0.1400	0.2606
Parameter 63	0.1400	0.2606
Parameter 8	0.1300	0.3439
Parameter 33	0.1300	0.3439
Parameter 35	0.1300	0.3439
Parameter 12	0.1300	0.3439
Parameter 62	0.1300	0.3439
Parameter 18	0.1200	0.4431
Parameter 30	0.1200	0.4431
Parameter 17	0.1100	0.5560
Parameter 32	0.1100	0.5560
Parameter 51	0.1100	0.5560
Parameter 20	0.1100	0.5560
Parameter 31	0.1100	0.5560
Parameter 49	0.1000	0.6766
Parameter 15	0.1000	0.6766
Parameter 28	0.1000	0.6766
Parameter 19	0.0900	0.7942
Parameter 7	0.0900	0.7942
Parameter 61	0.0900	0.7942
Parameter 23	0.0900	0.7942
Parameter 22	0.0800	0.8938
Parameter 45	0.0800	0.8938
Parameter 11	0.0800	0.8938
Parameter 6	0.0800	0.8938
Parameter 52	0.0800	0.8938
Parameter 4	0.0800	0.8938
Parameter 29	0.0800	0.8938
Parameter 16	0.0800	0.8938
Parameter 13	0.0800	0.8938
Parameter 47	0.0700	0.9610
Parameter 14	0.0700	0.9610
Parameter 55	0.0700	0.9610
Parameter 24	0.0700	0.9610
Parameter 2	0.0700	0.9610
Parameter 21	0.0700	0.9610
Parameter 57	0.0700	0.9610
Parameter 48	0.0600	0.9921
Parameter 27	0.0600	0.9921
Parameter 9	0.0600	0.9921
Parameter 43	0.0600	0.9921
Parameter 3	0.0600	0.9921
Parameter 25	0.0600	0.9921
Parameter 53	0.0500	0.9995
Parameter 42	0.0500	0.9995
Parameter 50	0.0500	0.9995
Parameter 5	0.0500	0.9995
Parameter 1	0.0500	0.9995

Parameter 38	0.0500	0.9995
Parameter 54	0.0400	1.0000
Parameter 56	0.0400	1.0000
Parameter 26	0.0400	1.0000
Parameter 34	0.0400	1.0000
Parameter 44	0.0300	1.0000
Parameter 37	0.0300	1.0000
Parameter 46	0.0300	1.0000
Parameter 36	0.0300	1.0000
Parameter 41	0.0300	1.0000
Parameter 40	0.0200	1.0000

Simulated prior distributions

Parameter	Prior Mean	Prior Variance	Prior Std. Dev.
Parameter 1 Improper Prior			
Parameter 2 Improper Prior			
Parameter 3 Improper Prior			
Parameter 4 Improper Prior			
Parameter 5 Improper Prior			
Parameter 6 Improper Prior			
Parameter 7 Improper Prior			
Parameter 8 Improper Prior			
Parameter 9 Improper Prior			
Parameter 10 Improper Prior			
Parameter 11 Improper Prior			
Parameter 12 Improper Prior			
Parameter 13 Improper Prior			
Parameter 14 Improper Prior			
Parameter 15 Improper Prior			
Parameter 16 Improper Prior			
Parameter 17	0.6861	0.3571	0.5976
Parameter 18	0.7108	0.3700	0.6083
Parameter 19	0.6802	0.3398	0.5829
Parameter 20	0.7062	0.3530	0.5942
Parameter 21	0.7018	0.3427	0.5854
Parameter 22	0.7217	0.3268	0.5717

Parameter 23	0.7568	0.3438	0.5863
Parameter 24	0.6970	0.3394	0.5826
Parameter 25	0.7035	0.3717	0.6097
Parameter 26	0.7161	0.3843	0.6199
Parameter 27	0.6991	0.3171	0.5631
Parameter 28	0.6951	0.3923	0.6263
Parameter 29	0.7018	0.3685	0.6071
Parameter 30	0.6806	0.3378	0.5812
Parameter 31	0.6897	0.3341	0.5780
Parameter 32	0.6982	0.3733	0.6109
Parameter 33 Not available			
Parameter 34 Improper Prior			
Parameter 35 Improper Prior			
Parameter 36 Not available			
Parameter 37 Not available			
Parameter 38 Not available			
Parameter 39 Not available			
Parameter 40 Not available			
Parameter 41 Improper Prior			
Parameter 42 Improper Prior			
Parameter 43 Not available			
Parameter 44 Not available			
Parameter 45 Not available			
Parameter 46 Not available			
Parameter 47 Not available			
Parameter 48 Not available			
Parameter 49 Not available			
Parameter 50 Not available			
Parameter 51 Not available			
Parameter 52 Improper Prior			
Parameter 53 Not available			
Parameter 54 Not available			
Parameter 55 Not available			
Parameter 56 Not available			
Parameter 57 Not available			
Parameter 58	0.5779	1.0620	1.0305
Parameter 59	0.5640	1.0241	1.0120

Parameter 60 0.6116 1.0287
1.0142
Parameter 61 Improper Prior
Parameter 62 Improper Prior
Parameter 63 Improper Prior
Parameter 64 Improper Prior

TECHNICAL 8 OUTPUT FOR BAYES ESTIMATION

CHAIN	BSEED
1	0
2	285380

ITERATION	POTENTIAL SCALE REDUCTION	PARAMETER WITH HIGHEST PSR
100	5.755	60
200	2.704	22
300	2.096	60
400	2.479	30
500	2.685	29
600	2.425	59
700	3.132	59
800	4.090	59
900	6.711	59
1000	6.667	59
1100	6.151	59
1200	5.695	59
1300	5.755	59
1400	4.863	59
1500	3.666	59
1600	3.633	59
1700	3.462	60
1800	3.572	59
1900	3.359	59
2000	3.117	59
2100	3.009	59
2200	2.857	58
2300	2.743	58
2400	2.453	58
2500	2.262	58
2600	2.230	58
2700	2.205	58
2800	2.215	58
2900	2.350	59
3000	2.678	59
3100	2.805	59
3200	2.771	59
3300	2.645	59

3400	2.347	59
3500	2.027	59
3600	1.691	29
3700	1.683	29
3800	1.651	29
3900	1.639	29
4000	1.617	29
4100	1.565	29
4200	1.531	29
4300	1.469	29
4400	1.383	29
4500	1.297	29
4600	1.266	32
4700	1.275	60
4800	1.309	60
4900	1.352	60
5000	1.423	60
5100	1.456	60
5200	1.457	60
5300	1.464	60
5400	1.492	60
5500	1.514	60
5600	1.449	60
5700	1.365	60
5800	1.336	60
5900	1.310	60
6000	1.283	60
6100	1.262	60
6200	1.234	60
6300	1.226	60
6400	1.236	60
6500	1.209	60
6600	1.170	60
6700	1.136	60
6800	1.112	60
6900	1.086	60
7000	1.072	64
7100	1.056	64
7200	1.046	59
7300	1.043	59
7400	1.039	59
7500	1.043	62
7600	1.044	23
7700	1.048	22
7800	1.052	62
7900	1.050	62
8000	1.051	62
8100	1.054	62
8200	1.055	18

8300	1.074	64
8400	1.069	64
8500	1.087	60
8600	1.103	60
8700	1.107	60
8800	1.100	60
8900	1.092	60
9000	1.082	60
9100	1.080	18
9200	1.079	18
9300	1.082	18
9400	1.073	18
9500	1.070	18
9600	1.065	18
9700	1.066	18
9800	1.072	18
9900	1.081	18
10000	1.086	18
10100	1.083	18
10200	1.079	18
10300	1.072	18
10400	1.065	18
10500	1.057	21
10600	1.061	64
10700	1.057	21
10800	1.057	21
10900	1.059	63
11000	1.066	63
11100	1.067	63
11200	1.068	64
11300	1.072	64
11400	1.078	64
11500	1.087	64
11600	1.097	64
11700	1.106	64
11800	1.109	64
11900	1.114	64
12000	1.124	64
12100	1.133	64
12200	1.142	64
12300	1.156	58
12400	1.170	58
12500	1.180	58
12600	1.195	58
12700	1.208	58
12800	1.221	58
12900	1.238	58
13000	1.258	58
13100	1.276	58

13200	1.302	58
13300	1.320	58
13400	1.325	58
13500	1.336	58
13600	1.356	58
13700	1.360	58
13800	1.362	58
13900	1.362	58
14000	1.364	58
14100	1.371	58
14200	1.384	58
14300	1.380	58
14400	1.371	58
14500	1.345	58
14600	1.337	58
14700	1.325	58
14800	1.310	58
14900	1.296	58
15000	1.269	58
15100	1.253	58
15200	1.247	58
15300	1.232	58
15400	1.217	58
15500	1.205	58
15600	1.204	58
15700	1.205	58
15800	1.212	58
15900	1.220	58
16000	1.215	58
16100	1.181	58
16200	1.139	58
16300	1.132	58
16400	1.127	58
16500	1.123	58
16600	1.113	64
16700	1.113	64
16800	1.112	64
16900	1.111	64
17000	1.110	64
17100	1.110	64
17200	1.109	64
17300	1.108	64
17400	1.107	64
17500	1.107	64
17600	1.106	64
17700	1.105	64
17800	1.104	64
17900	1.104	64
18000	1.103	64

18100	1.102	64
18200	1.102	64
18300	1.101	64
18400	1.100	64
18500	1.100	64
18600	1.099	64
18700	1.098	64
18800	1.098	64
18900	1.097	64
19000	1.096	64
19100	1.096	64
19200	1.095	64
19300	1.094	64
19400	1.094	64
19500	1.093	64
19600	1.092	64
19700	1.092	64
19800	1.091	64
19900	1.090	64
20000	1.089	64
20100	1.088	64
20200	1.087	64
20300	1.086	64
20400	1.086	64
20500	1.085	64
20600	1.084	64
20700	1.083	64
20800	1.082	64
20900	1.080	64
21000	1.079	64
21100	1.078	64
21200	1.077	64
21300	1.075	64
21400	1.072	64
21500	1.069	64
21600	1.067	64
21700	1.065	64
21800	1.062	64
21900	1.059	64
22000	1.057	64
22100	1.055	64
22200	1.053	64
22300	1.051	64
22400	1.049	64
22500	1.046	64
22600	1.043	64
22700	1.041	64
22800	1.039	64
22900	1.036	64

23000	1.034	64
23100	1.031	64
23200	1.033	61
23300	1.035	61
23400	1.039	61
23500	1.043	61
23600	1.045	61
23700	1.046	61
23800	1.044	61
23900	1.041	61
24000	1.041	61
24100	1.040	61
24200	1.040	61
24300	1.040	61
24400	1.038	61
24500	1.038	61
24600	1.038	61
24700	1.039	61
24800	1.039	61
24900	1.042	61
25000	1.043	61
25100	1.046	61
25200	1.047	61
25300	1.049	61
25400	1.053	61
25500	1.057	61
25600	1.057	61
25700	1.054	61
25800	1.052	61
25900	1.051	61
26000	1.050	61
26100	1.049	61
26200	1.049	61
26300	1.048	61
26400	1.047	61
26500	1.044	61
26600	1.043	61
26700	1.042	61
26800	1.042	61
26900	1.041	61
27000	1.042	64
27100	1.045	64
27200	1.046	64
27300	1.047	64
27400	1.041	64
27500	1.041	64
27600	1.044	64
27700	1.047	64
27800	1.050	64

27900	1.052	64
28000	1.056	64
28100	1.057	64
28200	1.058	64
28300	1.059	64
28400	1.059	64
28500	1.061	29
28600	1.065	29
28700	1.069	29
28800	1.068	29
28900	1.070	29
29000	1.070	29
29100	1.070	29
29200	1.068	29
29300	1.068	29
29400	1.070	29
29500	1.071	29
29600	1.068	29
29700	1.064	29
29800	1.062	29
29900	1.062	64
30000	1.061	64
30100	1.061	64
30200	1.061	64
30300	1.061	64
30400	1.060	64
30500	1.060	64
30600	1.060	64
30700	1.060	64
30800	1.059	64
30900	1.059	64
31000	1.059	64
31100	1.060	29
31200	1.063	29
31300	1.066	29
31400	1.069	29
31500	1.074	29
31600	1.077	29
31700	1.078	29
31800	1.078	29
31900	1.078	29
32000	1.079	29
32100	1.080	29
32200	1.081	29
32300	1.078	29
32400	1.076	29
32500	1.077	29
32600	1.074	29
32700	1.071	29

32800	1.071	29
32900	1.072	29
33000	1.074	29
33100	1.078	29
33200	1.081	29
33300	1.081	29
33400	1.081	29
33500	1.081	29
33600	1.079	29
33700	1.079	29
33800	1.082	29
33900	1.085	29
34000	1.085	29
34100	1.086	29
34200	1.086	29
34300	1.085	29
34400	1.083	29
34500	1.084	29
34600	1.081	29
34700	1.079	29
34800	1.074	29
34900	1.069	29
35000	1.066	29
35100	1.064	29
35200	1.064	29
35300	1.065	29
35400	1.068	29
35500	1.073	29
35600	1.077	29
35700	1.078	29
35800	1.078	29
35900	1.077	29
36000	1.077	58
36100	1.079	58
36200	1.082	29
36300	1.085	58
36400	1.086	58
36500	1.084	58
36600	1.085	29
36700	1.085	29
36800	1.087	58
36900	1.090	58
37000	1.094	29
37100	1.099	29
37200	1.106	29
37300	1.114	29
37400	1.121	29
37500	1.126	29
37600	1.130	29

37700	1.132	29
37800	1.137	29
37900	1.140	29
38000	1.144	29
38100	1.148	29
38200	1.150	29
38300	1.148	29
38400	1.146	29
38500	1.149	29
38600	1.151	29
38700	1.151	29
38800	1.155	29
38900	1.152	29
39000	1.152	29
39100	1.152	29
39200	1.154	29
39300	1.155	29
39400	1.151	29
39500	1.150	29
39600	1.152	29
39700	1.153	29
39800	1.152	29
39900	1.155	58
40000	1.158	29
40100	1.161	29
40200	1.161	29
40300	1.158	58
40400	1.155	58
40500	1.157	29
40600	1.160	59
40700	1.165	59
40800	1.168	59
40900	1.168	59
41000	1.167	59
41100	1.165	59
41200	1.165	29
41300	1.168	29
41400	1.172	29
41500	1.175	29
41600	1.173	29
41700	1.174	29
41800	1.176	29
41900	1.171	29
42000	1.167	29
42100	1.160	29
42200	1.156	29
42300	1.153	29
42400	1.151	29
42500	1.150	29

42600	1.145	29
42700	1.143	29
42800	1.138	29
42900	1.136	29
43000	1.131	29
43100	1.127	29
43200	1.124	29
43300	1.122	29
43400	1.121	29
43500	1.121	29
43600	1.119	29
43700	1.117	58
43800	1.117	29
43900	1.116	29
44000	1.113	29
44100	1.111	29
44200	1.110	29
44300	1.110	29
44400	1.112	29
44500	1.113	29
44600	1.111	29
44700	1.108	29
44800	1.103	29
44900	1.100	29
45000	1.093	29
45100	1.088	29
45200	1.086	29
45300	1.085	29
45400	1.081	29
45500	1.080	29
45600	1.079	29
45700	1.079	29
45800	1.077	29
45900	1.075	29
46000	1.072	29
46100	1.069	29
46200	1.067	29
46300	1.064	29
46400	1.062	29
46500	1.060	29
46600	1.058	29
46700	1.057	29
46800	1.056	29
46900	1.055	29
47000	1.055	29
47100	1.055	29
47200	1.054	29
47300	1.055	29
47400	1.056	29

47500	1.057	29
47600	1.059	29
47700	1.059	29
47800	1.058	29
47900	1.056	29
48000	1.055	29
48100	1.055	29
48200	1.056	29
48300	1.055	29
48400	1.056	29
48500	1.055	32
48600	1.054	32
48700	1.053	32
48800	1.052	32
48900	1.051	32
49000	1.052	32
49100	1.052	32
49200	1.050	32
49300	1.050	32
49400	1.049	32
49500	1.048	32
49600	1.048	32
49700	1.047	32
49800	1.046	32
49900	1.043	32
50000	1.041	32
50100	1.040	32
50200	1.036	32
50300	1.035	32
50400	1.035	32
50500	1.035	32
50600	1.034	32
50700	1.033	64
50800	1.034	64
50900	1.034	64
51000	1.034	64
51100	1.034	64
51200	1.033	64
51300	1.032	64
51400	1.031	64
51500	1.029	64
51600	1.027	64
51700	1.026	64
51800	1.024	64
51900	1.021	64
52000	1.019	63
52100	1.019	63
52200	1.018	63
52300	1.018	63

52400	1.018	63
52500	1.017	63
52600	1.017	32
52700	1.017	63
52800	1.017	32
52900	1.017	32
53000	1.017	32
53100	1.018	32
53200	1.018	32
53300	1.019	32
53400	1.020	32
53500	1.020	32
53600	1.020	32
53700	1.020	32
53800	1.020	32
53900	1.021	29
54000	1.022	29
54100	1.023	29
54200	1.023	29
54300	1.023	29
54400	1.022	29
54500	1.021	29
54600	1.021	29
54700	1.021	29
54800	1.020	29
54900	1.020	63
55000	1.019	63
55100	1.017	63
55200	1.015	29
55300	1.016	60
55400	1.017	60
55500	1.018	60
55600	1.019	60
55700	1.020	60
55800	1.021	60
55900	1.023	60
56000	1.024	60
56100	1.026	60
56200	1.028	60
56300	1.030	60
56400	1.032	60
56500	1.032	60
56600	1.033	60
56700	1.034	60
56800	1.035	64
56900	1.037	64
57000	1.038	64
57100	1.039	64
57200	1.041	64

57300	1.043	64
57400	1.044	64
57500	1.045	64
57600	1.047	64
57700	1.049	64
57800	1.049	64
57900	1.049	64
58000	1.049	64
58100	1.049	64
58200	1.050	64
58300	1.049	64
58400	1.050	64
58500	1.050	64
58600	1.050	64
58700	1.050	64
58800	1.050	60
58900	1.051	60
59000	1.053	60
59100	1.054	60
59200	1.056	60
59300	1.058	60
59400	1.060	60
59500	1.061	60
59600	1.061	60
59700	1.061	60
59800	1.061	60
59900	1.061	60
60000	1.061	60

SUMMARIES OF PLAUSIBLE VALUES (N = NUMBER OF OBSERVATIONS * NUMBER OF IMPUTATIONS)

SAMPLE STATISTICS

Means

	F1	F2	F3	F4
1	-0.007	0.015	0.028	0.037

Covariances

	F1	F2	F3	F4

	F1	F2	F3	F4
F1	2.600			
F2	1.002	0.863		
F3	1.462	1.128	2.178	
F4	2.185	1.629	2.167	3.530

Correlations

	F1	F2	F3	F4
F1	1.000			
F2	0.669	1.000		
F3	0.614	0.823	1.000	
F4	0.721	0.933	0.782	1.000

SUMMARY OF PLAUSIBLE STANDARD DEVIATION (N = NUMBER OF OBSERVATIONS)

SAMPLE STATISTICS

Means

	F1_SD	F2_SD	F3_SD	F4_SD
1	0.929	0.316	0.629	0.793

Covariances

	F1_SD	F2_SD	F3_SD	F4_SD
F1_SD	0.238			
F2_SD	0.019	0.006		
F3_SD	0.052	0.009	0.030	
F4_SD	0.104	0.020	0.039	0.097

Correlations

	F1_SD	F2_SD	F3_SD	F4_SD

F1_SD	1.000			
F2_SD	0.502	1.000		
F3_SD	0.616	0.617	1.000	
F4_SD	0.683	0.816	0.717	1.000

PLOT INFORMATION

The following plots are available:

- Bayesian posterior parameter distributions
- Bayesian posterior parameter trace plots
- Bayesian autocorrelation plots
- Bayesian prior parameter distributions
- Bayesian posterior predictive checking scatterplots
- Bayesian posterior predictive checking distribution plots

SAVEDATA INFORMATION

Save file
bayesian.xlsx

Order and format of variables

Y3	F10.3
Y4	F10.3
Y5	F10.3
Y6	F10.3
Y7	F10.3
Y13	F10.3
Y14	F10.3
Y15	F10.3
Y19	F10.3
Y20	F10.3
Y21	F10.3
Y22	F10.3
Y27	F10.3
Y28	F10.3
Y29	F10.3
Y30	F10.3
F1 Mean	F10.3
F1 Median	F10.3
F1 Standard Deviation	F10.3
F1 2.5% Value	F10.3

```
    F1 97.5% Value                     F10.3
    F2 Mean                            F10.3
    F2 Median                          F10.3
    F2 Standard Deviation              F10.3
    F2 2.5% Value                      F10.3
    F2 97.5% Value                     F10.3
    F3 Mean                            F10.3
    F3 Median                          F10.3
    F3 Standard Deviation              F10.3
    F3 2.5% Value                      F10.3
    F3 97.5% Value                     F10.3
    F4 Mean                            F10.3
    F4 Median                          F10.3
    F4 Standard Deviation              F10.3
    F4 2.5% Value                      F10.3
    F4 97.5% Value                     F10.3

  Save file format
    36F10.3

  Save file record length    10000


DIAGRAM INFORMATION

  Use View Diagram under the Diagram menu in the Mplus
Editor to view the diagram.
  If running Mplus from the Mplus Diagrammer, the
diagram opens automatically.

  Diagram output
    c:\users\bs28343\desktop\mplus
project\initial_sem_bayes_three factor_2nd order.dgm

     Beginning Time:  17:43:06
        Ending Time:  17:44:13
       Elapsed Time:  00:01:07



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Vita

Bharathwaj Sankaran was born in Tiruchirappalli city, in the State of Tamil Nadu, India. After earning his Bachelors in Civil Engineering from National Institute of Technology, Tiruchirappalli in 2011, he worked in India with the flagship oil refining and marketing company for 2 years as Operations Engineer before beginning his graduate studies at the University of Texas at Austin (UT Austin). While at UT, he received his Masters of Science in Civil Engineering in 2013. His Masters' thesis investigated the factors influencing the lifecycle utilization of digital technologies for highway project delivery. During his doctoral research, he worked on multiple projects funded by the Texas Department of Transportation and the National Cooperative Highway Research Program, the scope of which included both creation and adoption of BIM for highway industry. His doctoral studies focused on assessing the state of practice of digital technologies, identification of process-related specifications, and formulation of a maturity model for benchmarking. He also worked as a BIM Engineer and Construction Specialist intern with a reputed EPC firm in Colorado, where he assumed responsibilities for modeling and creating BIM standards and workflows. In 2016, he also obtained a Graduate Portfolio in Applied Statistical Modeling. He is a student member of ASCE and is also a reviewer for ASCE Journal of Computing in Civil Engineering and Journal of Construction Engineering and Management.

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