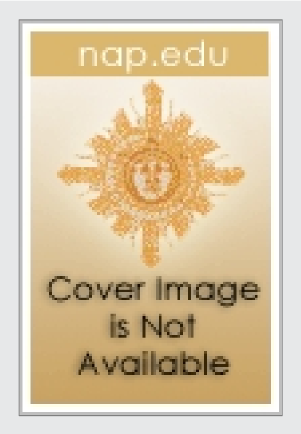

Civil Integrated Management (CIM) for Departments of Transportation, Volume 2: Research Report

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 831

Civil Integrated Management (CIM) for Departments of Transportation

Volume 2: Research Report

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2016

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research is the most effective way to solve many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

Recognizing this need, the leadership of the American Association of State Highway and Transportation Officials (AASHTO) in 1962 initiated an objective national highway research program using modern scientific techniques—the National Cooperative Highway Research Program (NCHRP). NCHRP is supported on a continuing basis by funds from participating member states of AASHTO and receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board (TRB) of the National Academies of Sciences, Engineering, and Medicine was requested by AASHTO to administer the research program because of TRB's recognized objectivity and understanding of modern research practices. TRB is uniquely suited for this purpose for many reasons: TRB maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; TRB possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; TRB's relationship to the Academies is an insurance of objectivity; and TRB maintains a full-time staff of specialists in highway transportation matters to bring the findings of research directly to those in a position to use them.

The program is developed on the basis of research needs identified by chief administrators and other staff of the highway and transportation departments and by committees of AASHTO. Topics of the highest merit are selected by the AASHTO Standing Committee on Research (SCOR), and each year SCOR's recommendations are proposed to the AASHTO Board of Directors and the Academies. Research projects to address these topics are defined by NCHRP, and qualified research agencies are selected from submitted proposals. Administration and surveillance of research contracts are the responsibilities of the Academies and TRB.

The needs for highway research are many, and NCHRP can make significant contributions to solving highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement, rather than to substitute for or duplicate, other highway research programs.

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C O O P E R A T I V E   R E S E A R C H   P R O G R A M S

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The research team wishes to thank the many people who have supported this research, not the least of which are the members of the NCHRP Project 10-96 panel. The panel provided invaluable feedback for focusing the broad topic of CIM to lead to a usable guidebook for departments of transportation. We have had assistance with data collection and useful feedback from individuals too numerous to list from DOTs, private industry, and Crossrail. This project truly reflects the wisdom and experience of the community engaged in CIM implementation.

FOREWORD

By Andrew C. Lemer
Staff Officer
Transportation Research Board

NCHRP Report 831: Civil Integrated Management (CIM) for Departments of Transportation, Volume 1: Guidebook, and *Volume 2: Research Report,* present guidance for state departments of transportation (DOTs) and other agencies for adopting and applying practices and tools entailing collection, organization, and management of information in digital formats about a highway or other transportation construction project. The business of facility production and management is moving rapidly toward all-digital practices, driven by the increasing availability, accuracy, and affordability of digital formats and advances in design technology and in-field positioning that use these formats. Much of the leadership for development and adoption of CIM practices has come from construction contractors, but DOTs and other transportation agencies stand to realize significant benefits from increased adoption of CIM. CIM can serve all project stakeholders, consistently providing appropriate, accurate, and reliable information from the asset's initial planning through its in-service maintenance. The guidance and background information presented in this two-volume report will be helpful to DOT staff and others responsible for the agency's project development and delivery activities.

The term *civil integrated management* has been adopted in recent years to encompass an assortment of practices and tools entailing collection, organization, and management of information in digital formats about highway or other transportation construction projects, that is, "horizontal construction." The term derives from similar practices used in production of building structures—vertical construction—under the umbrella term building information modeling (BIM), so called because these practices entailed generation and management of digital representations of physical and functional characteristics of places. Traditional practices for project delivery and physical asset management have relied on analog display and archiving methods—notably drawings, plans, printed specifications, and traditional survey methods—and required practitioners to mentally visualize in three and four dimensions (that is, space and time) what was represented by flat graphics. In recent years, increasingly sophisticated digital technologies enable computation to supplement or replace imagination. Formerly separated activities of facility design, construction, operation, and maintenance increasingly can be integrated to support effective life-cycle management.

Construction contractors have embraced BIM and CIM practices that help them estimate and control costs, manage job sites, and increase the quality of their products. Designers and facility managers likewise derive benefits from the increased ability to avoid conflicts among facility components and ensure that specifications are correct and met in the field. CIM can serve all project stakeholders (for example, owner, operator, constructor, designer, surveyor, planner, and operations or asset manager) by consistently providing appropriate, accurate, and reliable information throughout an asset's life cycle.

CIM practices have been successfully used in a number of notable projects, but they are not yet widely adopted in transportation projects of all scales. Neither the benefits nor the costs and management risks associated with adoption of CIM are as yet well understood. The objective of NCHRP Project 10-96, "Guide for Civil Integrated Management (CIM) in Departments of Transportation" was to develop a guide to CIM that would assist DOT managers to (a) assess their agency's use of digital information in project delivery and subsequent asset management; (b) improve project quality and more effectively control costs through increased reliance on digital project delivery and asset management; (c) identify the particular opportunities, benefits, obstacles, and costs for their agency through increased reliance on digital project delivery and asset management; and (d) identify practical strategies for increasing reliance on digital project delivery and asset management. The research was intended to draw on practices in vertical construction, case studies, and other experience of transportation agencies at various levels of reliance on digital project delivery and asset management.

The research was conducted by a team led by the University of Texas at Austin. The research team reviewed the literature and current practices in design and construction to characterize the current state of CIM practice and document the information flows typical in transportation-project delivery. Through this work and interviews with representative practitioners, the research team formulated guidance for transportation agency staff on how to consider effective mechanisms for adoption and expanding application of CIM. Useful background information from the research team's work is presented in the Research Report (Volume 2) that accompanies the Guidebook (Volume 1).

CONTENTS

CHAPTER 1

Introduction

This Research Report is a companion document to the *NCHRP Report 831: Civil Integrated Management (CIM) Implementation for Departments of Transportation, Volume 1: Guidebook.* The research team suggests readers read the Guidebook first for implementation guidance. This Research Report provides details of the research findings on CIM implementations through survey and case study research. While this report is a stand-alone document, readers may benefit from reviewing the Guidebook and then referencing this report for specific details.

"Civil Integrated Management (CIM) is the technology-enabled collection, organization, managed accessibility, and the use of accurate data and information throughout the life cycle of a transportation asset" (FHWA 2012). The focus of CIM is on promoting successful and effective life-cycle applications of modern technologies—such as information modeling, advanced surveying methods, subsurface mapping of utilities, and automated machine guidance (AMG)—and integration of project data with transportation asset management plans, among others. 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.

In practice, CIM is a set of technologies and processes that improves the predictability of project performance and leads to better outcomes at different stages of the construction life cycle—conceptual planning, design and engineering, procurement and construction, commissioning, and operations and maintenance (O&M). Implementation of information modeling and related digital technologies has seen considerable success in the building and commercial sector. These tools can also provide significant short- and long-term benefits as well as process improvements for transportation projects (Dodge Data & Analytics 2012). Researchers and practitioners have empirically demonstrated the positive impacts of digital technologies on several project work processes, such as design visualization, clash detection, utility relocation and coordination, constructability reviews, and work area management. The necessity to coordinate with many stakeholders (such as utility companies, governmental agencies, commuters, and businesses) within the project corridor emphasizes the importance of availability and accessibility of quality data to facilitate coordination and decision-making throughout project delivery. Yet, the widespread integration of digital practices in highway infrastructure delivery is limited because of several process challenges (O'Brien et al. 2012). Working with engineering packages and deliverables in 2D (that include plans, profiles, and cross sections) not only reduces the role and utility of electronic data, but also poses data integration challenges for tasks that require extensive collaboration, such as design reviews, conflict analysis, and constructability, among others.

Advances in design technology, computational power, and positioning systems have opened up possibilities to better integrate digital technologies into project delivery and mitigate some of the challenges stemming from traditional workflow. With many DOTs showing intent to execute their projects utilizing CIM technologies, there is an imperative need to analyze the current state of practice of CIM in its entirety and document the benefits and challenges associated with the increased use of CIM. The NCHRP Project 10-96 research team conducted research to address this objective and developed a generalized implementation framework to help systematize agency-wide efforts for advancement of CIM tools and practices.

This Research Report synthesizes the key findings from the literature review, the data sources considered throughout the project, the findings of the state-of-practice surveys, and the lessons learned from the case studies. It illustrates the methodical formulation of the implementation framework from the research findings. The Research Report also contains a summary of DOT practitioners' and external subject matter experts' observations on the utility, format, and content of the Guidebook.

1.1 Readers' Guide

Chapter 2 presents information from the literature review on CIM tools and functions. A global perspective on CIM has also been provided to give an understanding of relevant best practices and trends of CIM in other countries.

Chapter 3 lays out the contractual objectives used to develop the implementation Guidebook—*NCHRP Report 831: Civil Integrated Management (CIM) Implementation for Departments of Transportation, Volume 1: Guidebook*.

Chapter 4 presents the research methodology followed to address the overall objective of this research. The research team used various approaches in this effort, including an extensive literature review, two national surveys, and detailed case studies.

Chapter 5 explains the objectives and the results of the two nationwide surveys conducted as part of this research. The research team used the survey responses to determine the current state of practice of CIM and understand the agencies' capabilities related to their level of CIM use. The findings from a statistical analysis of the agencies' surveys are summarized to show empirical insights into some of the relevant issues and anticipated changes in project delivery processes that result from CIM implementation.

Chapter 6 presents the case study results that provide an in-depth understanding of the steps involved in integrating CIM with project work processes. The seven case study descriptions cover project characteristics and focus on CIM practices in project delivery processes. Significant inferences from each case study and lessons learned are also presented through cross-case analysis.

Chapter 7 demonstrates the process used to develop the three-stage implementation framework that is included in the Guidebook. It contains narratives supporting the development of the framework from the associated research findings. A report of the validation survey is also included to confirm the reliability and usability of this implementation plan at agencies.

Finally, Chapter 8 contains the conclusion and potential extensions of this work for future research.

CHAPTER 2

Literature Review

2.1 Overview of CIM Tools and Functions

As a system, CIM consists of both foundational processes and emerging practices in the highway construction sector. As the technology has grown, so has the taxonomy and definitions. This chapter explains CIM's scope and the associated terms. CIM encompasses several technologies that have the potential to improve the performance and predictability of the related project work processes, including scoping, surveying, design, construction, operations, and maintenance. The primary objective is to enable a transition to digital project delivery to better align it 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). To understand the benefits of CIM and develop systematic guidelines, it is helpful to classify CIM into two categories:

- *CIM tools category*, which includes the associated technologies and tools
- *CIM functions category*, which contains the functions (work areas) that one or more of the highlighted CIM tools improve or transform

As per FHWA, CIM, in its entirety, also encapsulates contractual and legal considerations (FHWA 2012). It is important to address these considerations when incorporating CIM functions into projects.

2.1.a CIM Tools

CIM tools represent fundamental, core technologies. They enable the opportunity to find new and improved solutions for performing project delivery functions. Figure 2.1 enumerates the list of CIM tools and their codes under three categories (used herein for identification purposes): modeling, data management, and sensing. An overview of the various CIM tools is included in Section 2.1 of the Guidebook.

2.1.b CIM Functions

Technology implementation positively affects the project's performance by transforming the functions in the pertinent project work areas. Figure 2.2 enumerates the identified CIM functions and clusters them under project activities. In this figure, project activities do not correspond to project phases. Rather, they represent a group of CIM functions that supports the broad activities of surveying, design, construction, and project management. This figure also depicts the functions mapped to the relevant CIM tools (see Section 2.1 of the Guidebook for CIM tool identification codes and descriptions). Each of the mapped CIM tools can transform or improve the processes associated with a function in a certain way.

The descriptions of the functions under four categories—Surveying, Design, Construction, and Project Management—are presented in Section 2.2 of the Guidebook.

2.2 CIM Trends and Strategies—A Global Perspective

As transportation projects increase in complexity, project personnel are resorting to various CIM technologies to ensure quality, on time, on budget project delivery. Civil infrastructure projects such as highway construction are complicated by design complexity, funding regulations, right-of-way (ROW) acquisition, utility relocation, and traffic management. There is an enormous amount of information that is being generated, organized, analyzed, and managed during various phases of a project (O'Brien et al. 2012). All these issues entail an inherent need for applying technologies to make the delivery of the project faster, safer, and of better quality. Table 2.1 provides a glimpse of the current practices of information modeling in

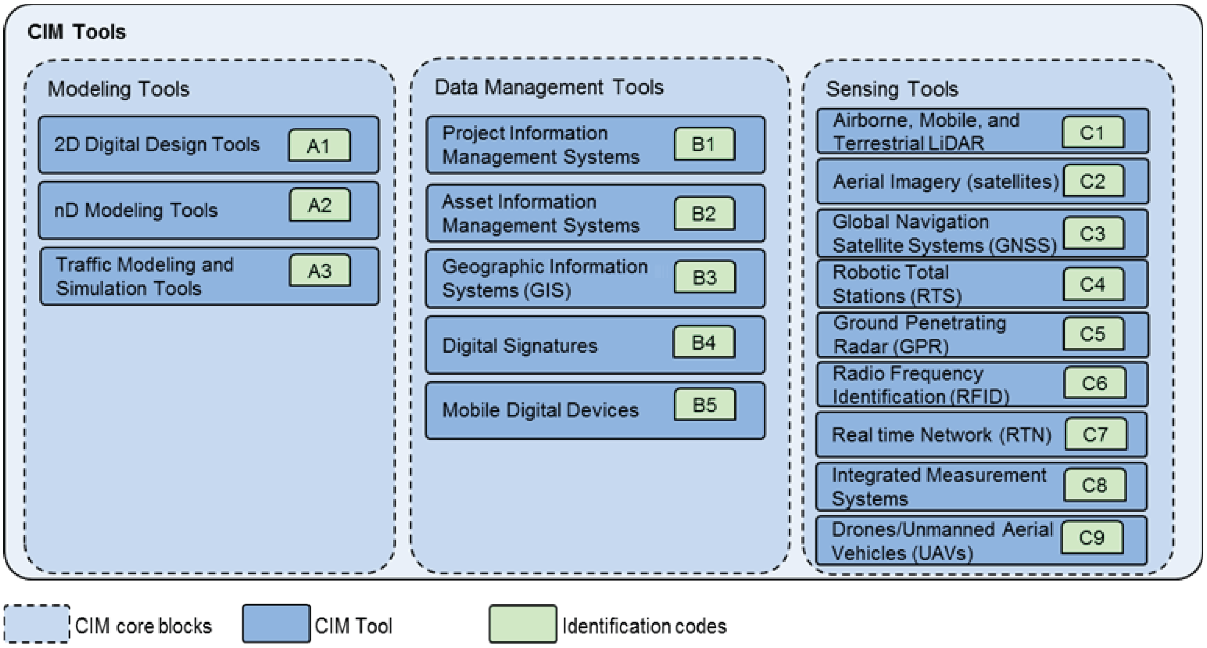


Figure 2.1. Pictorial representation of CIM tools.

various countries around the world (Construction Industry Council, Hong Kong 2011).

The governments of many countries have been actively involved in promoting or mandating the deployment of information modeling on infrastructure projects. In countries such as China, Japan, and Korea, the construction industry is driving its use for apparent benefits. In the United States, the U.S. Army Corps of Engineers is at the forefront of adopting information modeling for public infrastructure projects. With respect to highway construction, the leadership in promoting CIM has come from sophisticated construction contractors, with some state DOTs and other transportation agencies on-board. Note that in Table 2.1, and in later sections of this report, the term "CIM" has been replaced by "BIM" or "BIM for infrastructure" for the transportation infrastructure projects outside the United States. Though the technology and

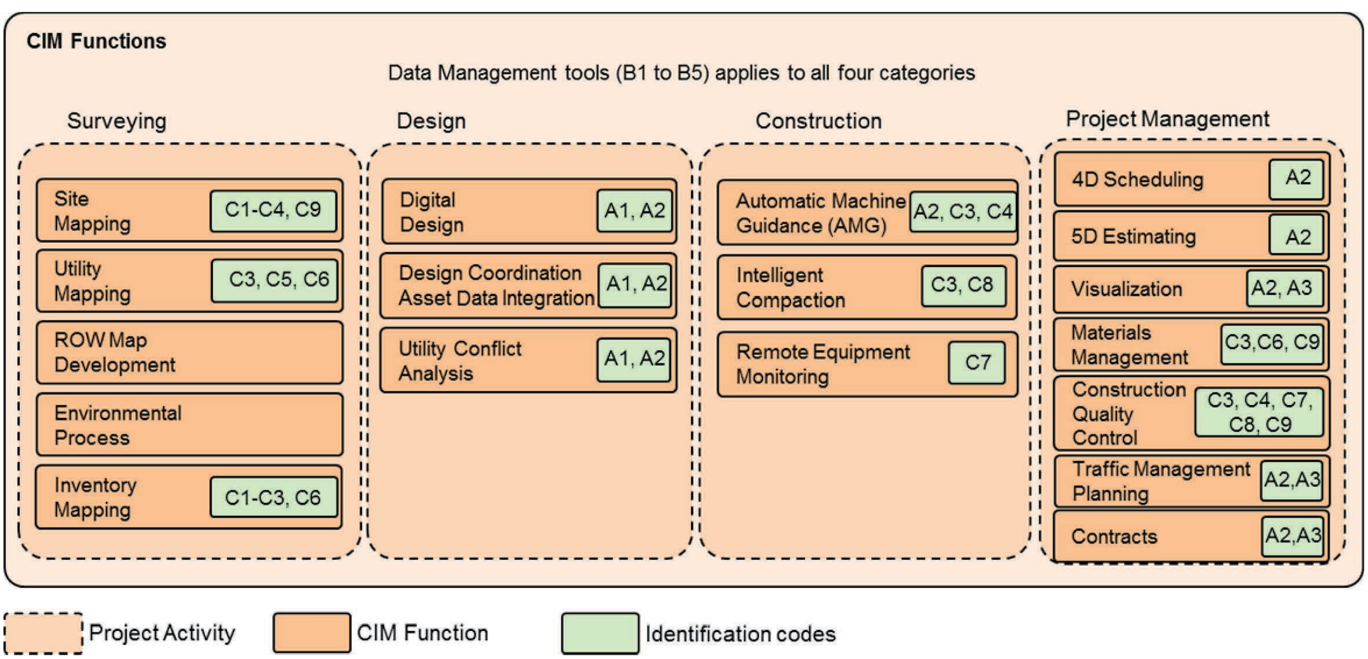


Figure 2.2. CIM functions (mapped to their corresponding CIM tools).

Table 2.1. Information modeling across the world—an overview.

Country	Type of Organization	Driving Organization/Agencies	Strategy
USA	Public companies	American Institute of Architects, General Services Administration, U.S. Army Corps of Engineers	Decided in 2008 to migrate to building information modeling (BIM)*.
		State DOTs of Wisconsin, Texas, Florida, California, and Michigan	Many modern techniques being practiced on many projects.
		City of Las Vegas	Created a preliminary 3D model of its underground utilities.
UK	Government	Crossrail Project	Project implemented collaborative BIM in 2009.
		The Cabinet Office of Government Construction Board, UK Government	Implement BIM by 2016 BIM UK Strategy Report (March 2011).
		London's Heathrow Airport	A case study demonstrating several strategies for improving accuracy of relocation information about underground utilities.
Canada	Association	CanBIM Council, The Institute for BIM in Canada	Aligned industry to promote use of BIM University of British Columbia published case studies report.
Australia	Public Organization	Organizations such as Australian Productivity Commission, the Australian Construction Industry Forum	Issued "BIM in Australia 2010 Report."
Denmark	The Royal Government	Individual state clients	Danish state clients such as the Palaces & Properties Agency, the Defence Construction Service, and the Danish University Property Agency required BIM use for their projects. Mandated use of BIM for projects > €2M.
Singapore	Government	Building & Construction Authority (BCA)	Enhanced the electronic plan submission system to mandate BIM use by 2015.
China	Industry	Private sector	Successful BIM use in Shanghai Tower project attracted attention.
	Government	Government	BIM included in the National 12th Five-Year Plan.
Hong Kong	Private sector	Building industry, Hong Kong Institute of BIM, BIM software vendors	Used by large contractors and developers. Actively studied by public sector, railway operator. BuildingSmart Hong Kong inaugurated in Hong Kong in late April 2013. Building department's "Feasibility study on implementation of electronic submission system in building" study to be completed in September 2013.

(continued on next page)

Table 2.1. (Continued).

Country	Type of Organization	Driving Organization/Agencies	Strategy
South Korea	Government	Public Procurement Service	Actively studied (especially in 4D) BIM application; South Korea's Public Procurement Service made the use of BIM compulsory for all projects over $50 million and for all public sector projects by 2016.
Japan	Multiple agencies	Universities, construction industry	Actively studied BIM implementation.
France	Government	National Institute of Geographic and Forest Information (IGN) and utility companies	A large 10-year, multi-billion euro project involving IGN and France's utilities to map France's entire underground utility infrastructure in 3D to an accuracy of 40 cm (about 16 in.).

*The term "BIM" is used in the table as a synonym for CIM; BIM is the term used internationally.

concepts remain the same, the term CIM is not frequently used in other countries.

2.2.a CIM in the United States—Trends and Projections

Information modeling and its utilization and integration throughout the project life cycle forms the basic tenets of CIM. The level of CIM adoption and use in the infrastructure sector is lagging behind vertical construction, but infrastructure projects are well suited to benefit from a model-driven digital approach to design, construction, and asset management, which supports the need for increased usage and broad acceptance of CIM in this sector (Dodge Data & Analytics 2014b).

The adoption of information modeling has seen a significant increase worldwide in the areas of building, infrastructure, and construction management. The percentage of companies using BIM jumped from 17% in 2007 to 71% in 2012 in North America. SmartMarket Report: The Business Value of BIM for Infrastructure presents a summary of a survey that involved 466 respondents across various infrastructure sectors in the United States (Dodge Data & Analytics 2012). Some of the interesting findings follow:

- Of all users, 67% reported a positive return on investment (ROI) for BIM use on infrastructure projects. Respondents were asked to estimate ROI in seven broad categories: negative, break-even, less than 10%, 10 to 25%, 26 to 50%, 51 to 100%, and over 100%.
- Of current users, 79% were expected to be using BIM on more than 25% of their infrastructure projects by 2013.
- Major investments were in marketing BIM capabilities, and software and hardware upgrades.
- Top benefits included reduced conflicts and changes (58%), improved project quality (48%), and lower project risk and better predictability of project outcomes (60%).
- The areas reported as weakest in implementation include software interoperability, workforce education/training, and legal and contractual issues.

Figure 2.3 shows that irrespective of an infrastructure sector, implementation of information modeling has been consistently on the rise. Specifically, the road transportation sector has seen an increase of 180% in adoption of CIM from the years 2009 to 2012. The acceptance of the model-driven approach for design and construction reiterates the need for all stakeholders to devise a tailored approach and establish guidelines in their respective agencies to facilitate seamless transition to digital project delivery and asset management.

Figure 2.4 shows that more than 51% of projects represent a "high/very high" utilization rate of technologies, with the report predicting that this number will likely increase in the future. The report also suggested that 89% of the agencies (architecture/engineering firms, contractors, and owners) had responded positively to the value offered by using information modeling in their projects.

The focus for this review is on analyzing the technology-related trends and projections for major roads and highway projects in the United States. With specific reference to transportation projects, a recent literature review conducted of state DOTs revealed the following statistics on usage level of CIM (FHWA 2013):

- State DOTs reported varying levels of 3D model usage (some are advanced, while some model the basic roadway prism).

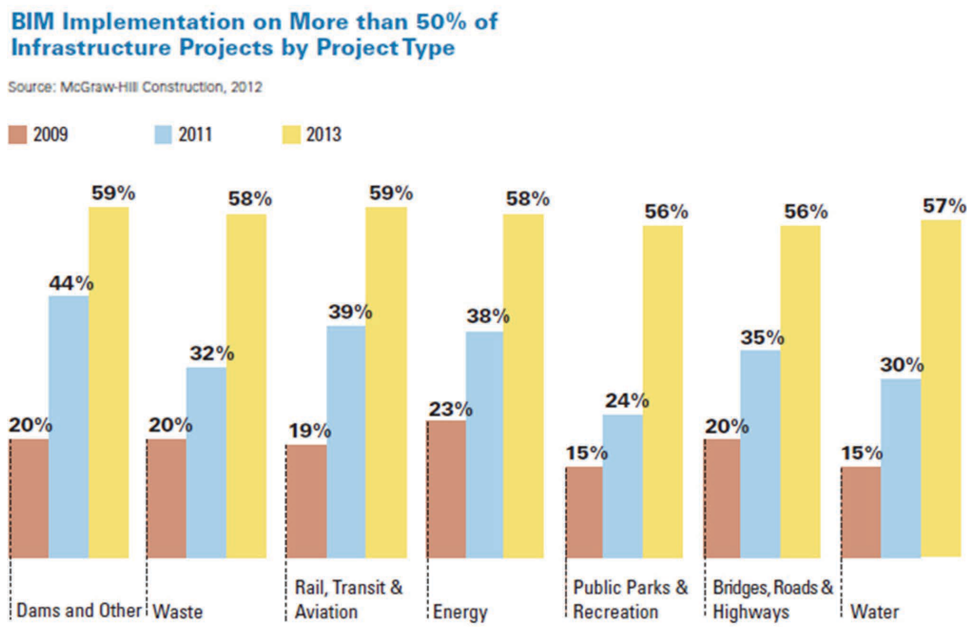


Figure 2.3. Level of adoption of BIM in infrastructure projects in various sectors. (Source: Dodge Data & Analytics 2012.)

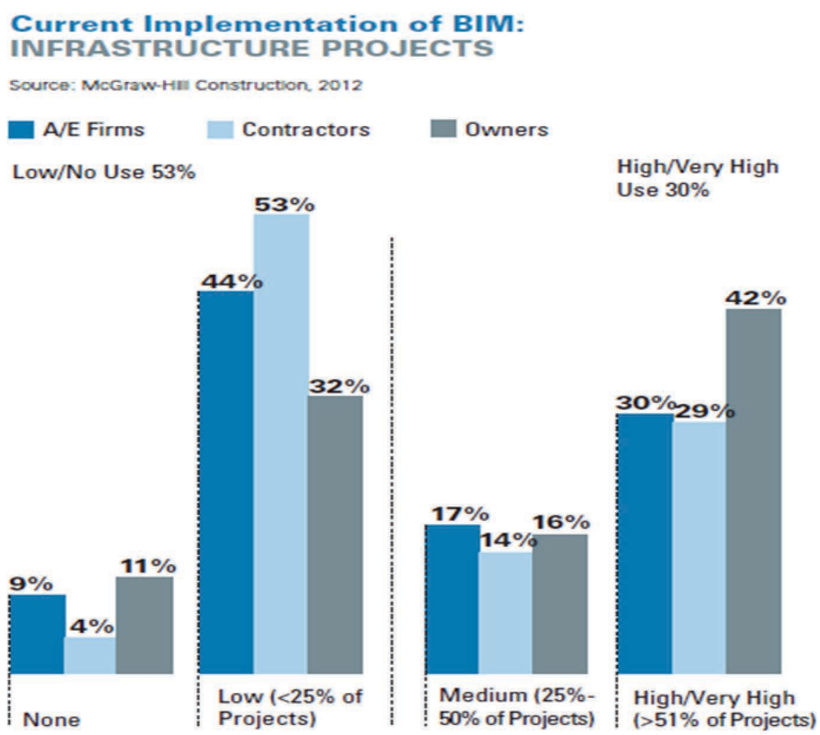


Figure 2.4. Agencies promoting application of BIM. (Source: Dodge Data & Analytics 2012.)

- Twenty-three state DOTs reported having already transitioned to 3D modeling.
- Seven state DOTs were using only traditional 2D plans and profile sections.
- Fifteen state DOTs stated that they were transitioning to 3D modeling.
- Of the state DOTs using 3D modeling software, 28 use Microstation and InRoads; 13 use Microstation and Geopak; 2 use Civil 3D; and 7 use Civil 3D and Microstation.
- Slightly more than one-half of state DOTs were using some type of LiDAR technology (aerial, static, or mobile). More statistics on LiDAR usage can be found in the *NCHRP Report 748* (Olsen 2013).

2.2.b BIM for Infrastructure in the UK

In the United Kingdom, the government's construction strategy mandates the use of BIM by 2016 to reduce carbon and costs as part of the overall economic development (Government Construction Client Group 2011). An important objective of this BIM strategic paper is a commitment to BIM on government projects over a 5-year time frame, and mandating a shift to BIM maturity Level 2 from 2016 onward as shown in Figure 2.5. The maturity models help in clearly articulating the levels of competence expected and the supporting standards and guidance notes pertaining to each level. It is also mandatory to categorize the types of collaborative environment and gain an understanding of the tools, techniques, and processes used at each level for organization and projects. While maturity Levels 0 and 1 mandate just the utilization of 2D/3D CAD with some standard data structures and formats (with no integration), Level 2 involves deploying BIM and Enterprise Resource Planning for data management and Level 3 mandates deploying a full-scale open data integration process assisted by Industry Foundation Classes (IFC) (referred to as *integrated BIM* or *i-BIM*). IFC is the open and neutral data format for OPEN BIM.

The report revealed an interesting finding: European BIM users—though fewer by percentage—are generally more involved in utilizing BIM than their counterparts in North America (Dodge Data & Analytics 2010). The UK also has many interest groups facilitating the industry-wide application of BIM and addressing the demands of the construction sector. Selected groups are described below.

The BIM Task Group

The objective of the BIM Task Group is to aggregate the expertise from industry, government, public sector, institutes, and academia (BIM Task Group, UK 2014). With the construction strategy established by the Cabinet office in 2011, the UK government mandated collaborative 3D BIM (with all project and asset information, documentation, and data being electronic) on its projects by 2016. This measure will not only make the application of BIM compulsory but will also decrease the construction industry's capital costs and the carbon burden

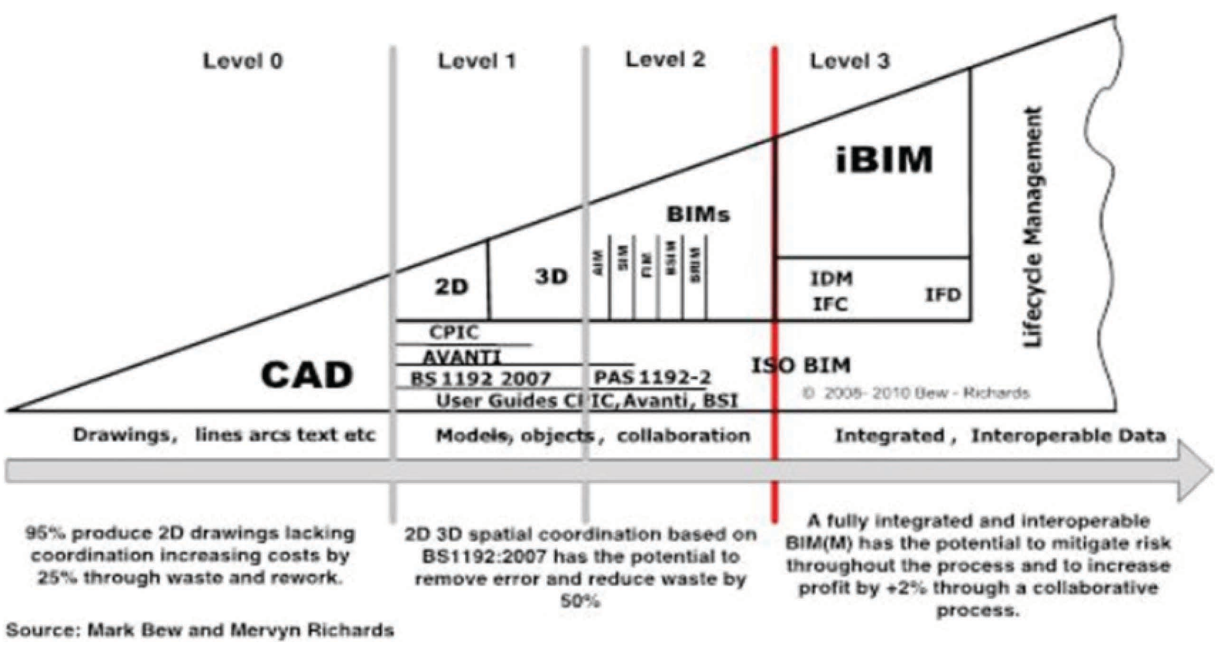


Figure 2.5. Maturity Levels of BIM Application. (Source: Government Construction Client Group 2011.)

from the life cycle of facilities by around 20%. Deployment of BIM technologies and other collaborative strategies is vital to progress toward efficient ways of working at all stages of the project life cycle (BIM Task Group, UK 2014).

A notable partner of this task group is *BIM 4 Infrastructure (UK)*. It is a Special Interest Group within the Association of Geographic Information, which is supported by the Institution of Civil Engineers, the Government BIM Task Group, and the Construction Project Committee. The group's objectives are to encourage knowledge sharing and learning between its members; assist appropriate industry bodies and institutions regarding application of BIM; identify and promote infrastructure-related case studies that demonstrate best practice and the integrated management of information across all stages of the asset life cycle; and explain how BIM and geospatial information can be integrated. Another important group promoted by the BIM Task Group is the *Infrastructure Asset Data Dictionary for UK*, whose objective is to develop a common asset data dictionary compatible for all UK infrastructure assets (BIM Task Group 2011).

OPEN BIM Network

The OPEN BIM Network is a UK-based independent, open, and non-product-specific group facilitated by Constructing Excellence, a construction sector organization. The group analyzes the common issues involved in implementing BIM and other technological tools by the construction sector (buildingSMART UK User Group 2014). It publishes periodical open-source magazines (*OPEN BIM Focus*) that report on issues relating to the successful implementation of BIM (challenges, organizational factors, market perceptions, etc.). Some relevant snapshots from Issue 2 of the magazine are shown in Figure 2.6.

2.2.c BIM for Infrastructure in Singapore

In Singapore, the Building and Construction Authority (BCA) implemented the "BIM Roadmap in 2010 with the aim that 80% of the construction industry will use BIM by 2015. This is part of the government's plan to improve the construction industry's productivity by up to 25% over the next decade" (Seng 2012). To increase the demand side of BIM, the BCA has implemented a strategy through which the public sector has been vested with the responsibility to lead the application of BIM. As per this measure, all the government/public enterprises were asked to use BIM in their projects beginning in 2012. To promote the widespread application of BIM and to increase the stakeholders' confidence regarding its reliability, the BCA created the Centre for Construction Information Technology to establish guidelines for business and professionals in the industry. To help the public sector lead the way, the BCA identified public sector procurement as an important strategy in the BIM Roadmap.

The BCA has adopted three major approaches to increase the collaborative usage of BIM (including improving the private's sector usage levels):

- Partnering with government entities
- Training public sector consultants
- Reaching out with joint industry efforts

The World's First BIM-Based e-Submission System

The BCA led a multi-agency effort in 2008 to create the world's first BIM-based electronic submission (e-submission) system via the Construction Real Estate NETwork (CORENET). The BIM-based e-submission system streamlined the process for regulatory submission. The project teams only needed to submit one building model, which contains all of the information needed to meet the requirements of a regulatory agency. By standardizing the way BIM models were being prepared across the industry, the process enabled members of the project team to efficiently share their data and plans across various construction disciplines. Building professionals could also use the same BIM model to perform value-added analysis. In 2010, nine regulatory agencies accepted architectural BIM 3D models for approval through CORENET. This was followed by the acceptance of mechanical, electrical, and plumbing (MEP), and structural BIM models in 2011. More than 200 projects have made BIM e-submissions as of July 2013. The effort had been lauded by the World Bank Group, Autodesk, and other interested stakeholder communities.

Successful case studies from Singapore include the ArtScience Museum at Marina Bay Sands, for which Arup Singapore developed fabrication-level digital models to reduce both the client's and the contractor's risks. The time to complete the project was also reduced by 3 months. The Housing and Development Board (HDB) completed two housing projects that used the BIM template for modeling and regulatory submission. HDB achieved up to 45% savings in work force in the preparation of building plans.

2.2.d BIM for Infrastructure—Other Countries

Information modeling adoption in the United States, UK, and Singapore have been discussed. This section summarizes the level of BIM utilization in other countries such as South Korea, France, and Germany based on findings by Dodge Data & Analytics (2014a).

The adoption of BIM is new to South Korea, and the industry has been cautious about adopting this new technology that affects so many aspects of the workflow. Only 13% of the

Figure 2.6. Perceived benefits and challenges of BIM. (Source: buildingSMART UK User Group 2014.)

contractors report being very heavy users, that is, using BIM on more than 60% of their projects. The production of "more accurate construction documents" was cited as the top benefit that would entice non-users in South Korea. Though the country is making significant strides in BIM adoption, current users perceive business and industry elements, such as contractual issues and the lack of sufficient project participants with BIM capabilities, as the most critical challenges to improving their current ROI on BIM (Dodge Data & Analytics 2014a).

BIM has generated a significant user base with high skill levels in Western Europe, although these users are still in the minority in terms of the overall industry (Dodge Data & Analytics 2010). In a survey published in *The Business Value of BIM in Europe*, France had the highest adoption rate of BIM (38%) among construction professionals surveyed (Dodge Data & Analytics 2010). French BIM users were the most optimistic about the ROI they get from BIM. Eighty-two percent of users perceived that they would get positive ROI, with 42% seeing ROI of 25% or more. Five percent of respondents reported getting negative ROI. They inferred that BIM provided the most value through reduced conflicts during construction (76%) and improved collective understanding of design intent (71%). France has also undertaken a significant initiative through a 10-year, multi-billion-euro project involving National Institute of Geographic and Forestry Information and major utility companies to map their entire underground utility infrastructure in 3D to an accuracy of 16 in. (Zeiss 2014). In comparison to French and Korean users, German BIM users reported the lowest positive perceived ROI at 67%. They were more aligned with UK users in that they saw the most value from BIM: reduced conflicts during construction (63%), improved collective understanding of design intent (58%), and reduced changes during construction (58%).

In summary, the construction sector worldwide has recognized the need for a paradigm shift in project management, paving the way for processes and technologies that can make digital project delivery a reality for infrastructure projects. Design complexity, project size, alternative delivery methods, compressed project schedules, shrinking profit margins, funding regulations, and work-zone traffic management have been catalysts for this transformation. Moreover, the amount of data and 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. Specifically, the highway agencies in the United States have used different sets of CIM tools depending on their functional/divisional capabilities and the project characteristics. As such, these agencies reflect varying levels of expertise and maturity in CIM implementation for project delivery and asset management. Many of these tools and technologies are being incorporated in various projects organically as engineers, consultants, and surveyors involved in developing these projects see cost/time savings, efficiency, and quality improvements through their use. The deployment of CIM is uncoordinated and uneven across DOTs and the specific challenges of transportation projects make direct translation from BIM implementations in other sectors intractable. DOTs need implementation guidelines that are scalable and customized to their business practices, delineating the anticipated investment needs and potential benefits from CIM technologies. The Guidebook will help agencies channel their efforts toward effective deployment of CIM tools and systematically support integration practices with project delivery methods and management practices across project life cycles.

CHAPTER 3

Research Objective

The topics discussed in the literature review highlight several points that need further investigation. The overall objective of NCHRP Project 10-96 was to develop a guidebook for CIM that DOT managers can use to obtain the following objectives:

1. Assess their agency's use of digital information in project delivery and subsequent asset management.
2. Improve project quality and more effectively control costs through increased reliance on digital project delivery and asset management.
3. Identify the particular opportunities, benefits, obstacles, and costs for their agency through increased reliance on digital project delivery and asset management.
4. Identify practical strategies for increasing reliance on digital project delivery and asset management.

With these four objectives in mind, the research team produced a comprehensive CIM implementation guidebook. This document, published as *NCHRP Report 831: Civil Integrated Management (CIM) Implementation for Departments of Transportation, Volume 1: Guidebook*, consists of a framework and steps to enhance agencies' use of CIM technologies in their project delivery processes. This Research Report provides details of the data collection process and the outcomes of the research methods used to develop the Guidebook.

CHAPTER 4

Methodology

The research team adopted multiple approaches to adequately address the breadth and depth of issues of the research objectives. First, a detailed literature review was conducted to collect information about the CIM tools and functions that are used on projects, their implementation challenges, and resulting lessons learned. The scope of the review included pertinent FHWA and NCHRP publications, state DOT specifications, academic journals, and other reliable open source data on CIM (Chapter 2). This process was followed by two nationwide surveys designed to capture the levels of integration of CIM technologies for project delivery across all DOTs. The outcomes of the review led to refining the queries for the surveys, making them focused on issues relevant for CIM. The analysis of the survey data helped identify projects that have demonstrated successful integration of one or more CIM technologies (Chapter 5). The research team investigated these projects to determine the characteristics and delivery processes that led to the effective use of CIM technologies. The team obtained detailed information for each project through interviews with representatives from each agency and project team. The research team also documented lessons learned concerning benefits and challenges to synthesize the best practices for implementation (Chapter 6). The team developed the three-stage framework that will help agencies assess their current level of CIM integration, determine the future investment needs, and consider the contract and legal issues arising as a result of digital project delivery (Chapter 7). Figure 4.1 displays the research methodology and the associated processes.

Chapter 2 gave an overview of the CIM tools and their impact on different functions that constitute the project delivery process. It provides an understanding of how these functions interact to enable the transition to digital workflow on projects. It describes a workflow for CIM that encompasses key concepts and components that will form the major requirements of digital project delivery in the future. Data, rather than documents, will form the central component for projects using CIM (Guo et al. 2014).

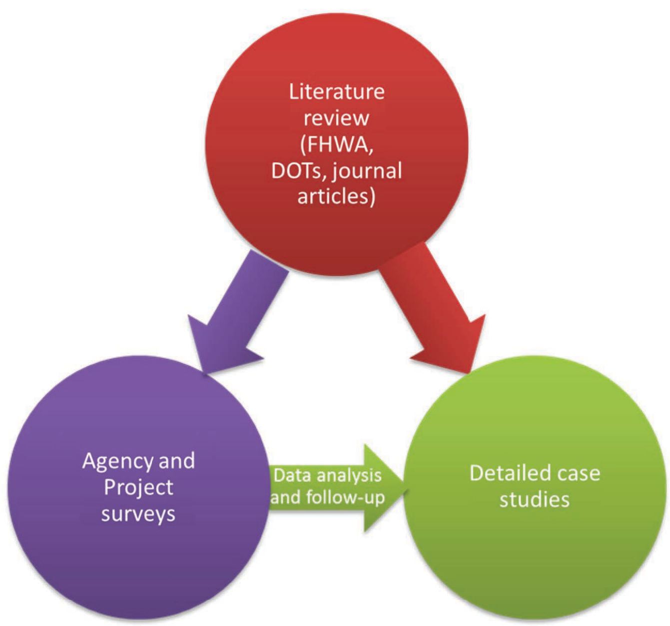


Figure 4.1. Research methodology.

CHAPTER 5

CIM State of Practice at DOTs—Agency and Project Surveys

CIM includes a wide variety of tools encompassing emerging technologies and practices. Literature revealed that no project or agency has systematically implemented CIM in its entirety. Moreover, agencies have different levels of expertise with several CIM technologies. Therefore, the research team decided to conduct nationwide surveys of agencies' practices to comprehend the variety of tools actually being deployed on their projects. These surveys were designed to understand the drivers and the constraints pertinent to the advancement of these technologies on projects. Two questionnaires were prepared to address this objective: agency survey and project survey. The actual questionnaires can be found in the Appendix A and Appendix B, respectively.

5.1 Survey Data

The agency survey was designed to gain an understanding of the incorporation of CIM technologies and availability of standards and guidelines at the organizational level. Questions were included to determine the impact on contracts and legal issues, as were opinion-based queries regarding the perceived benefits and implementation challenges. There were 71 responses, with 64 responses from state agencies (40 different states and 1 Canadian province), 4 responses from FHWA personnel, and 3 responses from engineering firms. The respondents were from different disciplines (survey, design, construction, and traffic management, among others) and areas of work, which provided diverse perspectives and opinions (see Figure 5.1, left). Most of the respondents were also experienced in their respective work areas, thus providing trustworthy and reliable data. Although the majority of the responding entities reported executing projects through design-bid-build (D-B-B), there were numerous responses for alternative contracting methods (see Figure 5.1, right).

The projects survey was designed to identify project characteristics that led to the deployment of specific technologies, and document the support offered by the Project Execution Plan for using CIM technologies. Specific questions were also included to capture the extent of the collaboration of stakeholders contractually or officially in promoting CIM. A qualitative assessment of performance measures of the project was also collected to understand the improvements in the cost, schedule, safety, quality, and avoidance of change orders. Overall, 14 responses were received, describing projects of different sizes (budget) and complexity. A few follow-up interviews were conducted on some projects that reported high levels of use and good performance measures to understand the benefits. A few projects that reported lower levels of use or lower performance measurements were also chosen for follow-up interviews to determine the implementation constraints.

5.1.a Discussion of Results—Agency Survey

The research team analyzed the responses of the survey to determine the various issues for deploying CIM tools on projects, such as technology usage, contractual requirements, organizational considerations, and governance issues. Considering the plethora of options, the usage levels of CIM technologies were evaluated by clustering them thematically into four different groups: 2D, 3D/nD, Sensing, and Data Management. Figure 5.2 displays the list of technologies scanned under these four groups.

At a higher level, different agencies and contractors reported varying levels of expertise in applying CIM technologies on their projects. Factors such as workforce capabilities, performance objectives, funding regulations, and project characteristics primarily tend to dictate the use of particular tools by agencies. Other significant inferences from the agency surveys are described below.

2D and 3D/nD modeling tools lay the foundation for integrating digital practices for design and construction. Figure 5.3 presents a summary chart for the usage level of the 3D/nD technologies group. Many agencies have incorporated 3D modeling at varying levels based on project char-

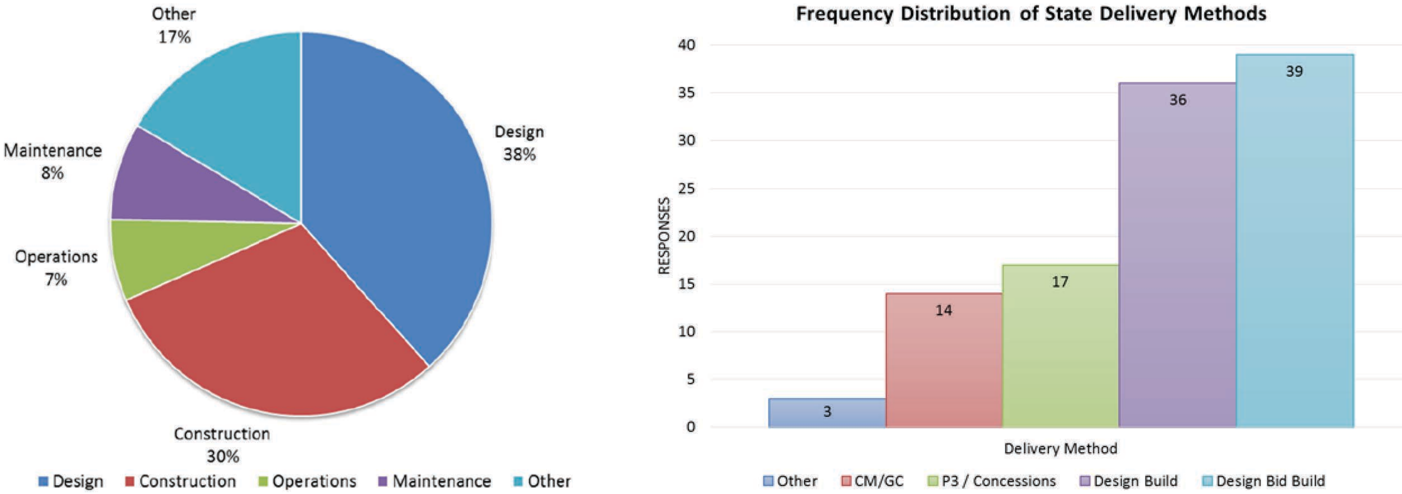


Figure 5.1. Frequency distribution: **(left)** ***participants' disciplines;*** **(right)** ***project delivery methods used in the responding states.***

acteristics. Forty-one percent of the agencies reported using 3D tools for visualization. However, in all the agencies surveyed, 2D plan sets, rather than 3D models, continued to be the governing contract documents. Modeling in 4D and 5D were predominantly used on those projects that had complex construction sequencing (such as bridges) to facilitate visualization and communication among stakeholders. Of the 38 responses for this area, 12% and 6% reported using 4D and 5D, respectively, showing that they remain emerging tools.

The survey inquired about different sensing technologies to determine their integration into project delivery processes. GIS and GPS had the highest reported usage levels—96% and 92%, respectively—since they have numerous applications in project delivery and asset management processes. Intelligent transportation systems (ITS) also showed an encouraging trend, with 89% of respondents reportedly using one or multiple variants. Eighty-four percent of the agency respondents have invested in collecting LiDAR information (3D imaging) of the facilities being built and reported employing it for facility management (such as recording bridge clearances or taking inventory of assets). Participants agreed that AMG using 3D design and intelligent compaction (IC) have proven benefits.

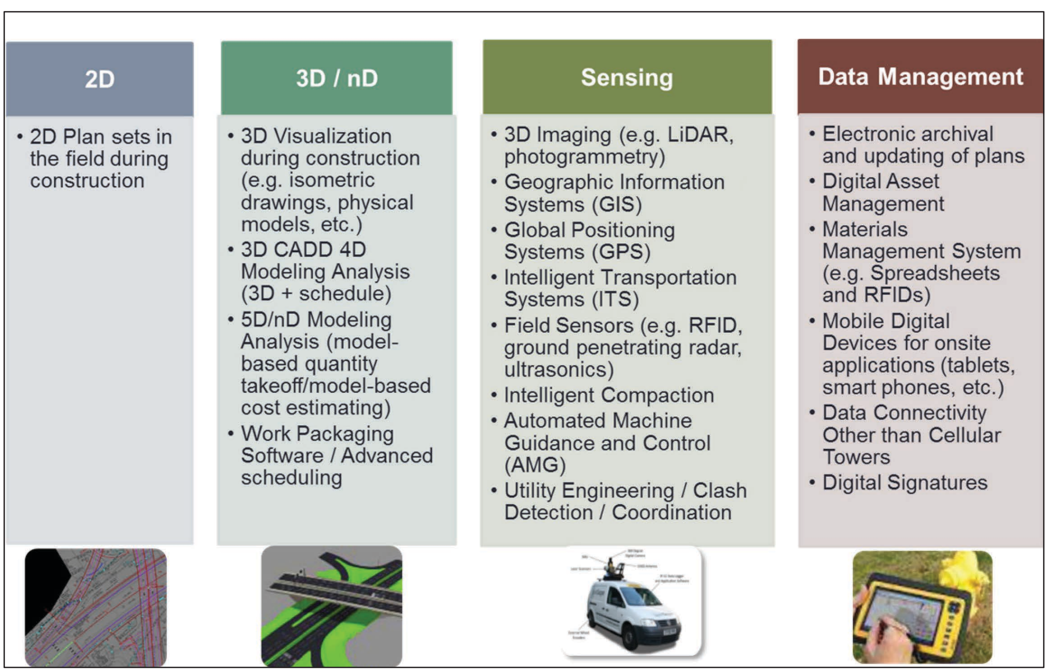


Figure 5.2. CIM technology groups used for surveys.

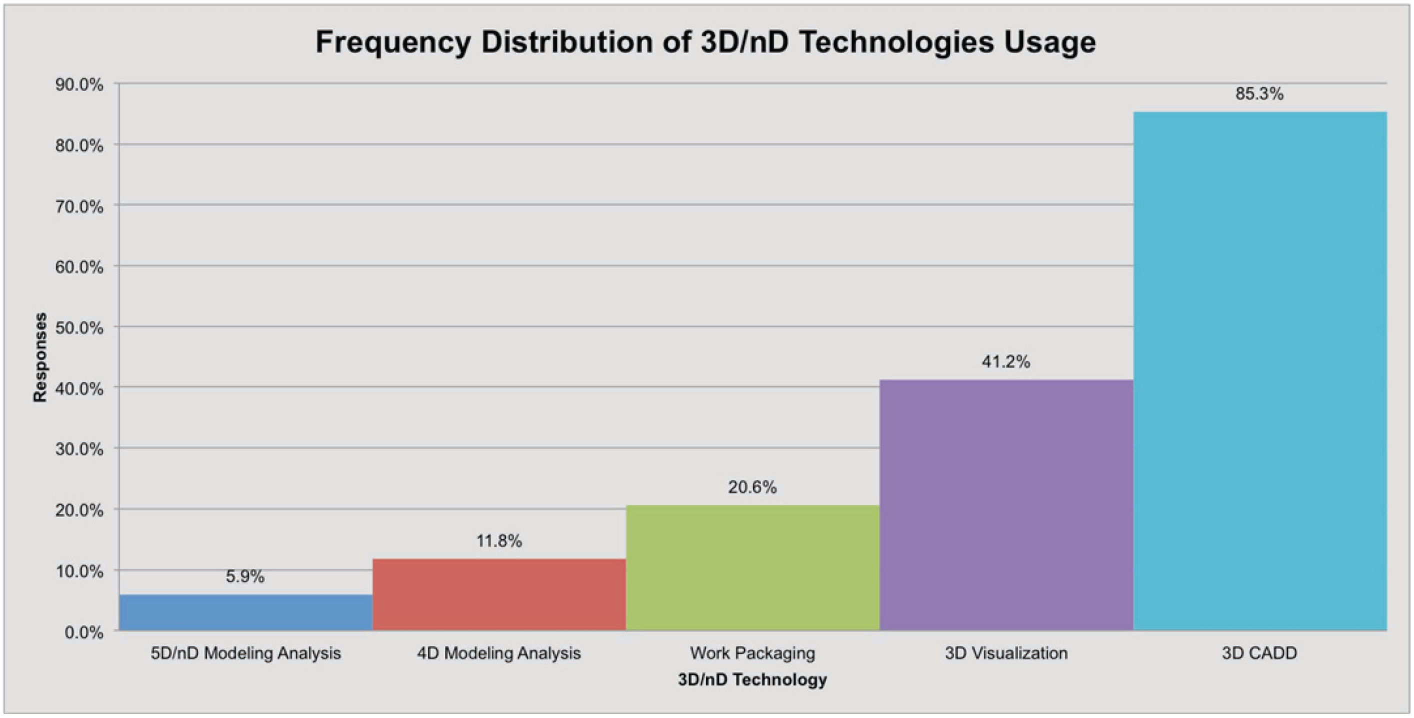


Figure 5.3. Histogram of frequency distribution for 3D/nD group.

However, non-standardization of the associated design processes and initial investment costs of these technologies were cited as a major reason for their lower utilization level. Sixty-eight percent of the respondents reported deploying AMG technology for earthwork operations (albeit not including finished surface stringless concrete/asphalt construction) and around 45% of the agencies reported investing in IC. Utility coordination using subsurface utility engineering (SUE) technologies was recorded at the lowest usage level under sensing technologies. This observation is also reflected in the literature review and the project management practices reported on coordinating with underground utilities. Collection and use of 3D geospatial data for design coordination by deploying advanced technologies (such as ground penetrating radar [GPR] or radio frequency identification [RFID]) remain an emerging practice. Figure 5.4 graphically depicts the usage level of CIM technologies as reported in agency surveys.

While technology can provide tools to facilitate the transition to digital project delivery, equally important is having in place robust and coherent data management tools (or standards) to manage the information being generated from various stakeholders throughout the project life cycle. Seventy-six percent of the respondents surveyed reported using electronic information management systems (such as the AASHTOWare Project suite or Bentley ProjectWise) for managing their resources across projects. The data management categories for CIM include electronic archival of plans, usage of mobile digital devices, digital signatures, materials management system, and data connectivity. Electronic updating of plans (or 2D as-builts) appears to be a conventional practice at many DOTs, with 84% of the participants endorsing this method. This observation also implies that the adoption of 3D models for O&M and asset management lags behind the conventional document-based approaches. Seventy-four percent of participants used mobile digital devices on one or more of their agency's projects, primarily for inspection, progress monitoring, and daily work reporting applications. Digital signatures, which have the potential to expedite document reviews and approval processes, saw active implementation by 61% of the survey participants. Finally, data connectivity tools that examined use of real-time site monitoring and control applications on projects (through advanced equipment such as telematics) recorded a 32% utilization rate among the responses.

Respondents also have varied perceptions on the ROI for these technologies. They cited the non-availability of a uniform methodology to guide the investment decisions as the primary concern. However, there was also consensus on the point that such tools can always be subjective and specific to a particular agency's business or its project environment. The importance of standardizing electronic deliverables and specifications to streamline the information exchange process was also highlighted in the agency survey responses.

Availability of quantitative data from several agencies provided opportunities to empirically understand the state of practice across DOTs and derive appropriate conclusions. It also enables identification of certain attributes that lead to increased or decreased use of CIM technologies for project delivery. Figure 5.5 depicts the level of integration of CIM

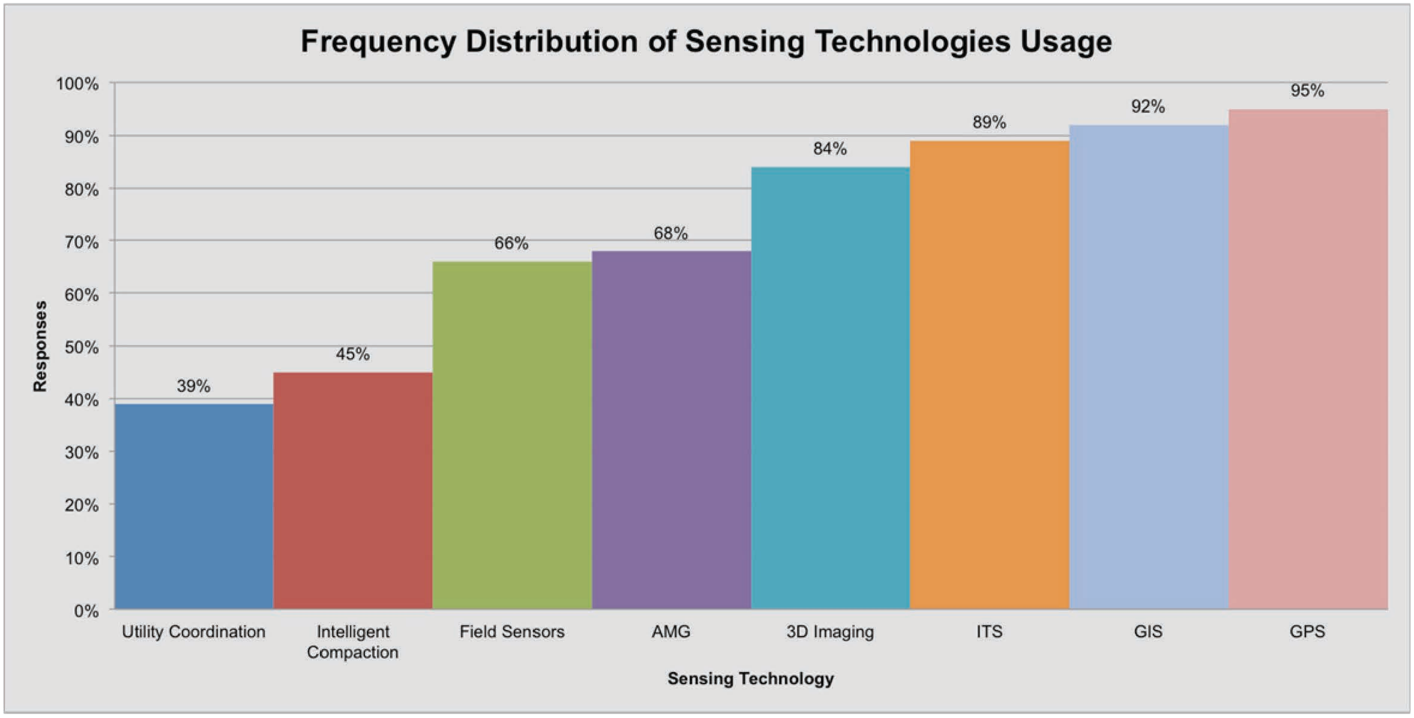


Figure 5.4. Histogram of frequency distribution for sensing technologies group.

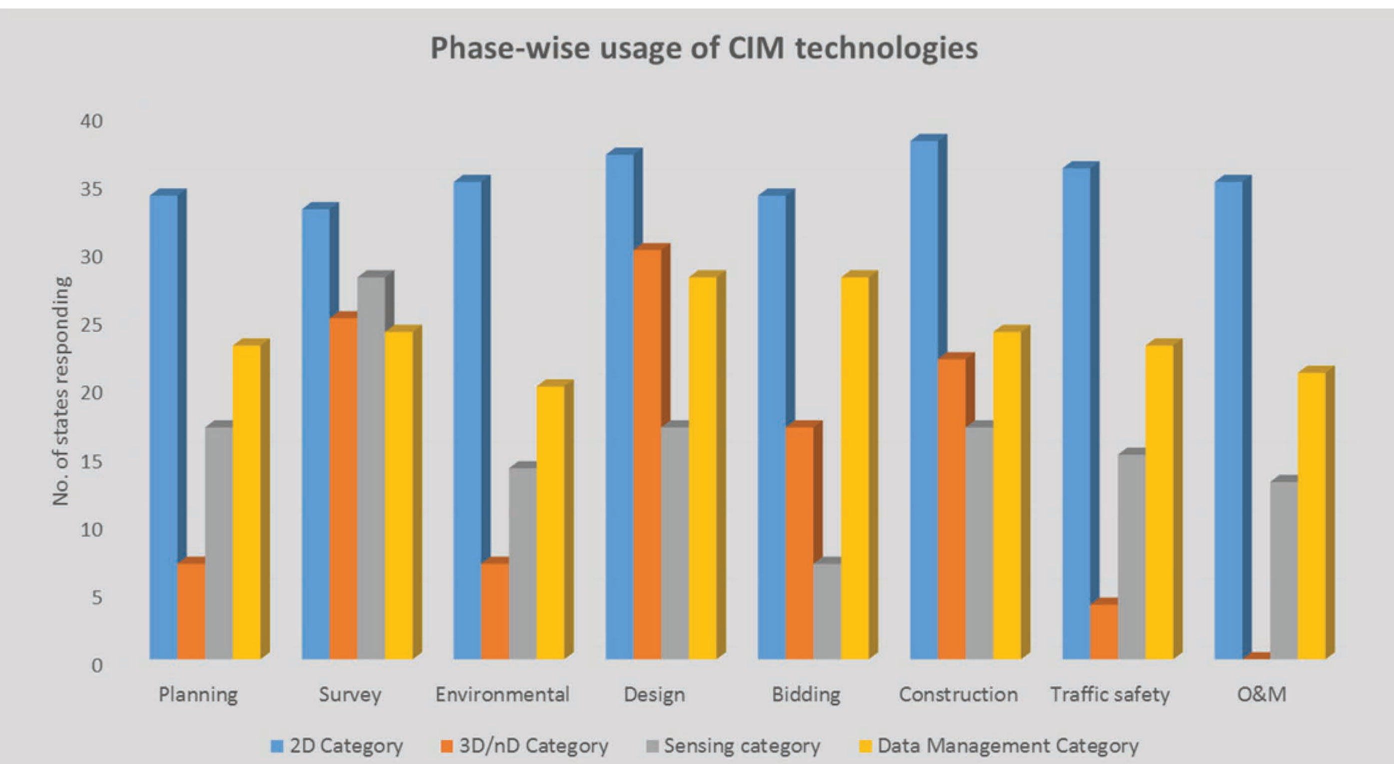


Figure 5.5. CIM technologies usage for project work areas at DOTs.

technologies (the four groups) across all the project work areas (from planning to O&M).

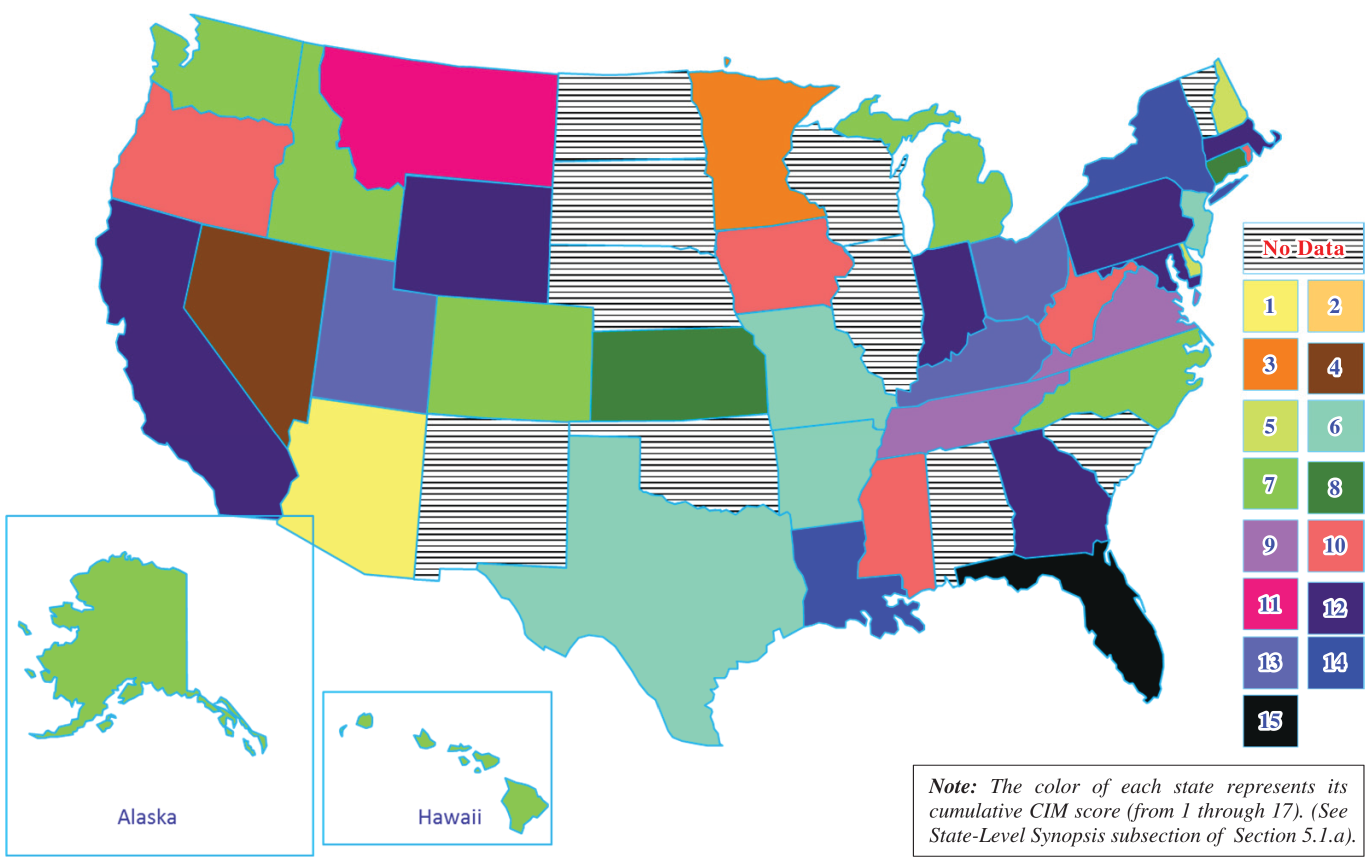
Figure 5.5 provides several interesting insights. Firstly, use of 2D processes (such as paper-based plan sets) is still prevalent across all DOTs in project delivery processes. The 2D group also has higher adoption than the other three groups. The 3D and sensing categories have lower integration levels in comparison to the data management and 2D categories. This inference may indicate that both 3D and sensing technologies are emergent and provide promising results for future implementation efforts. Another interesting finding is that, among project phases, design and construction areas recorded the maximum use of CIM technologies, whereas O&M reported the lowest use of CIM technologies. In particular, less than 2% of the respondents reported using 3D/nD technologies for O&M activities, indicating that significant technical and managerial improvements are required to enhance life cycle use of CIM at an agency level.

State-Level Synopsis

The degree of CIM use needs to be properly quantified to provide a state-level synopsis. A marking scheme was used for each technology in the four groups (shown in Figure 5.2). One point was assigned for a particular category if the agency deployed the tool in one or more of its projects. These points were then added up to arrive at a cumulative CIM usage score, the maximum possible value being 17 and the base score being 1 (since all the agencies use 2D plans for construction). The data from eight states were either unavailable or too incomplete to assess their use. Thus, they were not included in the analysis. Figure 5.6 presents a thematic map of the United States with the states identified in accordance with their usage score.

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

- Five states displayed a lower value of CIM maturity (1 through 5); these states use traditional and document-based workflow (2D) for project work processes and asset management. They had no or limited use of 3D/nD modeling categories. For the sensing and data management categories, some states reported wide variation in their uses. As an example, while Delaware reported using many advanced sensing tools on their projects (IC, AMG, and GPS, among others), they have not adopted many of the



Note: The color of each state represents its cumulative CIM score (from 1 through 17). (See State-Level Synopsis subsection of Section 5.1.a).

Figure 5.6. Cumulative CIM usage map.

data management technologies. On the other hand, Nevada reported usage of noted data management tools (such as mobile digital devices, digital signatures, and electronic as-builts management) while their integration of sensing technologies was limited.

- Thirty-two states exhibited a moderate level of CIM maturity (6 through 12) and the characteristic workflow of these agencies was discernibly different from the previous category. They demonstrated integration of 3D technologies on one or more of their projects (particularly for design and visualization), although advanced usage of modeling tools remained limited (4D/5D). Noticeably higher CIM maturity scores resulted from increased use of sensing and data management technologies. As an example, Iowa, Georgia, and California reported adoption of all the technologies examined under the sensing technologies group and the vital ones from the data management category (e.g., electronic updating of plans, mobile digital devices, and digital signatures). Virginia and Washington reported deploying all the data management tools, and experimenting with the prominent sensing tools (GPS, GIS, ITS, and AMG).
- Seven states emerged with a high CIM maturity (usage score: 13 through 17). As expected, extensive use of 3D/nD tools on their projects helped these agencies score considerably high in the modeling categories. Specifically, New York and Florida have expertise in using 3D, 4D, and 5D processes for project delivery, achieving a holistic maturity for modeling integration in practice. Furthermore, these states, in general, have completely integrated sensing and data management tools. California and Kentucky reported experience in implementing all the key sensing tools evaluated in this study, while states such as Florida and Ohio recorded the highest usage of data management tools. Overall, Florida (15) and New York (14) emerged as the agencies with the greatest technological integration and process capabilities, according to their cumulative CIM usage scores.

5.1.b Highlights of Results—Project Surveys

The responses to this survey were in agreement with the inferences deduced from the agency surveys. Other additional inferences are listed below:

- The respondents for this survey indicated that the agencies' stipulations and contractors' participation were the primary drivers behind the deployment of CIM on projects.
- It was also highlighted that incorporating all the required guidelines, specifications, and definitions in the Project Execution Plan is vital for predictable and profitable use of CIM technologies on projects.
- At the project level, respondents had varied perceptions of the improvements achieved in specific performance areas. While some believed that the CIM technologies benefitted projects in terms of lower costs (especially avoidance costs through clash detection) and better schedule performance, others perceived the maximum advantages are in the areas of safety and the reduction in the number of RFIs (Requests for Information) and construction inspection, such as Quality Assurance/Quality Control (QA/QC) checks.
- Interestingly, 70% of the projects surveyed had not performed an internal ROI analysis for the technologies used on projects. However, many agencies have examined the training, hardware, and software requirements for projects and documented the investments made to improve the processes. In the future, the agencies plan to assess performance improvements through detailed cost-benefit analysis for CIM technologies.

5.1.c Formalization of CIM Usage Analysis—Maturity Model

The results of the agency survey indicate the varying levels of CIM use across state DOTs (see State-Level Synopsis subsection in Section 5.1.a). Fundamental capabilities of the CIM integration processes were analyzed and a three-level maturity model was formulated to serve as an assessment tool for evaluating the current functionalities. Such a model would also provide a standardized language for communication purposes and setting a strategic goal for CIM implementation. Note that this assessment tool cannot directly translate to detailed planning and operational specifications at an agency; rather, its objective is to serve as a basic framework for devising operation-level standards. While the actual maturity model is included in the Guidebook (Chapter 3, Section 3.2), Section 5.1.c elaborates on the rationale behind the three maturity levels created to characterize all the asset phases.

Scoping and Surveying

The two major changes that influence the maturity levels in this phase include level of GIS use and the ability to deploy integrated surveying methods for supporting model-based delivery (including LiDAR, robotic total stations, and aerial imagery, among others). Many agencies now have application platforms that support the basic GIS requirements during project development. However, the research process revealed that agencies have differences in their use of surveying technologies to support CIM. Literature reveals that currently any DOT has to combine multiple surveying methods to collect and process the required data for digital design. Secondly, variation was observed in the usage levels of cloud-based technologies for project development. These tools create the opportunities to collaborate and share the required information among stakeholders. Accordingly, these objectives are organized into the three maturity levels. The research process (comprising the literature review and two national surveys) did not identify an agency that falls under a specific maturity level for scoping and surveying phase (as a whole). Nevertheless, there were examples of functional capabilities under project development planning and surveying that reflect an agency's maturity.

Preliminary and Detailed Design Phase

CIM implementation in design and associated deliverables plays a significant role in driving digital project delivery. Specifically, the levels of CIM use in this phase are related to an agency's potential to perform model-based 3D design for various project elements, comprehend and produce CIM-related information deliverables (such as for plans, specifications, and estimates [PS&E] or related contract language), and leverage clash detection capabilities for performing utility coordination tasks. The research process revealed that many agencies, in general, generate digital terrain models (DTMs) in CAD/DGN/XML formats and make them available for further design and construction purposes. However, major differences arise across agencies in the use of model-based design for utilities and structures (such as bridges and retaining walls). In addition, the contribution of CIM-based PS&E and contract documents varied from one project to another and across agencies. Also, agencies can experience several challenges in performing 3D clash detection, depending on their data expertise and resources availability. Thus, these capabilities were categorized as the three maturity levels in the model.

Construction Planning and Procurement Phase

Four primary functions are influenced by CIM tools in this phase: scheduling, estimating, traffic control planning, and materials management. The DOTs represented different levels of maturity for all four of these functions. In practice, 4D is implemented on projects that involve staged construction (to examine temporary structures, drainages, crossovers, and detour configurations). Use of 5D cost estimating and materials management is relatively new and currently few instances are reported in highway projects. There are also variations in using traffic microsimulation tools for visualization and other purposes on projects. While some agencies reportedly perform their traffic management planning in 2D, some agencies have used microsimulation for several analyses and a few have integrated it with the design visualization process. All these capabilities are included in the definitions of the three maturity levels.

Construction Phase

One major advantage of implementing CIM on projects is the potential to automate various construction operations related to pavements (such as grading, excavation, finished surface laying, and compaction, among others). The research process indicated that agencies use different levels of automation on projects ranging from commonly used grading for dirt work to performing finished surface construction using AMG. Furthermore, IC remained a specialized technology, reported in only a few instances of application based on project requirements. In addition, using CIM tools for monitoring and controlling site equipment remotely was also reported in a few projects, but the survey responses and literature review indicated that this usage might well increase in the future because this technology has productivity and safety benefits. These functional capabilities are used to define the three maturity levels to demonstrate the agencies' varying utilization levels.

Operations and Maintenance

The CIM-related O&M capabilities of an agency are primarily driven by two critical CIM functions: availability of geospatial data and the associated software platform to support various decisions and organize information in a digital data archive. Many agencies use GIS tools to track the condition of assets; however, inventories may or may not contain CIM (3D) data of assets. Similarly, agencies commonly use electronic (or paper-based) records of handover data from projects and the update intervals vary from one agency to another. Increasingly, agencies are envisioning creating and maintaining a digital data archive that will be used to collect, organize, and update the digital information of various project elements. Several CIM tools (including LiDAR, GPS, and GIS, among others) could be used to collect the data from projects to create this archive. The agencies' potential capabilities in these areas determine their maturity levels.

Information Management

Although it is unconventional to perceive information management as a separate category, this area needs special attention because information is generated, shared, organized, stored, and used for subject-related studies throughout a project's life cycle. There are several indicators that reflect an agency's expertise with CIM for information management. First, the ability of an agency to produce and manage information deliverables in document- and model-based formats can act as an indicator for measuring the flexibility of its information management systems. Second, the relative use of digital signatures by different functional areas can provide insight into the ease and effectiveness of information transfer among major stakeholders. Thirdly, an agency's current capabilities for spatially referencing data will also be a measure of the strength and usefulness of asset data throughout its life cycle. Adopting common industry standards across the agency for generating and sharing information is an indicator of information integration capabilities (examples include 3D design and deliverable standards, and interoperable standards for modeling such as IFC). Finally, the extent and frequency of updating as-built data and processes and continuous usage across the project life cycle also provide insights into the efficiency of information management. All these aspects of information management are separated into the three maturity levels detailed in the Guidebook.

CHAPTER 6

CIM Case Studies

The nationwide surveys conducted by the research team helped in shortlisting most of the candidate projects for case studies. Overall, 15 project representatives responded to the project survey, indicating their willingness to provide details. However, secondary resources (agency surveys, FHWA documents, CIM workshops, DOT websites, and academic journals) pointed to a few other exemplary projects and subject matter experts (SMEs). Thus, the research team decided to balance the data sources taken from the case study projects (those for which the pertinent agencies responded to the project survey) and interviews with CIM SMEs. Table 6.1 lists the projects chosen for case studies.

The SME interviews are listed below:

1. Lance Parve (CIM Design-Construction Engineer, SE Freeways, Wisconsin DOT [WisDOT])
2. Ron Singh (Chief of Surveys/Geometronics Manager, Oregon DOT [ODOT])

Following is an overview of each case study's objectives; the individual case studies are detailed in the subsequent sections.

1. The Connecticut DOT's (CTDOT's) *rotary upgrade project* is representative of a smaller roadway design project that performs 3D design of all its involved entities.
2. The *Kiewit case study* was conducted for the Colorado DOT (CDOT) I-70 project and was helpful for understanding a contractor's perspective on various 3D technologies.
3. The Kentucky Transportation Cabinet (KYTC) *KY7 relocation project* is the pilot roadway project of the agency that tested implementation of 3D design. The project also had a unique "special note" that gave priority to 3D models as contract documents over plan sets.
4. The *Kosciuszko Bridge Project* was studied in detail to understand the New York State DOT's (NYSDOT's) 3D design processes, QA/QC checks using GPS equipment, and 4D/5D modeling specifications.
5. The Michigan DOT's (MDOT's) *I-96 Livonia construction project* was examined to study the agency's e-construction initiative, its widespread traffic simulation efforts on projects, and its pilot effort to create a guide for data exchange for managing utilities.
6. The Massachusetts DOT's (MassDOT's) *Fore River bridge replacement* was selected because it involved 3D modeling and CIM implementation practices on a steel bridge project.
7. *Crossrail* is one of the few mega projects that has committed to deploying CIM—or BIM, as it is called in the UK—throughout its entire life cycle. It was also an interesting case study to understand the UK government's initiatives and legislation for adopting BIM on its public infrastructure projects.

Note that the case studies represent various types of projects and budgets—restoration (2R) to new construction (4R), $1.45M to $20B. Examined together, the case studies are a complete representation of all CIM-related practices on a typical transportation project. Such diversity in the case studies also enabled the research team to highlight the requirements for successful implementation of CIM on small-scale projects (i.e., projects with funding regulations or other constraints).

A semi-structured interview guide was developed to serve as a basis for conducting the case studies. It is included in Appendix C. Appendix D contains the specific questions under each section. The framework of the interview guide is divided into five topics representing all facets of CIM, as presented in Table 6.2.

Interviews were conducted based on the availability of the contacts, the scope and project complexity, and the potential opportunity for learning new practices related to CIM. The number of interviews (per project) ranged from 1 through 3 and the interviews lasted between 1.0 and 2.5 hours. The meeting minutes were synthesized and detailed case studies reports were then generated. Subsequently, a cross-case analysis was

Table 6.1. Brief characteristics of the case study projects.

No.	Project	Agency	Project delivery method	Approx. project cost ($M)	Actual/ estimated completion dates*
1	Rotary upgrade to modern roundabout	CTDOT	D-B-B	2.2	Apr. 2016
2	Kiewit case study on I-70 project	CDOT	D-B	18	Sep. 2013
3	Relocation of KY7 in Elliott County	KYTC	D-B-B	26.5	June 2016
4	Kosciuszko Bridge Project	NYSDOT	D-B	555	Nov. 2017
5	I-96 Livonia construction project	MDOT	D-B-B	124.1	Jan. 2015
6	Fore River bridge replacement project	MassDOT	D-B	300	Sep. 2016
7	Crossrail Ltd. (UK)	Crossrail	Various	20,000	2019

Note: D-B-B refers to the design-bid-build method, while D-B denotes the design-build method.

* The estimated completion dates were taken at the time of the case study and may have changed.

Table 6.2. Interview guide framework.

No.	Title	Brief description
1	Organization	CIM-related DOT practices, specifications, and guidelines
2	Contracts and governance	Issues concerning delivery methods and legal concerns
3	CIM integration with project work processes	Deployment of specific CIM technologies for the project being investigated
4	CIM lessons learned and best practices	Means and methods through which lessons learned are shared and best practices are recorded at the agency
5	CIM performance goals	Performance measures and objectives for CIM at the agency and project level

performed to capture the generalized trends and lessons learned from all the case studies. CIM implementation was analyzed in-depth for each of the case studies performed. The following section provides a report on the seven case studies.

6.1 Case Study 1: CTDOT—Rotary Upgrade Project

6.1.a An Overview of CIM Practices—CTDOT

- This agency is in the process of developing specifications for the kind of projects that would require CIM technologies and the level of detail for modeling purposes. Workforce training programs are currently informal—used at construction QA/QC areas for grade checking using rovers. The organization is also planning to train designers in 2015 for transition to 3D design. Though CIM use is desirable for designing all the highway elements (including terrains, bridges, and others), there are practical constraints that need to be overcome (regarding software, equipment, and staffing requirements).
- The agency has completed a few pilot projects experimenting with IC and stringless paving (although there are no results to share on the performance and benefits of IC right now). However, the agency believes that AMG will be used more in the future, along with rover-based QA/QC checks. Currently, there are not many indications from the contractors about increased use of AMG for all pavement construction operations. However, on some projects, contractors find it useful to develop the 3D model out of 2D plan sets (often using a third party). In such cases, the liability and risk of using them for AMG are transferred to the contractor.
- With the current understanding of AMG, the agency believes the maximum benefits of using this technology will occur in earthmoving for highway jobs. It also believes that for the digital workflow of all the project elements, the main challenges are as follows: non-availability of clear 3D specifications for all the elements, inadequacies of software tools, and challenges in managing design changes.
- The agency uses a combination of Bentley ProjectWise and AASHTOWare. These are project suites for document management, field reporting, quantity estimation, and payments to contractors. It plans to use SharePoint in the future.
- Bridges have been spatially located throughout the state and locating signals is 50% complete. They are currently working on collecting information related to retaining walls and sign supports. Bridge data was collected through Google Earth and the ET 2000 guardrails were located using

GPS technology. Existing survey information was also obtained using Bentley maps to create and validate the project limits.

- Important benefits of CIM technologies' implementation include improved safety on-site as well as time and cost savings. The process uses electronic engineered data (EED) and GPS/model-based controls for pavement construction. Additionally, rovers provide the added advantage of creating as-builts in real time and identifying quality issues before it is too late. The agency feels that the total benefits are much higher than the initial investment costs. Moreover, apart from the software upgrade, other tools and functionalities (e.g., rovers) do not rapidly change with time. CTDOT has a system of nine real-time network base stations called ARCON that help obtain accurate coordinate locations and real-time corrections.
- Modeling the structures, such as bridges, requires advanced software tools (integrated with roadway design packages) and additional training. Cost of design effort will also increase. As an agency that performs 25% of the design in-house, doing QA/QC checks on the remaining consultant deliverables will also be challenging. Hence, it is not widely used on its projects. 4D modeling is used only on rare occasions, where there is complicated construction sequencing/staging.

6.1.b Data Sources for Case Study

The research team used case study interviews and obtained some resources from project websites (http://www.biznet.ct.gov/scp_search/BidDetail.aspx?CID=32989).

6.1.c Introduction and Project Characteristics

The project's objective is to upgrade the rotary intersection of Route 188, Route 334, and Holbrook road in the town of Seymour to a modern roundabout facility. The need for the project arose as a result of traffic safety concerns at the rotary intersection, occurrences of high approaching speeds (~40 mph), and poor sight distance issues. After its completion, the modern roundabout is expected to benefit the commuters through controlled operating speeds at the roundabouts (15 to 25 mph) and enhanced safety conditions. The salient characteristics of the project are shown in Table 6.3.

6.1.d Brief Project Description

The proposed project would upgrade the current four-leg rotary to a modern roundabout by modifying the approach geometry, and raising and lengthening the splitter islands. To improve sightlines and visibility, the center island will be raised and the profile on Route 334 lowered. These improvements are anticipated to provide a safer intersection through reduction in approaching speed and providing maximum deflection to the circulating vehicles. A schematic representation of the proposed condition based on the preliminary design is shown in Figure 6.1.

6.1.e Motivation

This project was chosen as a case study based on the analysis of the survey response. It emerged as a reasonable candidate to provide insight into the suitability and adaptation of CIM technologies for the smaller projects undertaken by many DOTs. Additionally, this project used 3D design for all the major roadway components (existing surface, finished surface, drainage, and curbs, among others).

From an organizational standpoint, the CTDOT had prepared its specifications for documenting EED. It has also envisioned moving toward uniform 3D design for all roadway and major structural elements on projects in the future (as reported in its EED manual). Moreover, the agency is performing its pilot projects to experiment with advanced CIM technologies such as IC and AMG for stringless paving.

Hence, the research team investigated this project in detail to understand the practices of model-based workflow for roadway projects, as well as the organizational challenges of and motivation for embracing 3D technologies.

Table 6.3. Project characteristics—CTDOT.

Feature	Value/description
Project cost/Agency	$2.2M, expected to be fully state funded/CTDOT
Project no./Contract method	124-162/D-B-B
Project type	Roadway project (no major structures)
Current status	Currently in design completion stage; construction anticipated to start in spring 2015
ROW acquisition	Mostly within the limits of state's ROW
Utility coordination and relocation	No major utility conflicts expected due to low project complexity and minimum utilities interference. Two utility poles are to be relocated.

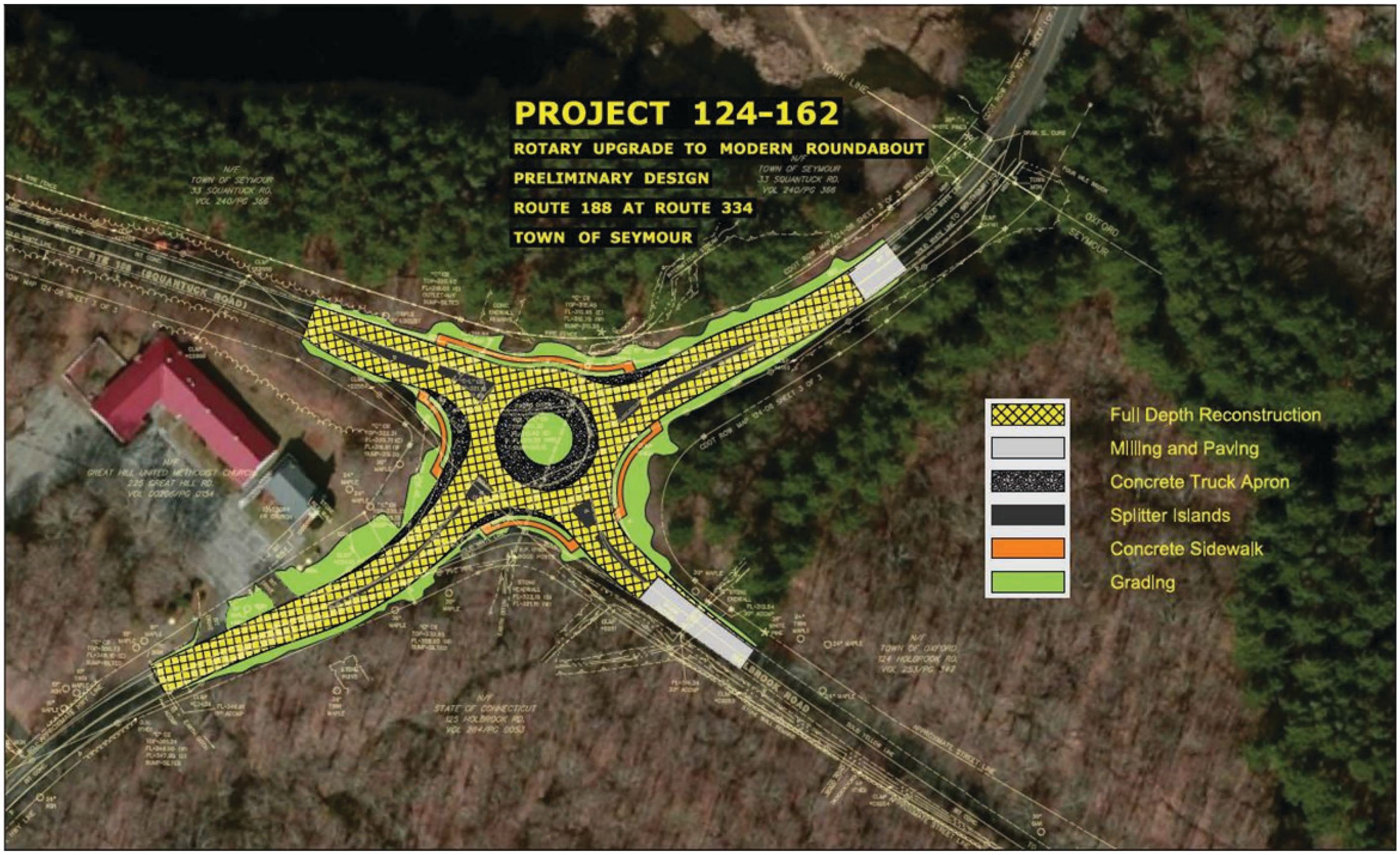


Figure 6.1. Schematic representation of the proposed conditions of Project 124-162.

6.1.f CIM Implementation Analysis—Rotary Upgrade to Modern Roundabout Project

- The rotary project, with smaller scope and lower complexity (no major structures such as bridges), is designed up to 90% in 3D using Bentley InRoads. The agency also believes the next planned software upgrade to SELECTSERIES 3 would facilitate designers' transition to the model-based design process for many projects.
- During the bidding process, the EED data (that was used to extract contract plans) and contract plans were both provided to the contractor. However, the contract plans were the official governing documents for the design and construction process. The provided EED information included surfaces (DTM), alignments, design files of existing ground, proposed ground, proposed traffic and landscape design, storm and sanitary database, and preference files. As per the specifications, the liability and risk of verifying and using the data for AMG and any other purposes is transferred to the contractor.
- Digital signatures had been used only to sign the contract plan sets. Models were not verified or vetted with them.
- Surveying was performed using total stations to collect the data required to create the 3D DTM models. The project conditions did not necessitate using advanced sensing technologies for data collection, although there was some minimal LiDAR support to supplement the drainage design.
- As reported in Section 6.1.c, interference with utilities in the project area was minimal and the entire ROW fell within the state's limits. There were no challenges expected in this regard and hence no advanced CIM technologies were used for these tasks. A "utility work schedule" was provided by each of the utility companies to the DOT, delineating their scope of work in the project. These schedules were then included in the final bid specifications to assist the contractor in his detailed schedule development. However, the contractor had been asked to verify its accuracy and coordinate with the concerned utility companies to incorporate the latest utility scheduling information.
- In the planning stage of the project, traffic modeling was performed using VISSIM to lay the roundabout and to visualize improvements in the traffic behavior and safety with the proposed conditions. The same simulation model was used for public information purposes.
- The staged construction and constructability reviews are performed during the final design using in-house construction expertise.

6.1.g Inferences

The agency has been reasonably successful in implementing several CIM technologies and practices. This case study has helped deduce some important lessons.

Defining and standardizing EED requirements is a significant step in ensuring seamless transfer of project information across all stakeholders, in a timely manner. The importance and requirements of each of the engineering elements and their associated deliverable formats should be clearly articulated in the specifications. This step helps align all the contractors and consultants with the agency's expectations.

3D terrain modeling of roadway elements can be performed in a cost-effective manner for smaller projects as well (e.g., roadway improvements). Selection of appropriate surveying techniques will assist in the collection of pertinent data for modeling. Wherever required and depending on budget, the data can be supplemented with aerial imagery (photogrammetry) and static LiDAR to obtain more accurate information. Good quality as-built data helps; however, utilizing that data for new project development is still a major challenge given the multiple data variants (2D plan sets, 3D spatial point clouds, electronic data, among others) and these data sets are not continually updated throughout the life cycle.

CIM consists of some emerging technologies that are not common to the business workflow of many agencies (e.g., IC, 4D/5D as reported in project surveys). Performing pilot projects to understand the benefits and challenges, engaging with relevant stakeholders (partnering), and jointly collaborating with other agencies (e.g., counties, state DOTs, FHWA) can help in promoting and integrating emerging technologies with project workflow. Systematic technology implementation planning at the organizational level also helps in phasing out and channelizing the implementation efforts for multiple technologies.

Workforce training programs are vital for ensuring smoother transition to CIM adoption—for both the designers (3D modeling and design, information management) and the field staff (pavement operations, QA/QC checks using rovers).

6.2 Case Study 2: Kiewit I-70 and Pecos Bridge Case Study

6.2.a An Overview of CIM Practices—Kiewit

- Kiewit Corporation has been using Bentley software to develop 3D models for construction for several years. The project type and delivery method have an influence on how the models are created. For example, for a traditional D-B-B project, the models would likely be developed 100% in-house from the 2D plans. However, if the project were an alternative delivery method such as design-build (D-B) or construction manager/general contractor (CM/GC), the model would be based on the electronic files from the design. The contractor found that most of the time the roadway and drainage design files were generated in 3D and those files could be used as a starting point to develop 3D files. When these new 3D files are developed, the contractor can use them to verify design information and for construction.
- During construction, the 3D files were typically used as a check against survey and roadway construction technologies such as AMG. On projects that are more complex, the 3D models are used for visualization purposes as well.

6.2.b Data Sources for Case Study

The research team used case study interviews and the CDOT website.

6.2.c Project Characteristics

This project involved replacing the Pecos Street Bridge over I-70, which was in poor condition, and improving the traffic operations at the interchange by installing roundabout type intersections and a pedestrian bridge. The estimated construction cost for the project was $18 million. It was determined that accelerated bridge construction (ABC) would be used to reduce the overall construction schedule thereby minimizing the impacts and traffic delays to the traveling public, especially along I-70. The project limited the impact to the commuters along I-70 to a 50-hour shutdown, as opposed to traffic control for approximately 12 months if built using conventional methods. Characteristics of the project are described in Table 6.4. Figure 6.2 represents schematic views of the project and bridge.

6.2.d Motivation

This project was chosen as a case study based on presentations given at the 2014 Western Association of State Highway and Transportation Officials conference. The conference presentation highlighted the innovative ABC techniques along with the alternative contracting (CM/GC) method. Moreover, it was indicated that 3D modeling was used in this project in the design and construction phases.

6.2.e CIM Implementation Analysis—Pecos Bridge Replacement over I-70

- Bentley's MicroStation and InRoads software were used to model the roadways and approaches during design. During construction, the same software was used to recreate the models for the roadway but also included the model for the bridge elements, superstructure, and substructure, as well as the bridge staging area. The project used 3D design

Table 6.4. Project characteristics—CDOT.

Feature	Value/description
Project cost/Agency	$18 M/CDOT
Contract method	Design-Build (D-B)
Bridge type	A 156-ft-long, single span, cast-in-place, post-tensioned concrete box girder bridge with a variable depth and a transverse post-tensioned deck. The deck overhang span varied from 8.5 to 15.5 ft. Bridge webs were post-tensioned internally and externally, exterior webs were curved, and web spacing varied from 16 to 23.5 ft.
Current status	Construction completed and Pecos Street opened on September 1, 2013

for the roadway and drainage, but had to develop additional bridge models because the design was carried out in 2D. As a result, 3D models of the bridge in the final design state and construction state (i.e., at the bridge staging area located 800 ft away) were developed for both constructing and moving the bridge.

- The 3D model of the bridge was developed as follows:
  – The bridge was modeled in the final condition using the 2D plans.
  – The bridge in the model was copied and moved to the bridge staging area 800 ft away. This was necessary to determine elevation lengths, and so forth, for the construction of the bridge.
  – The falsework for the bridge was designed and modeled at the bridge staging area.
  – The bridge was copied and moved back from the bridge staging area to the final location to verify that the constructed bridge still fit the final location. This was extremely important since the bridge was going to be moved via Self-Propelled Modular Transporters (SPMTs).

Figure 6.3 displays the 3D model of the bridge superstructure and Figure 6.4 presents the elements of the substructure included in the modeling processes.

- During the modeling described above, the modelers discovered that the bridge was approximately 3 in. higher than the proposed roadway profile when the bridge was moved from the construction area to the final location.

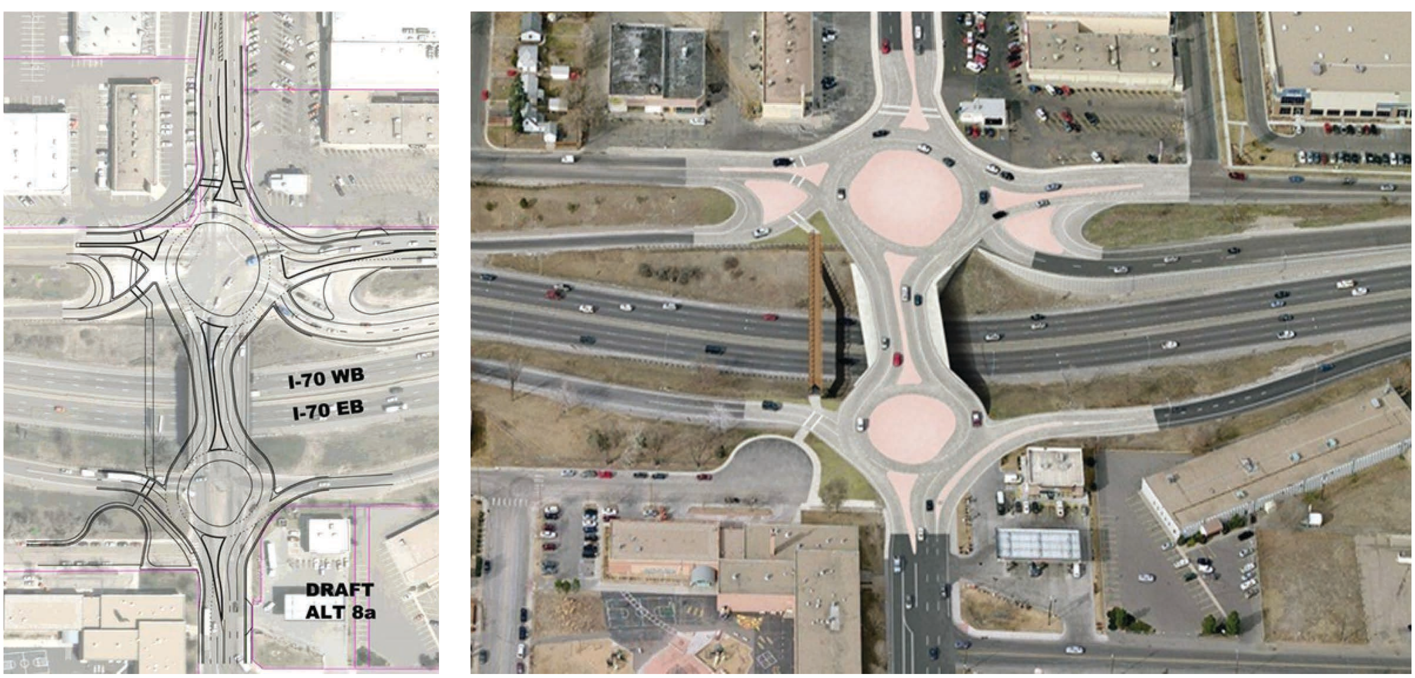


Figure 6.2. Schematic views: **(left)** ***a contextual view of the project plan;*** **(right)** ***simulation of the completed project. (Source: CDOT.)***

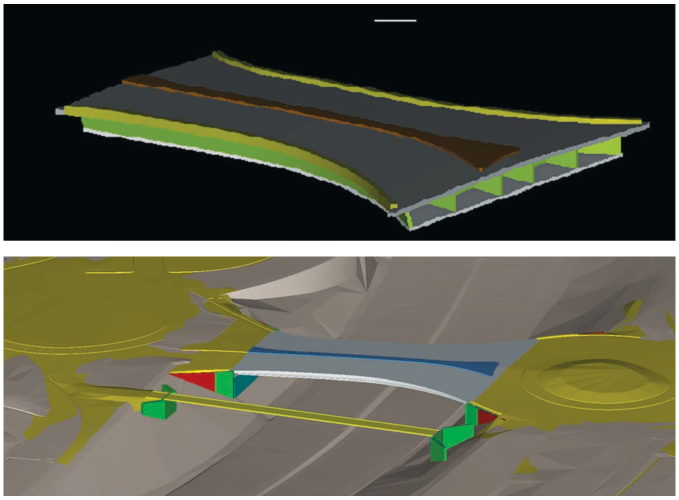


Figure 6.3. 3D models: (top) *bridge superstructure;* (bottom) *bridge superstructure in final position. (Source: Kiewit.)*

This difference in elevation arose because the bearing pads were not accounted for when the bridge was modeled at the bridge staging area. Making this discovery during the planning phase, rather than during the final move of the bridge was quite valuable.

- Once the models were completed and verified for the construction of the bridge elements, the bridge movement was modeled—a critical step, given the limit to the differential elevation between the SPMTs. This model was completed by taking cross sections of the roadway surface and then overlaying the SPMTs and bridge to ensure everything fell within the tolerable limits. Figure 6.5 is a graphical representation of cross sections used for modeling the planned final location of the bridge.
- Having the model of the sequence of movements on-site enhanced the communication among project stakeholders and contributed significantly to the outreach efforts to educate the public. Figure 6.6 shows a rendered image of the bridge movement simulated by using the model and the picture of the SPMTs used in the movement.

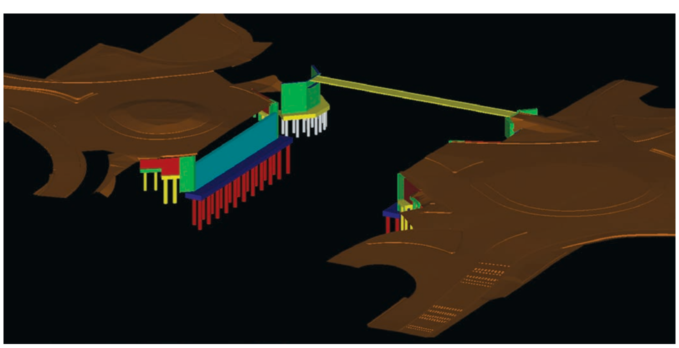


Figure 6.4. Model of bridge substructure elements and earthwork. (Source: Kiewit.)

6.2.f Inferences

On this project, the contractor was the primary driver for the use of 3D modeling. The contractor believed a significant benefit could be derived from the models. The critical aspect of having to build a bridge offsite and then move the bridge into its final location made it imperative that the dimensions and relative locations in space were accurate. Furthermore, while the step from 3D to 4D was not necessarily used for traditional scheduling purposes, it was used to help determine the move of the bridge over time.

This project illustrates that using 3D modeling for major bridge elements can reduce construction delays by resolving conflicts digitally rather than in the field. This project serves as an example of how to integrate design and construction digitally for future ABC projects.

6.3 Case Study 3: Relocation of KY7 in Elliott County

6.3.a An Overview of CIM Practices—KYTC

- Through this project, the agency is experimenting with incorporating specifications into contracts for using and prioritizing 3D models on roadway projects. KYTC will analyze the results of this project to determine whether these specifications can be included in the contracts of future projects.
- The agency uses a wide variety of electronic tools and web-based platforms to organize the information flow during project development. ProjectWise is used to manage and share the information during design (IFC, Notice for Design Changes files) and construction (daily reports). Bidding processes and documents are maintained in electronic plan rooms that are handled by a third party website; bidding and submittals are sent through the Bid Express online service.
- Designers are trained and motivated to perform their work in 3D. Currently, roadway structures are designed only in 2D. The agency plans to use 3D modeling in a twin bridge project in the future, but this may be limited to visualization. There is no imminent requirement to transform the design process to model-based delivery. Also, there are few reported cases of 4D/5D on Kentucky projects.
- The KYTC envisions preparing an effective Utility Conflict Matrix in the future. Field inspectors and permitting representatives will all be equipped with GPS equipment so that whenever a new utility construction/relocation takes place, the geo-located coordinates are obtained. There are

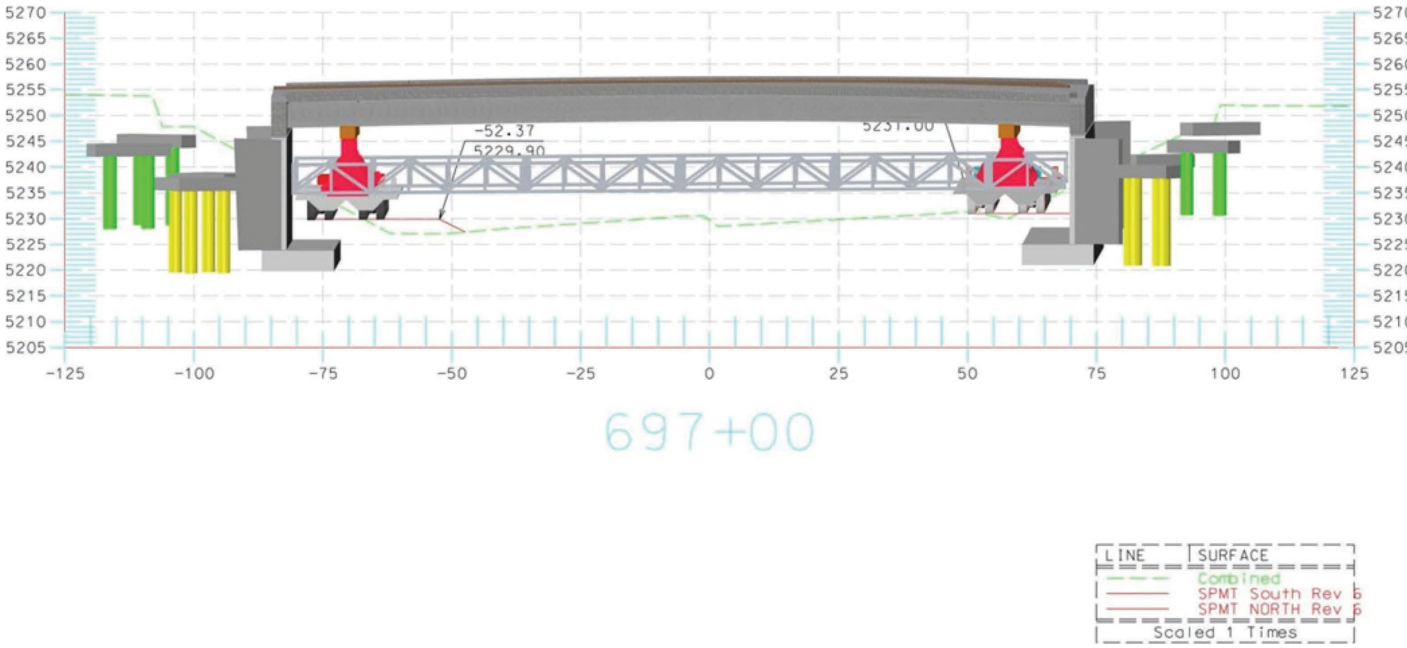


Figure 6.5. Cross section of SPMTs and the bridge in final location. (Source: Kiewit.)

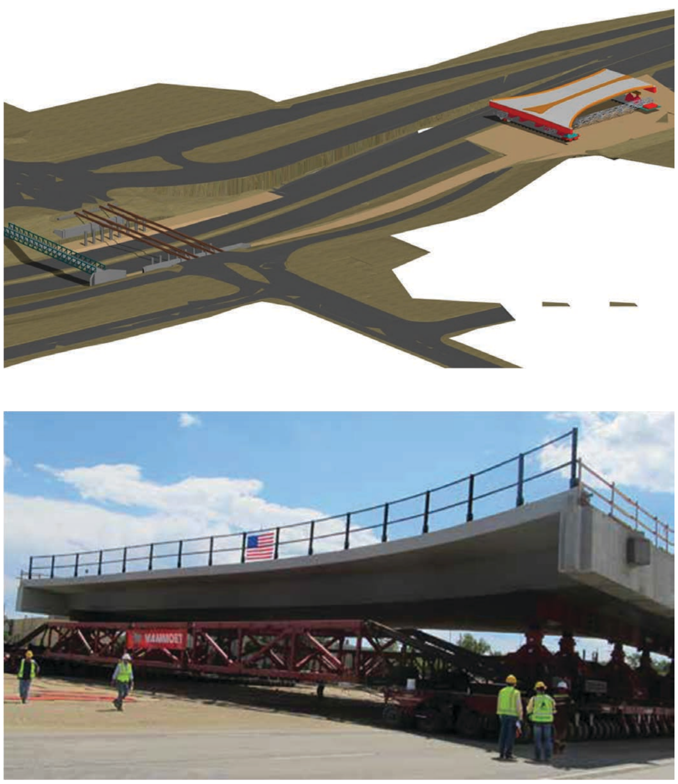


Figure 6.6. Pecos Bridge:* (top) *rendered view of bridge movement (Source: Kiewit),* (bottom) *picture of SPMTs and bridge superstructure (Source:* Aspire, *Winter 2014).

also plans to adopt quality level "A" subsurface utility engineering (SUE) to retrieve the geo-location of existing utilities. Currently, the efforts to obtain geo-referenced utility information are constrained to a project-specific environment and not transferred to a central state/district level repository. Initiatives will also be undertaken to create and maintain a sort of central database with this data. A major challenge in the SUE process is getting the utility companies on board. Utility companies maintain a significant portion of ROW information, but are not always willing to share that data, citing national security concerns. Legislative action may help here. (For example, Utah has mandated that utility companies locate all their assets in 3D, although this is not strictly enforced.)

- Construction inspection is performed by staff from section offices (a section office takes care of work from multiple counties). Although KYTC perceives rover-based QA/QC checks as an important benefit, lack of technology, training, and personnel hinders field implementation for inspection. KYTC plans to deploy rovers for this pilot project and to follow and implement the lessons learned on this issue across the entire state.
- Electronic signatures are primarily used to sign the plan sets. Engineers and consultants provide digitally encrypted PDF files and they are unencrypted for bidding purposes. InRoads/DGN files (3D models) are not encrypted.
- Kentucky takes initiatives to spatially locate most of its assets—handheld GPS was used to obtain information on a high-tension cable barrier and other facilities. KYTC

Table 6.5. Project characteristics—KYTC.

Feature	Value/description
Project cost/Agency	$26.5 M/KYTC
Project no./Contract method	09-0126.51/12-1363/ D-B-B
Project type	Roadway project (no major structures other than box culverts and circular pipes)
Current status	Construction anticipated to start in spring 2014 and completion expected in summer 2016
ROW acquisition	Mostly within the limits of state's ROW
Utility coordination and relocation	No major utility conflicts expected due to low project complexity and minimum utilities interference

generally uses trucks equipped with a variety of pavement sensing equipment to obtain information on cracks, durability, and so forth, but LiDAR has not been deployed on the trucks because of cost-related issues. However, there are plans to deploy mobile LiDAR for as-built new construction projects.

- The public information process is conducted through public meetings. For urban reconstruction/congested areas, dedicated Public Information Officers follow specific requirements. There is limited usage of visualization. Traffic simulation is provided only in cases involving complex interchanges or congested urban areas.

6.3.b Data Sources for Case Study

The research team used case study interviews and a presentation at the 2014 International Highway Engineering Exchange Program conference.

6.3.c Project Characteristics

The project's objective is to relocate an approximately 5-mile stretch of rural arterial KY7. The route consists of 60 approaches and entrances and involves 3 million cubic ft of excavation work. It started as an in-house (county) project and KYTC took over the project development after PL&G (Preliminary Line & Grade) submittals. Other salient characteristics of the project are given in Table 6.5. Figure 6.7 represents an aerial view of the project scope.

6.3.d Motivation

This project was chosen as a case study based on the survey response. The project involved a large amount of grading, drainage, and excavation operations. A special note written for this contract specifies that the 3D surface models supersede the plan sets if discrepancies arise between the two. As per the special note, "KYTC shall use the same model to inspect the contractor's work." This project adopted 3D modeling, AMG, and digital asset management in the delivery process.

From an organizational standpoint, Kentucky represents an aspirational agency that is in the process of integrating several CIM practices in its project workflow. The project is strategically important to successful CIM adoption in KYTC. It has leadership buy-in and expert guidance from the FHWA and the Kentucky Association of Highway Contractors, among others. The agency is testing 3D models and several other CIM technologies for the first time in the state. The lessons learned from this project will be used in the following ways:

- Ascertain and validate the best practices for 3D design adoption.
- Find out the best submittal practices for contractors and other stakeholders.

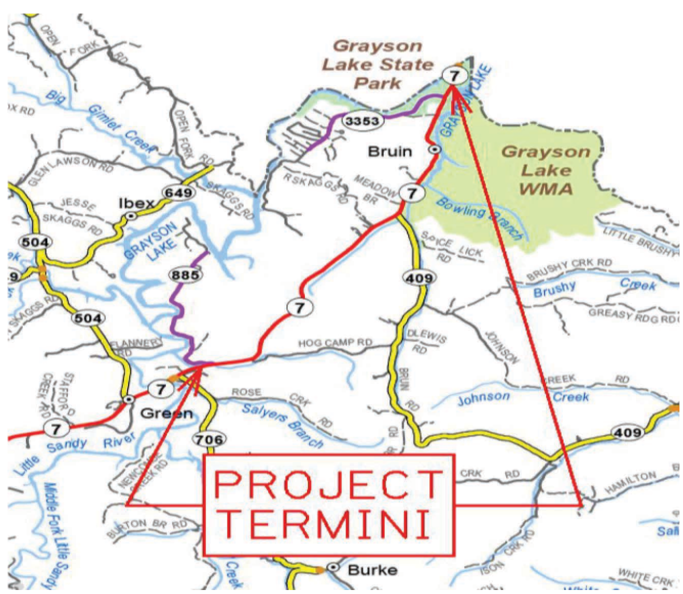


Figure 6.7. Schematic representation of project scope.

- Document the realized benefits and challenges.
- Understand the design(er) role and its impacts on the downstream construction process.
- Establish the level of detail and completeness required for 3D model development.
- Set comprehensive policies for future project development.

Hence, it was decided to investigate this project in detail to understand the motivation behind the "special note" on the contract and document the benefits and challenges faced while evaluating implementation of CIM technologies in this pilot project.

6.3.e CIM Implementation Analysis—Relocation of KY7 in Elliott County

- The agency's past experience indicated that unless they give the EED data (3D terrain model in this project) priority over 2D plan sets, contractors tend to always use the plans and digitize them to create their own models for various purposes (including AMG). It has to be noted that constructors are contractually obligated to use the KYTC's data. Hence, the agency believed that this change in specifications would ensure contractors use the EED and avoid redundancy.
- For modeling purposes, existing information was collected through aerial imagery that was then digitized (photogrammetry). It was supplemented with traditional surveying techniques to enhance accuracy on obscure areas (some drainage and tie-ins). Design of the elements was done in Bentley InRoads. The elements modeled in 3D include approaches, entrances, ditches, and surface elements (finished grade, subgrade). Utilities were not modeled in 3D.
- All the design files were provided to the contractor in both native and converted file formats. The deliverables included surface elements, breaklines, and alignments (existing and proposed conditions in both DTM and XML formats). On this project, machine control files are only used for grading operations and not for finished surface pavement construction, primarily because of the contractor's inability to afford all the machines. In addition, the contract did not explicitly specify the individual stages for which AMG had to be used.
- Documents are managed and shared across all the project stakeholders using the ProjectWise tool during design and construction.
- The agency also plans to analyze and quantify the benefits of using CIM technologies on this project. The design effort for this project happened mostly in-house and it amounted to 8 to 10% of construction costs. For this ongoing 2-year project, the KYTC plans to track change orders, assess their magnitude, and compare them with those of similar projects (in terms of budget, delivery method, earthwork, etc.). From a QA/QC perspective, although it is difficult to quantify, there are benefits resulting from greater confidence and accuracy in the inspection process and recording of as-builts.
- There were no major changes reported on this project, except a Maintenance of Traffic issue that arose early when temporary surface models were not considered for the culvert construction. However, the contractor resolved this issue.
- Advanced CIM technology such as IC is not used on this project. If KYTC wants the contractors to move in this direction, it will have to approach the grading committee, asphalt-paving subcommittee, and the contractors association to educate them, get their feedback, and address their concerns.

6.3.f Inferences

Although the project is not yet complete, the agency has reported that it has learned several important lessons and best practices from this pilot project.

The technology adoption experience has yielded important points to be followed while implementing model-based design. KYTC has realized that it is beneficial to use continuous breaklines for all the design entities. Deliverables should include DTM/XML/DGN files of all subsurface layers. Designers have to pay close attention and incorporate maximum design details when modeling complex elements of roadways (such as intersections, gore areas, lane additions/drops, widening for guardrail, etc.).

The project had a unique "special note" that gave contractual priority to 3D models for quantity calculations, QA/QC checks, and conflict resolution. However, the project team learned that it is more important to include clauses in contracts specifying how the model will be used (e.g., AMG during construction) and the extent of utilization (for grading, stringless paving, compacting, etc.). Such detailed definitions would help maximize the benefits of developing and using a 3D model. Also, it would help avoid any potential conflicts among various stakeholders. The agency also noted that prequalification for bidding may be necessary to ensure competent contractors perform the intended work.

Leadership buy-in and expert guidance have been the major organizational drivers in the agency undertaking and executing this pilot project. The agency has plans in place to perform a second pilot project to sustain its efforts in incorporating CIM technologies.

6.4 Case Study 4: NYSDOT Kosciuszko Bridge Project

6.4.a An Overview of CIM Practices—NYSDOT

- NYSDOT uses digital information and CIM technologies on any project of any size if the project may benefit from the usage. Typically, NYSDOT finds that contractors are requesting the digital information to use with the construction technologies that they have, such as AMG. In NYSDOT's experience, all the major contractors use AMG and GPS.
- The primary contractual/legal language used is its contract control plan for survey specifications (no.: 625). This survey specification requires use of GPS units, total stations, and terrestrial scanners. This extensive level of surveying is what the agency uses to verify quantities for payment. They pay overruns and underruns based on the quantities determined through advanced surveying techniques. CIM technologies such as LiDAR, GIS, and GPS are hardly ever used during the planning phase. There is a large learning curve in order to use these technologies during planning. As of now, there is no formal mechanism to determine the costs versus benefits of the use of advanced surveying techniques. However, they feel that regardless of the ROI, the contractors are upgrading their technology and the DOT needs to keep up—specifically for construction inspections, because they are at risk of delay claims if they are unable to turn around submittals in a timely manner.
- The agency used 3D models for design, construction, and producing electronic as-builts. They are in the process of determining how to disseminate the digital information to all stakeholders and how to implement usage throughout the organization. Furthermore, the agency sees a lot of value in good 3D models and getting the 3D design files to the contractor so that there is no question as to the intent of the design—thus minimizing RFIs, which will ultimately result in lower project costs. However, this will almost always come with a non-disclaimer form that the files are provided as supplemental information only. Also there may be some reluctance to share the models because sometimes the 3D model may only be developed well enough to generate 2D plans and not be fully "fine-tuned."
- The agency uses CIM technologies for both D-B and D-B-B projects. There is more that the agency can control concerning CIM usage, if the delivery method is D-B-B. If the delivery method is D-B, then the D-B team will typically only use CIM if it is needed/required by the contractor in order to build the project the way that they want to build it. For example, if the contractor is going to rely heavily on AMG to construct the roadway, then the design will be in 3D and that digital information will be used during construction. Additionally, the agency believes that the idea of alternative technical concepts may promote the usage of CIM.
- Using CIM while coordinating with utility companies can be difficult. The agency has found that many legal and security issues are related to underground utilities. While they try to mitigate any utility conflicts prior to construction, they have had numerous projects where unidentified utilities have been encountered. Sometimes this issue arises when the utility is old or abandoned, or when the utility is related to national security entities and cannot be put on record. The latter becomes a barrier when it comes to documenting as-builts and using digital information and CIM technologies for the O&M phase, because those utilities' locations cannot be documented (unlike the typical DOT information and records).
- Although the primary use of CIM within NYSDOT relates to advanced surveying techniques and 3D models, they have also begun using 4D and 5D models on larger projects. The 4D simulations seem to have worked well because the projects that have used 4D have come in on time. The 5D modeling is being used on a few current projects; if its use is successful, then it will probably be a requirement for future large D-B projects. In addition, NYSDOT uses traffic models for traffic management, especially when there is staged construction. When there is staged construction, a traffic model is used for every stage to illustrate anticipated traffic flows.

6.4.b Data Sources for Case Studies

The research team used the case study interviews, project survey, and NYSDOT website (https://www.dot.ny.gov/kbridge).

6.4.c Project Characteristics

This project involves replacement of an existing steel truss bridge with a cable-stayed bridge, intended to ease traffic congestion and enhance the safety and driving conditions of the travelers. The 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 use of a 3D design process and 4D modeling for constructability reviews and the public information process. Notably, it also deployed model-based verification of quantities and estimation of contractor costs (5D modeling). As of the compilation of this report, the project was under construction. Figure 6.8 shows rendered images of the perspective view and drivers' view of the bridge.

Figure 6.8. Kosciuszko Bridge: **(left)** ***perspective view from Newton Creek;*** **(right)** ***drive-through view during the day. (Source: NYSDOT.)***

6.4.d CIM Implementation Analysis—Kosciuszko Bridge Project

- During the planning phase, the agency procured the services of a third-party consultant for collecting and supplying LiDAR data. However, this information was supplied for "information purposes only" and the contractor was instructed to use the plans and specifications from the Request for Proposal (RFP) documents. Photogrammetry was used to prepare a preliminary engineers' estimate of quantities. The data was used for planning, public outreach, and visualization purposes.
- In the RFP phase, it was decided that the selected design-builder would develop, maintain, and hand over a 3D model integrated with schedule (4D) and cost (5D) information. Specifications associated with these requirements were also incorporated in contracts asking the project team to provide methodologies that would assist in using models for analyzing the construction sequence, tracking construction progress, and payments. In addition, it was also required to use the model for design visualization.
- The D-B process enabled the teams to present their technical concepts and proposals using 3D models. The design of the structure followed a model-centric process with 3D models developed from LiDAR and photogrammetry data. The roadways, approaches, structures, and utilities were all designed in 3D. The highway design and bridge models were also integrated using common survey control to analyze environmental issues and perform clash detection among the various entities. The model's level of development (LOD) met the specifications in the contract documents. The model helped the project team verify clearances, interface on issues, and check the structural integrity of the model. The required design data was shared with the contractor in machine-readable formats (e.g., XML) to support AMG operations.
- Design reviews and constructability analyses saw the active use of 4D and 5D modeling. The 4D schedule was resource-loaded to include labor and equipment data related to each work operation, which was created by a software vendor. The 4D model was then used to examine staging conflicts, traffic congestion, and reviewing project progress. The 5D model was to be kept updated by integrating it with information from an electronic document management tool that tracked daily work operations and quantity payments.
- During construction, the project staff used mobile devices (such as smartphones) and a compatible document management tool for recording daily progress and generating quantities. Quality control inspections also involved LiDAR and GPS-based technology (such as rovers) to verify compliance with design documents and survey standard specifications. The frequent checks improved the quality of work and the process, resulting in time and crew savings compared with traditional methods (using digital level or total stations). After the construction, the asset information in the paper plans was updated from the design survey based on the as-built information and was archived electronically.

6.4.e Inferences

This project replaced the existing steel bridge with a cable-stayed bridge. This project gave several insights on practices related to surveying and modeling. Firstly, the agency had revised its surveying specifications to enable field staff to use GPS-based inspection technologies for quality checks and quantity measurements. This step was critical to facilitate agency-wide adoption of this practice. Apart from the commonly reported uses of visualization and communication, the project actively deployed strategies to use 4D and 5D models for monitoring construction progress and verifying quantity estimates for payments. This process was facilitated through incorporating detailed specifications concerning model management plans in contracts.

6.5 Case Study 5: MDOT I-96 Reconstruction Project

6.5.a An Overview of CIM Practices—MDOT

- MDOT has been one of the leading advocates and national leaders in experimenting with electronic document management systems and digital signatures at the agency level for project and asset information management. This effort, formally recognized as an “e-construction” initiative, has now captured national attention through the Every Day Counts (EDC-3) program.
- The e-construction effort has strengthened the agency’s foundational information management systems by enabling the collection and organization of relevant data in digital formats throughout the asset’s life cycle—scoping and surveying, designing, bid letting, construction, and O&M. The ability to manage and provide data in digital formats is a major prerequisite for leveraging the complete potential of state-of-the-art CIM technologies. The agency has collaborated with several major state and national stakeholders such as the Michigan Infrastructure & Transportation Association, American Council of Engineering Companies of Michigan, FHWA, local agencies, and software vendors to keep abreast with the technological advancements and coordinate with them to design best practices and implementation specifications.
- The agency provides digital information—including 3D CAD and point cloud models and proposed surface files—to promote contractor innovation and lower construction risk (improved accuracy of the design data). The relevant files are uploaded to the letting-specific folder created in the ProjectWise system. The process not only streamlines data flow but also reduces the paper-based deliverables on projects (creating agency savings).
- During construction, the agency follows an electronic document submittal and approval system with digital signatures. All the required information—such as daily work reports, quality control reports, construction surveys, materials testing records, and shop drawings—are securely stored in ProjectWise. Access and modification of the files (or their hierarchy) is regulated by authorization systems put in place. Review and approval processes follow intelligent and secure workflow with the authorities using approved digital signatures. Most of the information is accessible through web-based systems.
- Another noteworthy effort related to CIM is the agency’s use of advanced traffic simulation tools to evaluate proposed lane closures and construction stages for projects. The agency has a proven record of executing major projects through full-closures strategies. The availability of quality alternative routes had been one of the major justifications for this approach; nonetheless, the decision-making process was supported by extensive traffic analysis that involved analyzing network-level impacts on measures of effectiveness (travel time, queue length, and average speed, among others). The agency normally uses the base network models from the local MPOs and builds them to the required granularity for the project-level microsimulation efforts. Quite often, it also produces interactive CIM models that combine design visualization with traffic simulation outputs. Such animations have been used in the past to assist in public outreach efforts and inform/augment some of the engineering/construction decisions.
- MDOT is currently in the early stages of integrating CIM tools and practices for activities beyond construction. Specifically, AMG is predominantly used for excavating and grading operations. The agency has been deploying mobile LiDAR and unmanned aerial vehicles for post-construction surveys and information handover.
- MDOT’s effort to create a geospatial repository for utilities has been one of the major strides of CIM implementation. In a pilot initiative, the agency collaborated with relevant utility companies (gas, electric, storm and sanitary sewers, and fiber-optic providers, among others) in creating GIS-based utility database systems for new infrastructure projects. In the near future, the agency plans to enhance the quality of this data by investing in SUE technologies.

6.5.b Data Sources for Case Studies

The research team used the case study interviews, the project survey, and the following website: http://www.96fix.com/project_information.

6.5.c Project Characteristics

This project involved reconstruction and rehabilitation of a 7-mile segment of I-96 from Newburgh Road in the City of Livonia to Telegraph Road in Redford Township. The intriguing aspect of this project is that the city had complete closures of portions of the interstate for approximately 1 year.

The scope of work involved repairing 37 bridges, rehabilitating and replacing pavements (roads), and adding on and off ramps. The primary objective of this project was to enhance the safety and mobility conditions of the project. A schematic representation of the project is shown in Figure 6.9.

6.5.d CIM Implementation Analysis—I-96 Project

Many of the project activities were consistent with the agency's practices. Information management and sharing primarily occurred electronically from design and bidding through construction phases. As with other agencies, the design information was provided in both native (CAD) and converted (XML) file formats. However, the electronic data was restricted as "information only."

The project team utilized ProjectWise for management, RFIs, shop drawings, contract submittals, and associated transactions. Mobile digital devices (such as tablets) and software applications such as SiteManager were used extensively for managing daily work and inspection activities.

The Maintenance of Traffic plans were visualized in 3D along with realistic traffic simulations extracted from micro-simulation analysis. The agency used 3D visualization aids and social media for public information purposes.

Although AMG is commonly used for excavation, grading, and other related activities, the roads were constructed using conventional methods. MDOT Transportation Service Center personnel performed QA/QC checks using GPS rovers and total stations to verify quantities and calculate payments to contractors.

6.5.e Inferences

The agency now has implemented tools to support electronic document management with digital signatures for approvals, reviews, archiving, and change management. Visualization tools (3D and traffic simulation tools) proved effective for public information.

The following are some of the key points that the project team and the agency identified as essential when transitioning to the use of emerging CIM technologies and practices:

- Identify core competencies that the DOT needs to retain, particularly in terms of staffing numbers, qualifications, and experience.

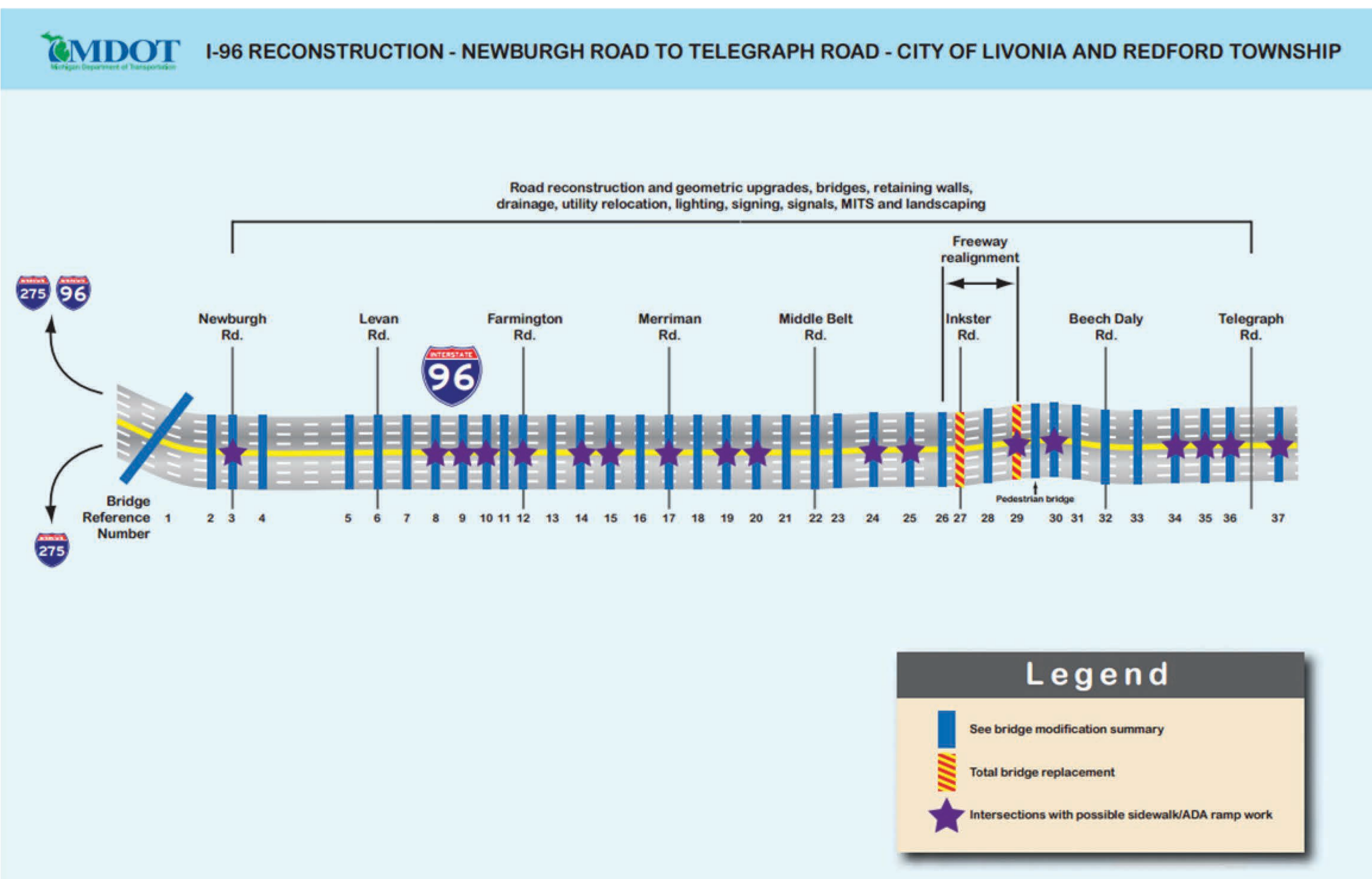


Figure 6.9. I-96 reconstruction project layout.

- Set the vision on the future and the tools the agency will be using; aim for enterprise-wide data management.
- Create solid foundations for geospatially identified data.

6.6 Case Study 6: MassDOT Fore River Bridge Replacement Project

6.6.a An Overview of CIM Practices—MassDOT

- The agency has been using AutoCAD Civil 3D-based design tools for roadway design since 2012. It has created standards and specifications, design templates, and all supporting documentation for all the stakeholders to assist in preparation of CAD files for highway projects. These specifications and templates also support electronic data sharing and management between various disciplines of the DOT and consultants working for the agency. The revisions and modifications to these standards are also performed at regular intervals to ensure updates with contemporary developments. The agency also issues formal "Engineering and Policy Directives" to promote adoption of new concepts in design or engineering procedures.
- The agency uses a wide variety of electronic tools and web-based platforms to organize the information flow during project development. SharePoint Site is used to manage and share the information during design (IFC, NDC files) and construction (daily reports). Bidding processes and submittals are handled through the online service Bid Express. The agency employs a standard prequalification procedure for contractors when projects are worth $50,000 or more.
- MassDOT uses a customized "Construction Project Estimator" application for current and future construction projects. It has also developed a "Construction Schedule Toolkit," a set of Primavera P6 templates that can assist contractors in meeting the new specifications of the Accelerated Bridge Program (ABP). However, the agency has maintained that these tools are provided for information purposes only and the associated risks and liability rest with the contractor.
- The agency also possesses a robust Global Navigation Satellite Systems (GNSS) network of continually operating reference stations (CORS) network to cater to the real-time positioning requirements of various operations, such as surveying, engineering, and GIS mapping. The agency has also developed detailed guidelines for using this network and the approximate estimates (costs) of the associated field equipment and infrastructure. It has documented potential uses of this network for its highway system under geodetic survey, utility poles relocation, asset management, automated grade control, and construction inspection. From a CIM perspective, the agency is in transition to realize the full potential of AMG technologies for grading and finished surface construction.
- Advanced CIM technologies have been tested through pilot projects. The agency issued an addendum in 2013 providing detailed IC specifications for hot-mix asphalt (HMA) applications. It plans to deploy IC in its ongoing "Route 2/I-95 Bridge Replacement Project" for the first time.
- The agency has deployed mobile LiDAR for collecting high-resolution point cloud data and colored imagery of the state highways and state numbered routes in the Commonwealth of Massachusetts. The resulting information is used to extract roadway signs and signage data to be stored in the asset inventory database.

6.6.b Data Sources for Case Study

The research team used case study interviews and the project website.

6.6.c Project Characteristics

The project's objective is to replace an existing bascule bridge that serves Route 3A over the Fore River between the towns of Quincy and Weymouth with a steel vertical lift span bridge. The imminent end of the existing bridge's serviceable life and an increase in daily traffic along this route are the primary drivers behind the replacement. Apart from providing better rides for commuting vehicles, the new bridge will also provide several other benefits, such as straight ROW, enhanced and safer traveling conditions for bicyclists and pedestrians, and improved vertical clearance (60 ft in closed position). Other salient characteristics of the project are given in Table 6.6. Figures 6.10 and 6.11 represent a schematic view of the proposed bridge.

6.6.d Motivation

This project was chosen as a case study based on analysis of the survey response. The Fore River bridge replacement represents a significant initiative for the ABP, whose main objective is rehabilitating structurally deficient bridges. Various innovative techniques have been proposed for this project—such as EDC-2's ABC techniques, advanced project scheduling and estimating tools, innovative construction sequencing, and alternative construction contracting (D-B). Moreover, the survey response also indicated that 3D modeling and design are actively used in this project from its conceptualization to environmental analysis through the design and construction phases. The scale and complexity of the project and its component structures also make it an ideal candidate to study CIM implementation for steel structures. Finally, the

Table 6.6. Project characteristics—MassDOT.

Feature	Value/description
Project cost/Agency	$300 M/MassDOT
Project no./Contract method	71680/D-B
Project type	Steel vertical lift span bridge. There are three approach spans on Quincy and Weymouth side; a main span with vertical towers at either end of it, with two lanes in East Bound and West Bound side and 5-ft bicycle lanes on both sides.
Current status	Construction underway and final completion by fall 2016
ROW acquisition	Apart from temporary easements or strip takings, no major ROW impacts on local communities and business are anticipated.
Utility coordination and relocation	No major conflicts were encountered during construction. Potential issues were identified during design but were resolved.

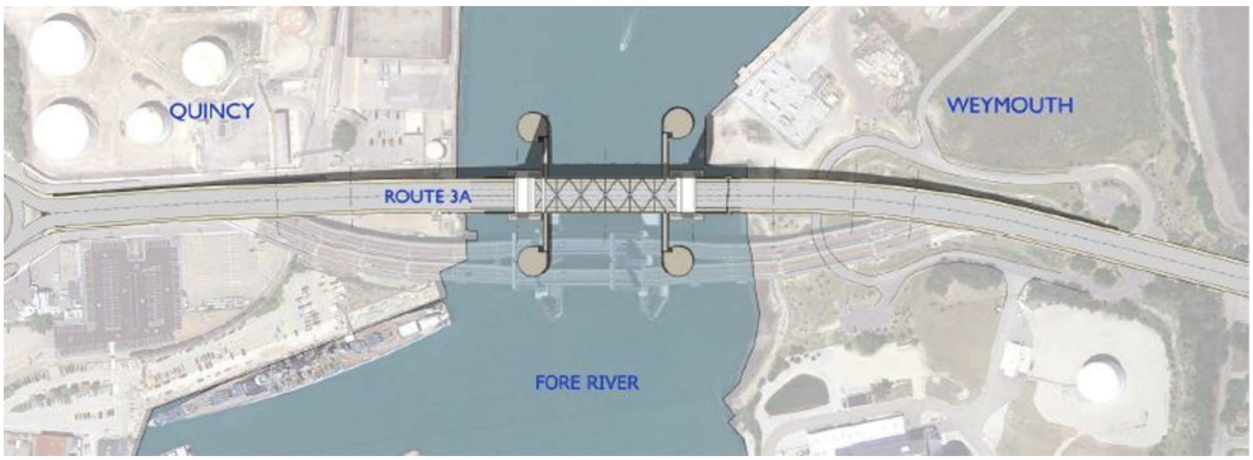


Figure 6.10. A contextual view of the project plan. (Source: MassDOT.)

Figure 6.11. A perspective view from the Weymouth Bank. (Source: MassDOT.)

agency plans to monitor the performance benefits of using these technologies on this project.

From an organizational standpoint, MassDOT has standardized the data collection requirements and specifications for model-based design. It is also investing in the testing and implementation of several advanced CIM technologies, such as IC, LiDAR, and AMG.

Hence, it was decided to investigate this project in detail to understand the CIM implementation from design to construction on a typical heavy civil construction project (steel structure).

6.6.e CIM Implementation Analysis—Fore River Bridge Replacement

- For preliminary design, Autodesk Civil 3D was used for modeling the roadways and approaches (geo-referenced modeling), and the superstructure (bridge) and associated utilities were modeled in Revit. Although the models were functionally separate, the footprint of the bridge was exported to Civil 3D to visualize and analyze all the elements together, which helped the project team address some environmental concerns regarding the footprints of the foundations: scour and potential obstruction of flow in the channel. As the design was being updated (requiring a couple of iterations), the civil engineering department was able to revise and update the foundation footprints comfortably. The model helped better coordinate this task.

- For modeling purposes, getting detailed information was challenging, especially for equipment. The bridge has a machinery house that sits in the vertical lift span of the bridge and two counterweights, one for each of the two vertical towers. For the electrical engineers, getting accurate information on the heights of panel boxes, transformers, and other electrical elements to be placed in this machinery house was challenging. However, this intensive data collection effort proved to be beneficial, because it was used to verify clearance and interface issues and check the structural integrity (with staircases connecting machinery and lift span, panel boxes, etc.). It also helped in positioning the mounting support assemblies for auxiliary counterweights—they were close to the front face of the control room and the task was coordinated with architects using the 3D model to ensure adequate clearance was provided in all directions.
- During the preliminary design, a potential interface issue was also found between the termination boxes of the electric submarine cable (buried under the river bed) and steel tower/bridge fender system. The conflict was identified using the CIM model, and a relocation strategy best suited for the electrical conduit was proposed. Another important benefit was efficient coordination/rerouting of drainage piping and electrical conduits that run through the vertical tower.
- At the end of the preliminary design stage, the model (LOD 200–300) and the plans ("Base Technical Concepts") were uploaded to the MassDOT SharePoint program for the D-B team to perform detailed design. After removing the redundancies in the file receipts, the D-B designer preferred to use the plans and implemented a number of major and minor changes. The major changes included an increase of 20 to 25 ft in tower height, a reduction in the number of panels from four to three, and a modification in the orientation of the triangular bracing in the towers. Issues related to the structural design also considerably increased the design effort. The design team also involved 13 specialization subs and they were given ProjectWise access to work and upload their files on to the system. The changes were so significant that it was decided to use the changed design plans and start the modeling process from scratch. This structural steel 3D model was then used for clash detection. Also included in the clash detection process were mechanical models (developed in AutoCAD inventor) and architectural models (developed in Revit using the structural model as a basis). During design development, weekly meetings were held with fabricators to integrate and understand their models.
- The availability of the CIM model helped identify and resolve several conflicts through clash detection. The designer reported that they developed their model based on the design plans, whereas the fabricators also prepared their own models based on the fabrication requirements and their interpretation of design plans. A few clashes were identified with fabricators' models (not evident with design models). The collaborative mechanism under the D-B strategy had facilitated this "second-check" clash detection process early on during the design development.
- Although the project had a mature design model, it was not used for developing 4D (schedule) or 5D (quantity takeoffs [QTOs] and cost estimating). The project team believes the organization has not reached a stage where doing a detailed 4D/5D during construction presents a good business strategy. Most of the projects currently use them in the planning/preliminary design stage (either to market their capabilities during bidding or for public information and stakeholder's communication). The project team also believes that lack of available in-house expertise may have been a factor in the project's use of the model.
- The characteristics of the project do not necessitate the implementation of other CIM technologies such as IC or LiDAR. MassDOT reported that the performance of the project would be monitored to understand the benefits of 3D design and its associated functionalities.
- The public information process is coordinated through regular meetings, routine updates through project websites, and social media. The project has robust control measures to mitigate the impact of construction on the neighborhood communities. They include traffic control plans, noise control plans, dust control plans, regular public outreach, hazmat handling and disposal plan, and community liaisons.

6.6.f Inferences

The design has reached 100% completion and IFC drawings have been issued. Construction is in progress for the bridge towers, lift span, and machinery. Although the project is not yet complete, it has already imparted important lessons concerning best practices, benefits, and challenges of model-based design for a steel bridge construction project.

Agencies in transition to model-based design can adapt their business processes by standardizing the relevant procedures (through developing process-oriented specifications and software templates for assisting modeling) and coordinating with project stakeholders to ensure compliance.

On this project, the team incorporated CIM-related practices for 3D modeling and design. The project involved specialized components pertinent to the engineering and design of a movable steel bridge, such as machinery house, counter-

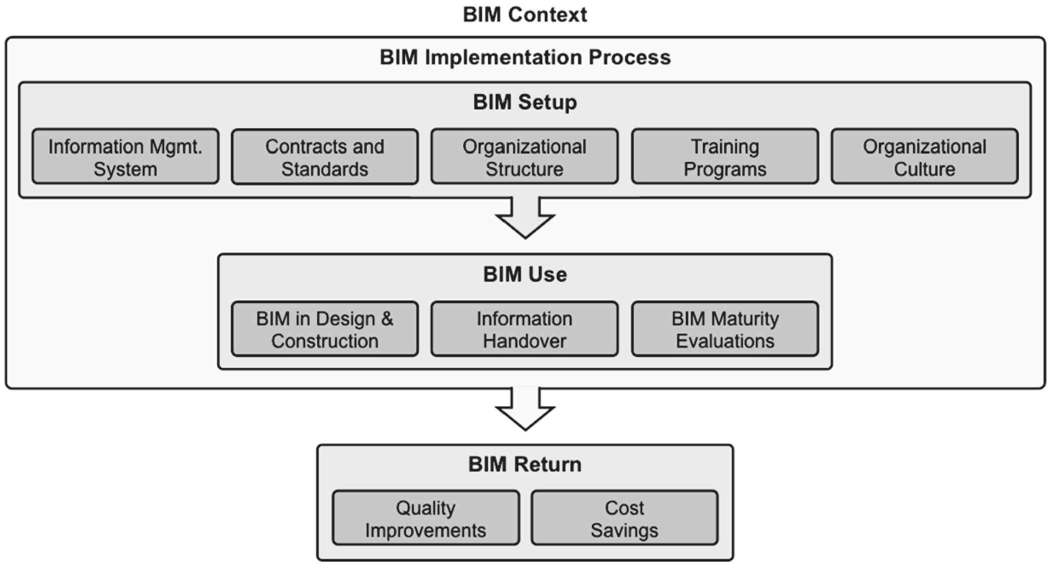


Figure 6.12. BIM implementation program components in Crossrail.

weights, sheaves, panel boxes, and other electrical utilities. The team found it necessary and beneficial to integrate 3D modeling processes with the model development. The 3D model had been very useful for tasks such as environmental impact assessments and alternative analysis during preliminary design. Use of model-based clash detection has helped detect and avoid conflicts in a timely manner. Other applications such as 4D and 5D modeling are not quite common, although many projects use them during the planning stage or for marketing and public information purposes (unless the project involves complicated detour configurations and construction staging).

Effective change management is critical for successful integration of model-based design with project development processes. This project experienced several changes between preliminary and detailed design, and the team decided to develop the model from scratch with the updated design plans. Avoiding redundancies in information, timely collection, and management of pertinent data, better communication/coordination strategies among project participants during design development, and change management protocols can all help in mitigating the impacts of design changes.

6.7 Case Study 7: Crossrail Ltd. CIM Case Study

This section presents the principal findings and lessons learned concerning BIM implementation in Crossrail, a 118-km railway line under construction in London. Please note that the structure of this case study and the terminologies have been adapted to report the observations of this UK project. The most significant one is the replacement of CIM with BIM, because this term is best known in the UK construction industry.

A proper understanding of the BIM implementation process in Crossrail requires three components: first, an analysis of the context where such a process takes places; second, an examination of the implementation process itself (which involves setup requirements and actual use); and third, a review of the cost and quality impacts derived from BIM implementation (Figure 6.12). This is the framework of the analysis used in this study, as well as the structure followed throughout this section.

6.7.a BIM Context

Crossrail's context is characterized in this study by the nature of the stakeholders involved in the project (Figure 6.13). In turn, the nature of these stakeholders is defined by (a) their level of authority and (b) their level of BIM maturity, relative to that of Crossrail Ltd. (CRL). The level of authority refers to the power to impose the use of BIM processes or standards on some other entity. The level of BIM maturity, on the other hand, refers to the degree to which BIM tools and processes have been adopted within each entity.[1]

Thus, according to the authority level, Crossrail's BIM context includes three different groups of stakeholders: (1) CRL, (2) the agencies to which CRL reports, and (3) the contractors for which CRL is the client. On the other hand, according to the level of BIM maturity relative to CRL's level, Crossrail's BIM context includes two different groups of stakeholders: those with a high level of BIM maturity (letter α), and those with a low level of BIM maturity (letter β).

[1] For the purposes of this section, the value of these parameters has only been determined intuitively as *high* or *low*. In reality, however, these parameters would cover a wide range of values based on different indicators.

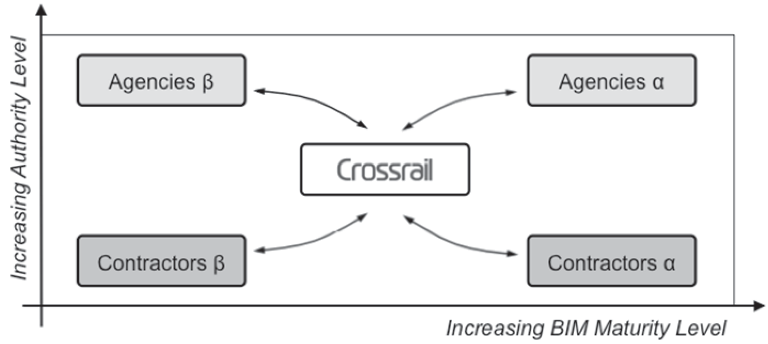


Figure 6.13. Crossrail's BIM context.

This case study involved interviews with CRL (the owner) and four contractors, the latter representing the range of BIM maturity. Two of the contractors would be classified as a contractor α, and two of the contractors would be classified as a contractor β. Thus, contractors will be referred to as contractor α1, contractor α2, contractor β1, and contractor β2.

This distinction is important, because it reflects the four different types of relationships maintained between CRL and the other entities involved in the project. Each of these relationships is associated with specific challenges and opportunities that both CRL and the stakeholders in question are facing (Table 6.7). Further, BIM-related contractual requirements changed from one contractor to another, depending on their BIM maturity level.

6.7.b BIM Setup

Any agency or contractor wanting to operate within a BIM environment must address the following organizational dimensions:

- The information management system that will serve as a platform for collaboration.
- The specifications that will guide and regulate performance.
- The organizational structure that will support the project or projects in question.
- The training programs that will ensure project teams understand and follow the abovementioned specifications.
- The organizational culture that will best align with this new environment.

This section explores each of these dimensions from the perspective of both CRL and four different contractors.

Information Management System

The first and foremost prerequisite for BIM implementation in a mega-project like Crossrail is the existence of a single platform for collaboration and information exchange among stakeholders. This platform includes both an Electronic CAD Management System (ECMS), where the 3D model can be shared, and an Electronic Document Management System (EDMS), where non-graphical data and documentation can be stored. It is the owner's responsibility to decide which platform to use, and to make this platform available to all stakeholders. Making the decisions to deploy these systems and support their data requirements became one of the biggest challenges for CRL.

Table 6.7. Challenges and opportunities based on level of authority and BIM maturity.

Partner	Challenges	Opportunities
Contractors β	Owner faces resistance to change, achieves fewer BIM outcomes, and spends more resources in training and engagement.	Contractor adopts owner's BIM practices.
Contractors α	Conflicting or not shareable BIM practices between owner and contractor.	Owner benefits from contractor's expertise; achieves more BIM outcomes, and expends fewer resources in training and engagement.
Agencies β	Owner faces resistance to change and is unable to impose its own practices.	Agency adopts owner's BIM practices.
Agencies α	Conflicting BIM practices between owner and agency. Owner forced to adopt agency's approach.	Owner benefits from agency's expertise.

Table 6.8. Summary of the most notable BIM-related clauses in Crossrail contracts.

#	Impacts	Description
1	Design Coordination	Contractor must prepare and maintain a coordinated 3D CAD Object Oriented Model in the ECMS,[6] produce a 3D Model Issues Report, use the 3D CAD Model to demonstrate that the design is fully coordinated, and have a Design Management Plan and Interface Management Plan in place.
2	Design Submission	Contractor must submit complete sets of Drawings at "ready for acceptance" status produced using the ECMS that allow construction, manufacture, or installation of all or part of the work.
3	Design Production	All permanent CAD data must be created and managed through the ECMS using the BS1192 workflows and be in accordance with the CRL CAD Standard. All 3D Objects must be fully modeled using discipline specific object oriented software from the *Bentley Building* suite of products to a minimum level of development. All 2D models and resultant drawing deliverables must be generated from 3D models. All CAD models must be split according to their design content.
4	Information Handover	Contractor must manage redlines in accordance with the Management of Redlines Procedure, and the as-builts in accordance with the Management of As-Builts Procedure. Asset Information is provided in spreadsheets in accordance with pertinent standards.

CRL chose ProjectWise as its ECMS and eB as its EDMS; both pieces of software were developed by Bentley Systems, Inc. Selecting Bentley as a single vendor solution was controversial for two main reasons. First, IFC and Construction Operations Building Information Exchange (COBie) are open-file information exchange formats that, unlike eB, are not controlled by any vendor. Second, the UK BIM strategy establishes COBie as the format to be used across the construction industry for public projects.

Unfortunately, at the time CRL was developing its information requirements, agnostic standard-based approaches did not seem mature enough for Crossrail's needs. On the contrary, eB was better adapted to linear infrastructure assets requirements, and BAS 1192 was built into their systems.[2] Moreover, eB could be easily linked to the 3D models in ProjectWise.[3] Therefore, CRL decided to partner with Bentley and use its software.[4]

Regardless of CRL's choice, the very fact that CRL as a client requires a specific ECMS (which is an inevitable prerequisite for agency-level BIM implementation) has posed problems for some contractors, whose IT policies would not allow interaction between their own ECMS and that of a client.

An additional challenge for CRL involving its ECMS and EDMS pertains to the level of workflow automation in each of these systems. ProjectWise includes about 70% automated workflows. eB, however, has about 20% automated processes and 80% manual processes. As a result, EDMS processes are much less efficient than ECMS processes.

Specifications

While in general Crossrail's specifications seem to have suffered minimal changes in comparison with traditional pre-BIM specifications, a number of new contractual clauses[5] have been added to each contract, and several related standards have been developed. For the most part, these clauses and standards address design coordination, design submission, design production, and information handover requirements. Table 6.8 briefly describes each of these contractual requirements.

Besides enforcing the use of one unique collaboration platform, imposing contractual consequences on the handover of the asset information is arguably one of the most relevant features of Crossrail contracts. According to CRL, defects in asset information can be as costly in the long term as defects in the physical asset itself. Therefore, the handover of defective asset information and the handover of a defective asset must be penalized in equivalent ways.[7]

The above clauses apply to all projects in Crossrail, but CRL also adapts them to the particular capabilities of each contractor. Thus, while contractor β1 was required to deliver only redlined models, contractors α1 and α2 were required

[2] CRL was aware of the burden that requiring proprietary software could pose on some contractors. Thus, CRL committed to provide 10 free Bentley licenses for all Tier 1 contractors, provided they made a compelling business case.

[3] Despite the apparent simplicity, establishing this link between ProjectWise and eB became an issue that has remained unresolved until very recently.

[4] In order to comply with GCS prescriptions, CRL is currently working with COBie to develop COBie for All, which will suit COBie to the needs of linear assets like Crossrail. Also, because open-file information exchange formats are more mature today than they were a few years ago, future mega-projects in the UK (e.g., HS2) are following a more agnostic approach, and plan to request the information in IFC or COBie formats.

[5] As explained in previous sections, Crossrail's contracts have relied heavily on the BIM Protocol (Construction Industry Council, UK, 2013a), developed by the Construction Industry Council (CIC). To complement the BIM Protocol, CIC has also developed a guide dealing with insurance issues when using BIM (Construction Industry Council, UK, 2013b).

[6] Note that the model is owned at all times by CRL; the contractor only develops it.

[7] CRL, on the other hand, is also contractually obliged to provide the necessary briefing and training sessions that ensure contractors are aware of their responsibilities within these new processes.

Table 6.9. Crossrail's BIM work-streams.

#	Name	Main Responsibility	Specific Activities
1	Technology Development	Develop a complete suite of BIM solutions.	Articulate standards. Develop BIM Academy. Record lessons learned.
2	Adoption of data into Information Management Systems	Establish and maintain a single source of reliable information and models, and ensure migration of reliable information to the systems.	Develop data migration strategy. Create asset classifications. Populate and manage Asset Information Management Systems.
3	Leading BIM in Construction	Ensure the use of appropriate technical information tools during the construction phase.[12]	Develop mobility tools, maximize use of modeling tools, and ensure appropriate as-built data incorporated.

to submit full as-builts. These contractors were also the only ones developing a BIM Execution Plan, as PAS 1192-2 stipulates[8] (CRL requested this documentation on a voluntary basis). Likewise, contractual clauses have evolved over time, meaning that newer contracts include clauses not included in older contracts, and older contracts have been amended to include these new clauses. Thus, while 4D scheduling was not an initial requirement for the earliest projects, it has been included as a requirement in later stages (again, for the most BIM-mature contractors).

Despite the great care exerted in producing these clauses, CRL acknowledges that its contractual base is not as advanced as it should probably be, in two respects. First, Crossrail contracts do not include pain/gain-share mechanisms. Both CRL and Crossrail contractors agree that these mechanisms adapt better to BIM environments, for one main reason. Since the risks inherent to BIM implementation are shared with the owner, the use of pain/gain-share mechanisms indirectly encourages the contractor to aim for higher levels of engagement with BIM. Higher levels of BIM engagement, on the other hand, as has been seen in some studies,[9] tend to result in higher returns. Crossrail contracts do not include this sort of mechanism, but CRL has tried to compensate for this by explicitly assuming the costs of BIM-related investments (managers and tools) for contractors. Second, Crossrail contracts do not always facilitate the level of collaboration that most benefits BIM implementation. As a result, there are a number of commercial disputes that have remained unresolved, and which CRL will have to deal with at the end of the project.[10]

Complementary to the above contractual clauses, CRL has developed a careful set of process standards, the most notable ones being the CAD Standard, the 3D Model Review Procedure, the Redline Drawing Procedure, the 3D Laser Scanning Survey Procedure, and the Asset Information Provisioning Procedure.[11] Crossrail contractors have highlighted three main weaknesses of these standards. First, they are not prescriptive enough (Crossrail standards "suggest" rather than "require"); second, they are updated with too much frequency (some standards have changed up to five times); and third, in some cases, they are not specific enough (such as with the model's level of detail or with the particular information required for the handover stage). Crossrail, however, is a pilot project. Its BIM requirements were set out in 2007, 4 years before the Government Construction Strategy was published. It is therefore somewhat justifiable that Crossrail's BIM standards have changed (and improved) over the life of the project.

Organizational Structure

Both Crossrail and its contractors have undergone organizational changes to include BIM as part of their structures. These changes, however, were especially noticeable on the owner side. In CRL, BIM responsibilities are concentrated within the Technical Information Department, where three interdependent work groups were created to address needs related to BIM implementation (Table 6.9).

Besides these teams, in the summer of 2012, Crossrail and Bentley launched the Information Academy, a conservatory whose goal is to provide hands-on training to the Crossrail supply chain on the latest software and technology being used to design and build the new railway. However, the BIM Acad-

[8] PAS 1192-2 describes three different sets of documents, one for each stage of the project. These are the Employer's Information Requirements (EIR), the BIM Execution Plan (BEP) and the Master Information Delivery Plan (MIDP). The employer develops the EIR, while the contractor develops the BEP and the MIDP, before and after the procurement stage, respectively.

[9] "The more deeply that construction companies become engaged with BIM, the greater their ability to receive its benefits, and to realize very strong return on their investment" (Dodge Data & Analytics 2014a).

[10] Future mega-projects in the UK (e.g., HS2) are working with contractual bodies to develop contracts that adapt better to BIM implementation, as far as both collaboration and risk sharing are concerned.

[11] Some of the Crossrail BIM standards can run up to 50 pages long. CRL has included a two-page summary in many of them.

[12] This work-stream includes three sub-groups: the Mobility Task Group (to develop mobility tools), the Modeling Task Group (to maximize the use of modeling tools), and the As-Built Task Group (to ensure appropriate as-built data is incorporated in the model).

emy is not only a knowledge hub that gathers and communicates best practice, but it also acts as a lab where contractors can test the potential of new applications.

Training Programs

BIM training in Crossrail takes place at three different levels: (a) on the owner side for the supply chain, (b) on the contractor side for their own staff, and (c) with external institutions for the current and future workforce. CRL's training program, however, is probably its most notable initiative.

Through Crossrail's BIM Academy, CRL has developed a curriculum particular to Crossrail, which includes four major training modules: (1) Crossrail Vision and Strategy, (2) Document Control and Information Management using eB, (3) Management and Control of Design Information in ProjectWise, and (4) Asset Information Provision. These sessions are directed to any member of a Tier 1 or even a Tier 2 or Tier 3 contractor. BIM managers, however, are considered BIM "super-users" and thus they receive more specialized sessions. In sum, the Academy explains Crossrail standards, and teaches the necessary skills to achieve them.

While contractors acknowledge the value provided by the Academy, they consider that training at the in-house level is also fundamental. Their common approach is to appoint one person from each project team as the "BIM Champion." BIM Managers then train the BIM Champions, and these are responsible for passing that knowledge and skills on to the rest of their team. BIM Champions are also asked to use their experience to provide suggestions on how to maximize the use of BIM, and to report the challenges they encounter.

The combined result of CRL's and each contractor's training program results in a waterfall model for knowledge and skill transfer similar to that depicted in Figure 6.14, where training is passed from CRL to the contractor and its specific teams, and then again back to CRL.

The last pillar of BIM training in Crossrail results from collaborations between Crossrail and educational institutions. While this strategy has not been fully exploited in Crossrail, it is becoming one of the major focus points in future projects such as HS2, a planned high-speed railway. Projects like HS2 and Crossrail have started to collaborate to define the curriculums of programs in universities throughout the country to educate the country's future professionals.

CRL has put special effort into training document controllers. In Crossrail, only 18% of the information is stored in the ECMS (3D CAD data), as opposed to 75% that resides in the EDMS (non-graphical data and documentation). Moreover, most of the EDMS workflows are not automated. Therefore, the mission of document controllers in Crossrail (and in any other project where BIM is applied) becomes especially relevant. However, while 3D modelers are always certified engineers, document controllers are seldom professionally trained individuals.

Organizational Culture

While the UK mandate for implementation of Level 2 BIM is clearly pushing industry-wide adoption of BIM in the country, it is still hard for many contractors (and future maintainers) to see the benefits of BIM implementation. In fact, resistance to change has been one of the biggest challenges for BIM implementation in Crossrail.

There seem to be three main reasons behind such resistance. First, BIM technologies are only now becoming mature enough not to disappoint its users (past attempts have often distanced potential users); second, there is little evidence that proves the return of BIM investments (see Section 6.7.d); and third, BIM requires collaborative approaches that are uncommon within the construction industry.

CRL has therefore spent a great deal of time and effort in explaining the value of BIM to all levels of the supply chain. In particular, the BIM Academy has become the main instrument through which this message has been transmitted to contractors, subcontractors, and future maintainers. On the other hand, CRL has also been very careful in selecting the individuals within its Technical Information Department. Rather than staffing the department based on extensive construction experience, CRL has selected personnel with new ideas who are willing to do things differently.

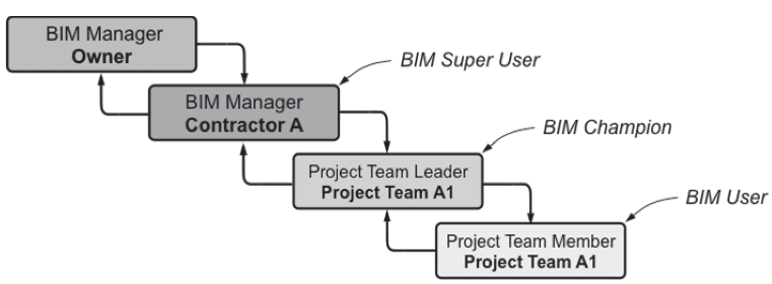


Figure 6.14. Waterfall model for BIM training in Crossrail.

6.7.c BIM Use

Once Crossrail's BIM environment was set up, CRL and its contractors started to operate and deliver its work within this environment. This section investigates BIM use in design and construction, BIM use in handover, measures of BIM use for each contractor, and Crossrail overall.

BIM in Design and Construction

Contractors in Crossrail received structural, architectural, MEP 3D models, and 2D drawings from framework design consultants. These models and drawings were developed to different LODs depending on the contract. In most cases, however, accuracy was good but geometry was improvable. Crossrail contractors must develop the design and hand the as-built (or redlined) version over to CRL. Throughout this process, different contractors used the model in different ways to fulfill different goals, and used different platforms.[13]

All surveyed contractors claimed to use the model to perform design reviews with both construction and design teams. Before 4D became a requirement, contractors α claimed to use 4D, as well as temporary works modeling, but only for difficult interfaces. It is not clear whether the ROI justifies implementing 4D for the entire project. Such implementation entails significant changes in work processes for project planners. These contractors are also using laser scanning to develop as-builts or incorporate surroundings into the model (which has proven useful for constructability studies). The use of GPR for utilities has been limited (utilities are usually not included in the model and belong to an independent work package), and in most cases the use of 5D has been discarded.

Most contractors tended to produce only the information that is required by the contract. CRL, however, has worked against this tendency to try to maximize the use of BIM in construction, through different initiatives, such as the BIM in Delivery Working Group (which brings CRL and contractor individuals together to solve business problems through the deployment of BIM technologies[14]), and the Innovate18 program (a CRL-led initiative that allows contractors to submit proposals and obtain funding to develop BIM-related applications). Through Innovate18, some contractors (contractors α) have engaged with different software developers to leverage the potential of BIM and mobile devices in the field. The result has been a toolset of BIM-based apps that improves work efficiency around pre-existing procedures specific to one contractor. The most basic examples include site diary and field inspection apps.

Information Handover

At the end of the project, CRL must hand in all the asset information to the operations and maintenance team. This information, which is provided by Crossrail's contractors at different stages throughout the project, must be linked to the model to build in the concept of "intelligent objects." It is precisely in establishing this non-graphical-graphical data linkage where Crossrail has faced some of the biggest challenges.

Crossrail's contractors are contractually required to provide a digital model of the asset, as well as a number of Excel spreadsheets including the asset data. Contractors were instructed to use AssetPainter by Bentley to establish this connection, but the process proved to be less efficient than originally expected. As a result, contractors have been providing these two elements separately, meaning that the link between them is inexistent.

This circumstance motivated different contractors (contractors α) to develop systems that automatically linked model elements and asset information. The benefits derived from establishing this link during construction as opposed to upon completion were substantial, the most important of which was the ability track work packages against asset information, which generated significant benefits during construction.

CRL and Bentley, however, seem to have found a solution to the problem that does not involve manual linking. This solution will most likely come at a cost for one of them, but arguably, this cost was inevitable. The product of BIM implementation in Crossrail is very well established, but the tools that make it possible seem to be still under development. This misalignment entails an inherent risk—a risk that in the interest of later savings Crossrail was willing to take in the first place.

BIM Maturity Evaluations

CRL included a clause in every Crossrail contract whereby, as part of its Performance Assurance Framework (PAF), it ensured the right as a client to measure the contractors' performance at any time during the project. Since 2012, CRL has made use of this clause to evaluate areas that reflect BIM implementation in Crossrail on a quarterly basis. CRL has two different BIM evaluations in place: a Design Control Assessment and a BIM Maturity Scoring. Both studies are presented and further analyzed in this section. It is worth mentioning that only contractors α were included in these audits. This includes 10 different contracts/projects.

Design Control Assessment. This assessment included four different indicators that were all associated with CAD-related contractual requirements. These included (1) design

[13] Some contractors raised the concern of interoperability issues between their platforms and Bentley's ProjectWise, which arguably kept them from achieving higher efficiencies.

[14] The BIM in Delivery Working Group (BiDWG) falls within the "Leading BIM in Construction" work-stream, and it is the last component of the Academy's curriculum.

Table 6.10. Crossrail's design control indicators, scores, and descriptions.

#	Performance Indicator	Definition	Scores and Description	
			1 - Compliance	2 - Beyond Expectations
1	Design Coordination	Contractor is using adequate design coordination methods to demonstrate that all interfaces between individual elements, systems, and parts of the design are fully coordinated.	Prepares and maintains a coordinated 3D CAD Object Oriented Model in the ECMS, produces 3D Model Issues report, utilizes the 3D CAD Model to demonstrate design is fully coordinated, has a Design Management Plan and Interface Management Plan in place.	Shares the coordinated 3D CAD Object Oriented Model in a controlled Central Data Environment (CDE) that is accessible to all Project Teams throughout the design review period, uses 3D CAD Model as part of regular design review meetings.
2	Design Submission	Contractor is using accepted and instructed design submission processes and systems.	Submitted a complete set of Drawings at "ready for acceptance" status produced using the ECMS that would allow construction, manufacture, or installation of all or part of the work.	Passed a Gate review at first attempt with no significant conditions.
3	Design Production	Contractor is using accepted and instructed design production processes and systems.	All permanent CAD data is created and managed through the ECMS utilizing the BS1192 workflows and is in accordance with the CRL CAD Standard. All 3D Objects are fully modeled using discipline specific object oriented software from the Bentley Building suite of products to a minimum level of development. All 2D models and resultant drawing deliverables are generated from 3D models. All CAD models are split according to their design content.	3D model is used as the basis for construction sequencing (4D modeling) and for cost estimating (5D modeling). Other extended applications include the modeling of temporary structures, model-based construction progress monitoring, model review for risk management, model-based construction work packaging, model support for procurement and supply chain management, and model use in field applications via mobile devices.
4	Information Handover	Contractor is using accepted and instructed redlining, as-built and technical information handover processes and systems.	Managing the redlines in accordance with the Management of Redlines Procedure, managing the as-builts in accordance with the Management of As-Built Procedure.	Use of laser scanning/point cloud surveys to accurately verify the condition of the installed works.

coordination, (2) design submission, (3) design production, and (4) information handover procedures. Each indicator had four possible values: zero (0) for *non-compliant*, 1 for *compliant*, 2 for *beyond expectations*, and 3 for *world class*. The definition, scores, and score description for each indicator are included in Table 6.10 (for the sake of brevity scores 0 and 3, which no contractor obtained, have been excluded). Figure 6.15 displays a bar chart with average values of each of these indicators along with the range of data (maximum and minimum values).

The results of the sixth run for the Design Control Evaluation showed that *design production* (#3) obtained the highest average (1.65), and the highest minimum and maximum

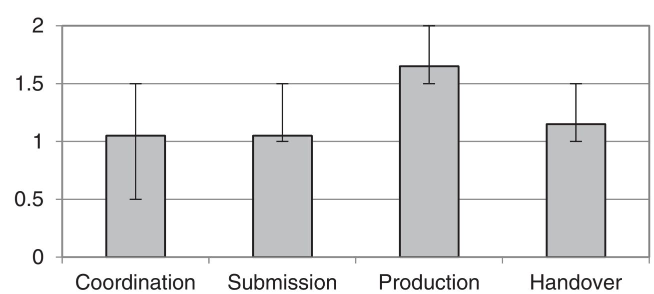


Figure 6.15. Round 6 design control assessment results.

scores (1.5 and 2, respectively) (Figure 6.15). This suggests that many contractors were close to achieving the "Beyond expectations" level on this particular category, meaning that the model was developed using instructed tools, and 2D drawings were generated from the model. Furthermore, often times the model was also used as the basis for other BIM applications such as 4D scheduling, 5D estimating, or construction progress monitoring.

On the other end of the spectrum, *design coordination* (#1) obtained both the lowest average (1.05), and the lowest minimum and maximum scores (0.5 and 1.5, respectively) (Figure 6.15). This implies that very few contractors surpassed the "Compliance level," and some even failed to comply with these contractual conditions, meaning that not only did they not use it as part of regular design review meetings, but they also failed to share an up-to-date model in the ECMS or develop the required reports.

BIM Maturity Scoring Assessment. Besides the Design Control Assessment, CRL developed a BIM Maturity Scoring Assessment that allowed for a more detailed analysis of the specific applications for which BIM was being used among different contractors. This assessment included 20 different indicators. Unlike in the previous case, all the indicators were measured according to the same criteria, which specifically addressed the level of implementation (Table 6.11). The list of indicators and their descriptions are included in Table 6.12.

The results of the sixth run for the BIM Maturity Scoring assessment showed that *design authoring* (#3) and *drawing generation* (#4) obtained the highest average scores (Figure 6.16), above 2.5, meaning that for many contractors these two use cases were "business as usual" practices, or at least their processes were in place (although not prescribed). These results are coherent since these indicators address implementation areas that are contractually required. In fact, these two use cases represent the "compliant" level of the *design production* indicator in the Design Control Assessment presented in the previous section.

The categories *3D model design reviews* (#6), *temporary works modeling* (#10), *safety and risk* (#12), and *stakeholder engagement (visualization)* (#14) obtained scores between 1 and 2 (Figure 6.16). For the most part, these results are consistent with those obtained for the Design Control Assessment, since use cases #10, #12, and #14 represent the "beyond expectations" level of the *design production* indicator. Use case #6, however, is embedded in the *design coordination* indicator of the Design Control Assessment, which had the lowest score. This result might suggest that the issue of *design coordination* has more to do with sharing and keeping the model updated, as opposed to using as the base for design reviews.

The rest of the use cases obtained scores below 1 (Figure 6.16). Among these, *traditional surveys* (#2), *phase planning* (#7), *cost estimating (5D)* (#9), *construction work packaging* (#13) and *augmented reality* (#17) showed significantly low levels of maturity, with scores of less than 0.5. Note that no data was provided for *asset tagging* (#15) or *operations and maintenance* (#20), most likely because projects were still not advanced enough to implement these use cases.

Figure 6.17 shows average scores for each of the 10 surveyed contracts, on both the Design Control (DC) and the BIM Maturity Scoring (BMS) assessments. Both measures are to an extent equivalent, so proportionality among results is to be expected.

The average score for all surveyed projects was 1.23 for the DC assessment, with no contract falling below 1 in average score. Thus, on average, BIM-related contractual clauses have been fulfilled. For the BMS study, however, the average for all surveyed projects was 0.94, with several contracts falling below 1 in average score. Thus, while in most cases BIM contractual requirements have been met, except for a few additional applications, in general contractors have not implemented BIM uses beyond what the employer required.

As observed throughout this project, BIM implementation affects multiple dimensions of an organization and its workflows. Thus, the progression into a BIM environment will most likely occur over a period of several years, and these results may just be a reflection of this slow pace. Nonetheless, as it is explained in the following section, this low rate of BIM use among contractors might also be due, among other reasons, to the lack of empirical evidence that demonstrates actual returns of BIM investment. Generating studies to share returns on BIM investment, however, has

Table 6.11. Crossrail's BIM maturity scoring criteria.

Score	Description	Meaning
N/A	Assessed/Not implemented	Assessed and decided not to implement based on project scope.
0	Not assessed/Not implemented	Not assessed or assessed and not yet implemented.
1	Implemented—Level 1 (Bronze)	Evidence of trial or implementation in progress.
2	Implemented—Level 2 (Silver)	Trial completed, processes defined, but not yet prescribed as standards.
3	Implemented—Level 3 (Gold)	Processes defined, traditional mechanisms removed, tools in place to measure value.

Table 6.12. Crossrail's BIM use cases.

#	Title	Description	Phase*	Value
1	Laser Scanning	Capturing existing as-built environment into a model.	DCO	Faster and more accurate production of terrain and as-built drawings.
2	Traditional Surveys	Importing survey information into the model.	DCO	Faster and more accurate production of terrain and as-built drawings.
3	Design Authoring (3D Modeling)	Modeling the facility in 3D using CAD object oriented software.	D	Fewer coordination errors, more accurate content.
4	Drawing Generation	Producing drawing deliverables directly from the 3D model.	D	Fewer coordination errors, more accurate content.
5	Design Change Monitoring	Base-lining the model at different stages to keep a record of changes.	DPCO	Less confusion over correct versions of the design, better estimates.
6	3D Model Design Review	Reviewing the design with the 3D model for coordination (clash detection).	DP	Highlights problems with the design. Clearer understanding of timing.
7	Phase Planning	Replacing model elements with Work in Progress (WIP) model elements.	DPC	Highlights problems with the design. Clearer understanding of timing.
8	Construction Scheduling Works (4D)	Tying elements in the 3D model to activities in the project schedule.	PC	Highlights problems with the design. Clearer understanding of timing.
9	Cost Estimating (5D)	Exporting quantities of elements from the model to perform cost tracking.	P	Helps in decision-making.
10	Temporary Works Modeling	Modeling of major temporary works to aid with sequencing and buildability.	C	Clearer understanding of timing and constraints.
11	Construction Progress Monitoring	Updating the model with construction status (electronically or not).	CO	Information is available faster, easier, and is more accurate. Number of changes reduced.
12	Safety and Risk	Integrating safety and risk information into the model to link risks with elements.	DPC	Helps in decision-making, and safety and insurance discussions.
13	Construction Work Packaging	Collecting information related to Construction Work Packages.	C	Information is available faster, easier, and is more accurate.
14	Stakeholder Engagement—Visualization	Supporting design and client meetings.	DPCO	Enables clearer vision of proposed design.
15	Asset Tagging	Collecting information against each functional unit and linking it to the model.	DPCO	Information is available faster, easier, and is more accurate.
16	Field BIM	Providing model and data to field operatives to assist them on-site.	C	Information is available faster, easier, and is more accurate. Reduces RFIs.
17	Augmented Reality	Overlaying the model view onto the camera view of a mobile device.	C	Clearer vision of proposed design, reduced number of changes.
18	Reporting and Metrics	Faster and more accurate reporting and metrics for project management.	DPCO	Information is available faster, easier, and is more accurate.
19	Supply Chain	Model component details are passed electronically to supply chain machinery.	C	Improve efficiency of supply chain and reduce materials waste.
20	Operations and Maintenance	Supplying asset information for future O&M of the asset.	O	Improve efficiency of O&M.

*Note: Phases are defined as follows: D = Design, P = Planning for construction, C = Construction, O = Operations and Maintenance

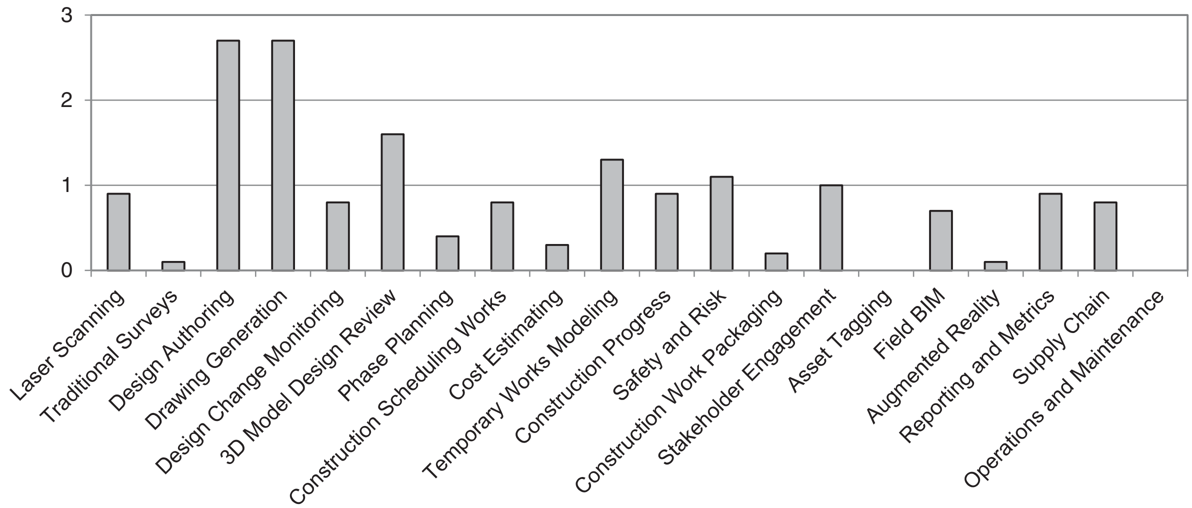


Figure 6.16. Round 6 BIM maturity scoring assessment results.

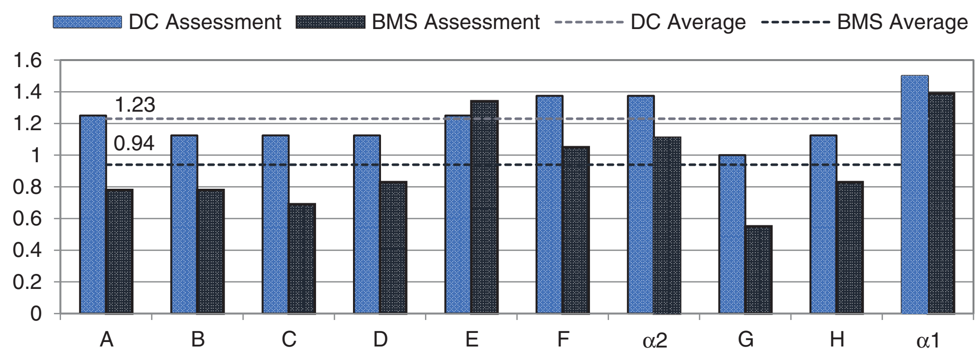


Figure 6.17. BIM maturity scores by contractor.

proven to be one of the biggest challenges for both CRL and Crossrail contractors.

6.7.d BIM Return

Measuring the return of BIM investment in Crossrail has proven to be one of the most difficult challenges for both CRL and the entire pool of contractors. This section presents some of the findings that Crossrail has provided about measurable returns from BIM implementation, in terms of both quality and cost savings.

Quality Improvements

The end goal of Crossrail's PAF initiative is not only to measure BIM implementation in Crossrail, but to evaluate, for every Tier 1 contractor in the project, a wide range of indicators that reflect both inputs (i.e., what is implemented) and outputs (i.e., what is achieved with what is implemented) associated to six different performance categories (namely, safety, environment, social sustainability, quality, commercial performance, and community relations). Each category's results are then plotted in an *Inputs versus Outputs* chart that shows overall contractor performance (Figure 6.18).

Tier 1 contractors should in theory fall somewhere in the *Potential Zone*. These contractors are complying with all contractual requirements and performing just as expected. On the other hand, those falling in the *Major Improvement Zone* are doing worse than CRL would expect, potentially failing in their contractual obligations. Lastly, those falling in the *Value Added Zone* or the *World Class Zone* are going above and beyond the employer's requirements, and performing better than CRL would expect.

To drive performance, the results of Crossrail's PAF initiative will be shared among all contractors (their identities are kept anonymous), as well as with future projects, for which these results will become integral criteria of their procurement processes. Contractors agree to these conditions, but they also take part in defining the list of indicators that comprise PAF evaluations.

About BIM performance, to date, CRL has only been able to measure the input indicators presented in the previous sec-

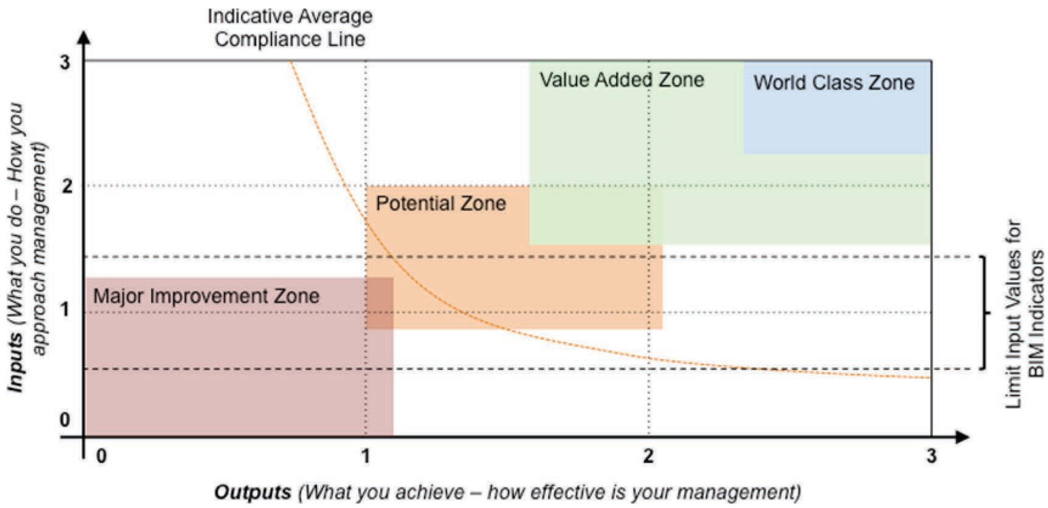


Figure 6.18. Crossrail's PAF chart.

tion. Output assessments have not yet been performed, and so this study can only define the upper and lower boundaries within which the values of BIM output indicators will fall (Figure 6.18).

Cost Savings

According to contractors surveyed in this study, the biggest benefit of BIM implementation derives from reduction in errors, omissions, and rework. This is consistent with what other studies have reported. Unfortunately, it is usually very difficult to quantify these benefits in dollar terms. In fact, both CRL and its contractors seemed to struggle when attempting to calculate cost savings from BIM implementation.

This study was nonetheless able to gather some figures on cost savings associated to particular BIM use cases. In particular, *3D model design reviews* (use case #6) have allowed Crossrail to save a major incidental rework on every station every year since the project started; *construction scheduling works* (use case #8) have reduced contract interface risks (i.e., contingency funds) in one of the stations by 8,000,000UKP (5%) after a required investment of 350,000UKP; and *temporary works modeling* (use case #10) has generated savings of around 500,000UKP for one of the contractors.

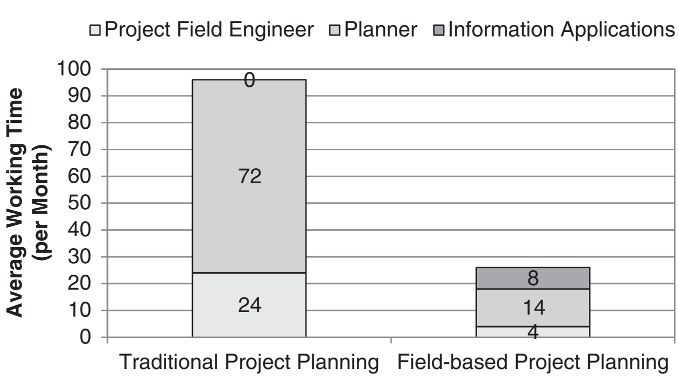


Figure 6.19. Time comparison for traditional and BIM-based project planning.

The following section presents the findings of one particular study developed by CRL in collaboration with Bentley Systems, Inc., where they analyzed savings derived from the combined application of *construction scheduling works* (#8) and *augmented reality* (#17) BIM use cases.

Cost Savings from Field-Based Project Planning (Augmented Reality + 4D). CRL collaborated with four different contractors to prove whether Field-based Project Planning (FPP) brought process and quality efficiencies to Crossrail. FPP allows "construction progress updates to be captured electronically in the field and automatically pushed back into the 4D model environment to assist with project planning activities."[15]

A cost savings evaluation was performed on the construction of pre-cast concrete structures forming the superstructure of one of Crossrail's stations. Results showed an overall productivity gain of 70 staff-hours, or equivalently, a time improvement of 73%.

This productivity gain translated into realized costs savings for the team in question and for a 1-year period of 53,481UKP ($89,738[16]). These cost savings did not include those derived

[15] In essence, this is a variation of use case #11 in Table 6.12, construction progress monitoring, when done electronically. This use case reached an average BIM maturity score close to 0.9, meaning that in most cases it had been not been implemented, or implemented only as a trial.

[16] Exchange rate used is the average exchange rate between February and August 2014, which is the period of time during which the study took place. Exchange rates were obtained from www.x-rates.com.

from a more informed and timely decision, which was however acknowledged as a major benefit.

A second stage of this study involved a forecasted ROI analysis, where predicted savings for the FPP use case, over 4 years, and on four different sites, were calculated by projecting the realized costs and benefits from the first stage. Results estimated benefits of up to 500,000UKP (around $840,000), with a break-even period of less than 1 year, and a ROI of 325%.

6.8 Cross-Case Analysis and Lessons Learned

6.8.a Agency Practices

- On a broader scale, the business processes of each of the collaborating stakeholders (agencies, contractors, utility companies, and consultants) can have an impact on effective CIM implementation on the projects.
- Workforce training programs for CIM are significant and they should take the form of a continuous process focused on design and construction areas. While construction training equips the field staff with necessary expertise and infrastructure to handle CIM operations (GPS, rovers for QA/QC, as-builts), design training facilitates the transition of the design process to handling the 3D surveying data and performing collaborative 3D design. The design-related training reportedly involves considerably more effort than the construction training. Approaches such as "Bring Your Own Device" (BYOD) (as implemented by NYSDOT through its 625 specs for contract control plans) can facilitate rapid adaptation to CIM on the construction side.
- Technology implementation planning (TIP) for CIM is mandatory at both the organizational and the project levels because it encompasses a system of technologies/practices that can affect agency workflows and project delivery processes. Experts noted that it is important to prepare, organize, and continually track an agency's progress with respect to its baseline TIP. Table 6.13 presents the major requirements for a comprehensive TIP (as understood from case studies and SME interviews). The list might not include the entire set of requirements; it is provided to identify the important needs. The TIP shall also encapsulate any other organizational processes for CIM.

6.8.b CIM Integration with Project Work Processes—Trends and Lessons Learned

3D Design

3D design necessitates different workflows and implications for the constituent elements of highway infrastructure projects. 3D design is more commonly used for elements of

Table 6.13. Technology implementation planning for CIM.

	Organizational level	Project level
Typical contents	• Vision statement for CIM • Identification of CIM technologies to be promoted • Short-term and long-term mission requirements for promotion (investment/funding requirements) • Critical organizational workflows being impacted or having impacts • Allocation of lead responsibilities, executive management buy-in • Definition and measurement strategies for performance objectives • Strategies for involving pertinent stakeholders (contractors, vendors, and utility companies) • Tracking and reporting requirements	• Integrating CIM technologies with Project Execution Plan • Specifications, standards, and guidelines development for the CIM technologies and their associated deliverables on projects • Workforce-training/motivation programs • Project-specific performance measures for CIM—anticipated benefits over investments
Examples	• WisDOT's 3D Technology Implementation Plan (Vonderohe 2013) • ODOT's Engineering Automation Plan (Singh 2008) • BIS BIM Strategy Report (BIM Task Group 2011)	• Iowa DOT's EED specifications for 3D design (Iowa DOT 2014) • ODOT's 3D Roadway Design Manual (ODOT 2012) • WisDOT's ROI analysis for CIM (Parve 2012)

roadway surface models rather than for drainage elements, utilities, or structures (such as bridges).

Roadway surface models include elements such as existing ground and proposed surface, alignments, datum points, and breaklines, among others. A good number of DOTs have reportedly performed 3D design for many roadway elements using Bentley InRoads/AutoCAD Civil 3D[17] workflows. The relevant EED specifications are also provided in contracts.

3D design for structures and utilities is still an emerging functionality of CIM. Agencies and projects have deployed 3D design if the projects involve complex interchanges, multistage construction, and steel structural (cross-river) bridges. Clash detection (hard clash and clearance issues) is reported to be the major application. The work processes typically use Autodesk Revit/Civil 3D and Bentley InRoads/LEAP tools.

Some of the "best practices" identified for 3D design include the following:

- Performing integrated surveying (LiDAR, total stations, aerial imagery, etc.) to support the 3D data requirements for design (WisDOT).
- Providing 3D (roadway surface) models to the contractors pre-bid.
- Ensuring availability and implementation of EED specifications for 3D design.
- Standardizing software workflows, LOD specifications, and templates of deliverables—examples include WisDOT's Project Modeling Matrix (Parve 2014), software templates from the DOTs of Florida and Massachusetts (Civil 3D), and Oregon (InRoads).
- Managing design changes (schematic to detailed design) is critical for effective 3D modeling in complex structural projects (MassDOT case study).
- Attempting pilot projects for transitioning to 3D design (KYTC case study) and extracting best practices for the agency.
- Motivating all the disciplines to perform design in 3D (developing discipline-specific 3D design guidelines).
- If need arises, draping (geospatial) can be used for elements not modeled in 3D (ROW, buildings).

Major benefits include effective downstream application (AMG), clash detection, and other applications, such as creating 4D and 5D models and enhancing public information processes (through visualization). Major challenges include initial capital investments, workflow disruptions, and funding constraints.

Benefit-cost analysis can be performed for 3D design for some functions, such as clash detection (among disciplines such as drainage, utilities, and structures), productivity, and labor savings in AMG. Investments in 3D design can also help reduce the overall program costs of future projects (such as WisDOT's Mitchell Interchange and Zoo Interchange projects).

[17] The software names are provided in this document for the purpose of illustration. The research team does not prefer a particular application or tool.

4D and 5D

4D design adds the "time" component to a 3D model to simulate construction processes. In other words, a 4D model integrates a construction schedule within a 3D model. The technique has numerous benefits for the identification of spatial and temporal conflicts, work area management, constructability analysis, and evaluating site logistics, among others.

In practice, 4D is implemented on projects that involve staged construction (to examine temporary structures, drainages, crossovers, and detour configurations). Common software tools include Bentley Navigator/Autodesk Navisworks/Synchro. Some of the candidate projects that reported use of 4D include Multnomah Oregon Sellwood Bridge Project, San Francisco Oakland East Span replacement, CTDOT's I-95 New Haven, TxDOT's Dallas Fort Worth Connector, and WisDOT's SE Freeways project.

Interviewees observed that the challenges are more process-oriented than technology-based. Some of the lessons learned are listed below:

- A clear technical objective and business motive is mandatory for operationalizing such technologies.
- Understanding the relationship between the LOD of the model and the schedule is paramount for achieving completeness and integrity shown in the 4D simulations.
- Connecting model elements and schedule activities can be automated if there is an appropriate protocol in place for synchronization. It appears that software tools have the potential to facilitate the process and greater collaboration among the project team (especially modelers and schedulers) to solve problems. Recommendations can be drawn from the building industry where assembly codes (Uniformat classification systems) are used to generate rules for automating the linking of model elements and schedule activities.
- 5D (cost loading the model) is still an emerging application.

Machine Controls for Construction—AMG

AMG is an important CIM technology that many agencies are deploying in their projects. The case studies and surveys indicated that AMG is predominantly used for dirt work/excavation-related operations. Although it is feasible, few examples are available for studying the use of AMG for finished surface (concrete/asphalt) construction; the requirements for more total stations and better control equipment are cited as the major barriers. Contractors have reported using equipment and software from vendors such as Trimble/TopCon systems. Some of the best practices that can lead to widespread implementation of AMG include the following:

- Preparing and implementing specifications (especially for finished surfaces)
- Having contractor buy-in and equipment affordability
- Providing 3D EED deliverables in both native (DWG/DGN) and converted (XML/machine readable) formats
- Performing pilot projects and extracting suitable lessons
- Preparing appropriate contract clauses favoring application of AMG
- Implementing BYOD approach so that contractors use their own equipment (NYSDOT case study—625 spec)
- Using guidance such as FHWA's 2014 circular when "construction inspectors are responsible for quality assurance" (FHWA 2014b)

Integrated Surveying—LiDAR

Many agencies have reported constructing and operating a CORS network for surveying and real-time positioning purposes. The system has numerous benefits, despite the high initial costs. MassDOT has documented investment costs and potential life-cycle applications for operating such a CORS network (MassDOT 2013).

Having a coordinate system that provides low distortion in horizontal and vertical measurements could potentially save a lot of effort in analyzing the survey data (for example, the ODOT has reported that through its Oregon Coordinate Reference System, the need for "rubbersheeting" and introducing "Surface Adjustment Factors" has been eliminated—as per SME interview with Ron Singh).

Mobile LiDAR appears to be a central CIM technology, because it has proven benefits throughout the life cycle of a facility (Olsen 2013). When used, mobile LiDAR plays a significant role in aiding digital project delivery and asset management. The case studies and SME interviews revealed that investments in mobile LiDAR would assist in rapid collection of semantically rich point cloud models and high-resolution imagery that has agency-wide applications for project development. These point cloud models are useful at all phases of the capital project life cycle—from design to maintenance.

Several agencies are evaluating their prospects and investing in collecting this data for their highway systems. The ODOT (SME interview—Ron Singh) is part of a major consortium that is involved in collecting LiDAR data of its highway systems (the Portland LiDAR Consortium). Caltrans and Washington DOT have performed detailed benefit-cost analysis that examined different strategies of using a mobile LiDAR for agencies' requirements (including such options as contract, rent and operate, purchase and operate, and partial ownership). The study concluded that purchasing and operating a survey-grade mobile LiDAR has tangible life-cycle benefits that considerably outweigh the initial investments (Yen et al. 2014). Some of the experts also noted that at a holistic level, investing in collecting 3D LiDAR data would be beneficial for agency-wide CIM implementation regardless of the mode of the ownership.

Utility Engineering

CIM technologies pertaining to utility engineering (e.g., GPR, SPAR clouds, Electromagnetic Imaging) are generally adopted on projects that have considerable risks and uncertainties in locating the underground utilities (especially the elevation information). Although the information on existing utilities resides in 2D plan sets or databases, agencies are now exploring ways and incorporating strategies (technological, contractual) to obtain geospatial utilities data on new projects (especially 4R).

Utilities are generally modeled in 3D to perform clash detection with other design entities such as drainage, structures, ITS, and lighting, among others. Although the process has several benefits, some process-oriented challenges could be overcome by use of the following:

- Greater collaboration with utility companies (addressing their security concerns)
- Optimized deployment of SUE practices such as GPS/GPR and EMI to identify the location of utilities (Maintaining an up-to-date digger's outline is crucial.)
- Extending current utility conflict resolution standards (such as Utility Conflict Matrices being developed by various DOTs) to include CIM data (3D geospatial utilities)
- Having agencies request as-built utility data from contractors on their projects (through specifications)

Data and Information Management

- Most of the agencies have reported using online/electronic modes for the bidding and submittals phase of a project. These are often managed by the agencies or handled by third-party agencies (websites).
- For document controls (especially during design and construction), the agencies have used tools such as AASHTOWare Project suite, Bentley ProjectWise, and Microsoft SharePoint.
- Some DOTs have deployed the capabilities of electronic document management systems to perform major functions such as revising and approving plans, field verifica-

tions, daily log reports, change management, among others (MDOT e-Construction initiative).

- Model-based workflow is usually supplemented with traditional project control techniques for estimating, scheduling, change management, design reviews, and approvals (Trimble tools, Primavera). There are a few reported instances of directly using model-based tools for estimating QTOs and calculating earthwork quantities.
- Some of the lessons learned are as follows:
  - Cloud-based technologies can be leveraged to organize and share the information among all stakeholders.
  - Extensive and accurate design of all the disciplines in 3D can make the model usable for all tasks. This would require training (and overcoming the learning curve) and increased coordination efforts among all the stakeholders (involving the various design disciplines and contractors).

Intelligent Compaction

The case studies and SME interviews suggested that IC is an emerging CIM application with greater prospects for the future. This technology provides real-time verification of various compaction indicators. The general trend among all the DOTs is that they are performing pilot projects with this technology and developing specifications for its widespread use on other projects. Some of the commonly reported challenges include the high initial cost of equipment and lack of contractor buy-in. Following are some of the lessons learned:

- Since this is an evolving technology, DOTs should collaborate and develop standards from other agencies, as applicable for soils, asphalt, and aggregates.
- The FHWA's website "www.intelligentcompaction.com" can be a tremendous resource because it reconciles current practices, specifications, pilot projects, and future trends of IC from many DOTs. Agencies can make use of this data to understand and develop specs. Table 6.14 provides a snapshot of practices at DOTs taken from the website.

GIS

Locating CIM data geospatially is important for all phases in project development. Many DOTs have used GIS technology during the project planning and development phases for a variety of applications, such as Environmental Impact Assessments, Alternative Analyses, and ROW acquisition planning. Agencies have also described using GIS data for design evaluation and visualization.

Table 6.14. Specifications of IC across DOTs (FHWA 2014a).

Agencies	Asphalt IC Specs	Soils IC Specs
FHWA	Asphalt	Soils
AASHTO	Asphalt-Soils combined - PP 81-14	Asphalt-Soils combined - PP81-14
Central Federal Land HD	Asphalt	
Eastern Federal Land HD	Asphalt	
Alaska DOT	HMA	
California DOT	HMA (draft), CIR (draft)	
Georgia DOT	Asphalt	Soils
Indiana DOT		Soils
Iowa DOT	Asphalt	Soils
Michigan DOT		Soils
Massachusetts DOT	HMA	
Minnesota DOT	Asphalt-Soils combined, Thermal profiles	Asphalt-Soils combined
Nevada DOT	Asphalt	
New Jersey DOT	HMA - coming soon	
North Carolina DOT	Asphalt (draft)	Soils (draft)
Oklahoma DOT	Asphalt	
Pennsylvania DOT	Asphalt (draft)	
Rhode Island DOT	HMA	
Tennessee DOT	HMA	
Texas DOT		Soils, Approved IC rollers
Utah DOT	Asphalt	
Vermont Agency of Transportation	Asphalt	Subbase

Some of the nationwide best practices of GIS applications have already been reviewed during this project including the following:

- Utah DOT's UPlan
- South Carolina DOT's Project Screening Tool
- Washington DOT's State Route Web Tool
- Florida DOT's Environment Screening Tool

Other Innovative CIM Technologies

Technologies examined thus far have already found their strategic significance for digital project delivery and asset management. This section describes other emerging technologies that have been studied in only a few instances, but that hold greater prospects for the future.

An emerging technology that is enabling and complementing the use of AMG is equipment telematics. The telematics tool, when incorporated with construction equipment such as excavators, dozers, and graders, can provide numerous benefits, such as improving machine utilization, allowing real-time tracking of vehicles, reducing fuel consumption, and increasing overall efficiency of the construction operation through an optimized fleet management (Anderson 2012). This web-based tool provides the ability to remotely access the equipment data from the office and helps upload the recent design files for use by operators in the field. Higher initial cost, lack of operator training, and non-availability of standards are some of the reported challenges for this technology. Example applications include Trimble/Topcon/Leica products.

Advanced material management systems are also an important emerging CIM application. A web-based tool—such as FiveCubits—can be deployed to efficiently manage the purchasing, transit, and delivery of bulk materials. It optimizes the truck fleets and facilitates real-time sharing of information among all stakeholders (owner, contractor, supplier, and subcontractors). These tools could be seen more prominently in large infrastructure projects in the future.

Digital Asset Management

Among all other phases, asset management can benefit considerably if CIM tools are implemented. Current issues for digitizing this process are presented below.

- Different forms of data for asset management—2D as-builts, 3D electronic, 3D point clouds. Appropriate technical and management strategies have to be defined to deal with heterogeneity in the asset data.
- Archival and regular updating of asset information would help complete the life cycle of CIM data. However, there are several organizational and technical challenges that hinder this process.

Contracts

- SMEs and case study participants had varied perceptions of the relationship between alternative contracting methods (such as D-B) and CIM practices. While everyone agreed that the D-B mechanism fosters a collaborative environment among the major stakeholders, some believed that essential benefits of CIM tools might be available for any project delivery method. Some participants also noted that the CIM data have utility value for the entire life cycle of a facility, including the long-spanning O&M and asset management functions. Thus, the benefits of CIM have to be understood from an agency-wide (system) life-cycle analysis rather than project-specific parameters.
- Contractually, 2D plan sets remain the governing documents. Some DOTs have carried out pilot projects wherein 3D surface models are given priority over 2D plans (KYTC case study). However, for widespread implementation of this practice, it would require extensive collaboration of all the design disciplines (roadways, bridges, utilities, ITS, lighting, signs, etc.) to perform their designs and detailing in 3D.
- Although DOTs provide electronic data in both native and converted file formats for AMG, the models are usually supplemental or provided for information only. The risk, accuracy, and liability issues arising from using them for downstream construction applications are transferred to the contractor.

Following are the current best practices:

- The agencies should generate their plan sets automatically from 3D (surface) models and include additional details on them.
- 3D models and 2D plan sets should be cross-checked for QA/QC and models have to be kept updated.
- Incorporating detailed specifications on LOD in contracts would help standardize the modeling and reporting practices among all the stakeholders on projects (Crossrail case study).

Governance (Legal)

DOTs often use digital signatures in encrypted form for plan sets. These signatures are rarely used for signing the 3D electronic data (due to security and authenticity concerns). Experts believe that this practice might arise in the future because it could save time and money. Some of the best practices to address legal concerns include the following:

Table 6.15. A brief summary of ROI analysis for CIM technologies.

Organization	Focal point for analysis	Brief description
MDOT	E-document management systems (ProjectWise)	MDOT has calculated potential savings of its "e-construction" initiative driven by paper-less work processes. After validating it through their "pilot" projects, the agency is planning for widespread implementation (Farr 2013).
WisDOT	3D design (clash detection)	WisDOT has evaluated discipline-wise ROI analysis (roadways, traffic, structures, etc.) by implementing 3D design and performing clash detection processes. Savings due to potential conflicts are designated as "avoidance costs" (Parve 2012).
Caltrans and WSDOT *NCHRP Report 748*	Mobile LiDAR	Caltrans and WSDOT have performed benefit-cost analysis that examined different strategies of deploying a mobile LiDAR for agencies' requirements (Yen, Lasky, and Ravani 2014). *NCHRP Report 748* has also provided guidelines on procurement considerations and implementation plans.
MassDOT	GPS/CORS network	MassDOT has documented investment costs and potential life-cycle applications for operating such a CORS network (MassDOT 2013).
TxDOT	3D design and ProjectWise	TxDOT is envisioning implementation of 3D design on its projects and ProjectWise to support the 3D workflow. It has performed a preliminary NPV analysis considering direct IT and bid savings over initial investment costs (TxDOT 2014).
ODOT	Information Technology Benefit-Cost Evaluation report	ODOT evaluated the benefits and costs of nine IT systems put in place by the agency and the Oregon Bridge Delivery Partners in support of OTIA III State Bridge Program. The systems include GIS infrastructure, environmental analysis tools, electronic document management systems, engineering tools, work zone analysis tools, among others (Hagar 2011).

- Defining software use to avoid interoperability issues and information loss.
- Ascertaining pertinent federal and state agency laws impacting use of digital intellectual property on the projects.
- Apportioning responsibilities for maintaining and updating models.
- Specifying ownership and copyright issues of 3D models.
- Protecting collaborators on models, such as through "read-only" files, access control, and disclaimer clauses.
- Establishing conflict and dispute resolution mechanisms. (Example: If discrepancies arise between 3D model and plan sets, priority should be given to plan sets). Using partnering on projects to avoid potential disputes.
- Defining public information and disclosure issues.
- Understanding and implementing digital signatures and their utility on projects.
- Working with government and regulatory authorities on strategic decisions to accelerate the implementation of digital technologies. These authorities pave the way for uniform implementation of technologies across organizations and their projects (Crossrail case study, Singapore's e-BIM submission system).

Some national and state standards (for example, *NCHRP Legal Research Digest 58*) are in place to provide specific guidelines on implementing the aforementioned practices on projects.

6.8.c Performance Measures—Investment Analysis

Participants had varied perceptions of quantifying the benefits of CIM practices. They also cited non-availability of a uniform methodology to guide the investment decisions as the primary concern. However, there was also consensus on the point that such tools can always be subjective and specific to a particular project and business processes.

Researchers have performed ROI analysis for BIM implantation at an organization level; these resources were reviewed during this project. DOTs have also evaluated the ROI for individual CIM processes, as shown in Table 6.15.

CHAPTER 7

CIM Implementation Framework—Formulation and Validation

The research team analyzed the project's research findings and expert insights to understand DOTs' fundamental requirements for integrating CIM tools and functions with project delivery processes. Surveys and case studies demonstrated that DOTs have varying levels of expertise with processes, and operations for project delivery and facility management varying widely among them. A generalized implementation framework for DOTs to use to determine their current state of CIM practice and prioritize their decisions on investing in CIM tools by gauging the practical challenges would be valuable. The framework would also form the basis for widespread implementation across agencies. Accordingly, the data and knowledge gathered through the research efforts was reorganized and a process cycle developed. Explanations of these stages and associated terminologies are described in detail in the companion Guidebook. Table 7.1 illustrates the conceptual relationship among the research findings, the implementation stages (in the Guidebook), and the objectives of this research.

The research team also conducted external validation of the Guidebook, collecting and implementing specific comments as per the request of participating organizations. The team prepared a questionnaire, focusing on the content and organization of the draft Guidebook, for the validation process to ensure consistency in the data collection process. Options were included to help the participants think independently and critique and comment on the draft Guidebook.

The organizations that participated in the validation process include TxDOT, CDOT, and Bentley Systems, Inc. The research team conducted meetings with experienced personnel and executives from each of the participating agencies, either online or in a face-to-face format. There were several rounds of meetings, each lasting 1 to 2 hours. The research methodology and implementation framework were presented to the participants, followed by a discussion of key research findings. The team received several useful comments and recommendations from these meetings. Appendix E contains the detailed questionnaire used. A consolidated summary of these comments and associated modifications in the Guidebook are presented in this chapter.

7.1 Validation Process—Consolidated Summary of Comments and Recommendations

The participants made several recommendations for revisions to the Guidebook. The research team revised the Guidebook accordingly. The participants also reviewed the implementation framework and the supporting case examples presented in the Guidebook. The general conclusion was that the proposed framework makes a favorable case for integrating CIM in agencies' practices and provides a sequence of steps that are practical and comprehensive. They stated that the maturity model adequately captured the range of practices typically found in practice today and the potential opportunities for the future. The experience-based case examples and lessons learned sections were found to be useful for addressing the implementation challenges encountered while advancing CIM. In addition, some key points were put forward for discussion and potential inclusion in the Guidebook. They are presented in the following subsections, with notes on the way they are implemented in the Guidebook.

7.1.a Construction Modeling

One of the expert participants made the following comments:

> *There needs to be some consideration for the common practice of Construction Modeling, which, most commonly, entails transforming design content to 3D content suitable for machine control/machine guidance. Contractors have hired construction modelers or employ independent consultants from the cottage industry that has sprung up to support this need. The text appears to imply that "digital design data" can be used directly with AMG without data preparation. It is rarely that straightforward. In between receipt of the digital design data, the model must be densified and other*

Table 7.1. Summary of relationship between implementation framework and research objectives.

Implementation framework (see Guidebook)		Supporting research findings from this report	Objectives of the research
Stage	Description		
Assessment (Stage I)	This stage begins with a holistic analysis of the functional capabilities of DOTs using a formal maturity model and identifying areas (i.e., divisions such as surveying and design, among others) that warrant further attention for potential process-related improvements through CIM tools. It requires that the DOTs communicate and identify authorized needs through a CIM Implementation Plan (CIP).	The state-of-practice survey data (Chapter 5) helped in gauging the state of practice across the United States and establishing baseline maturity levels. The empirical data on CIM usage at project work areas (Figure 5.5) and statistics for cumulative CIM usage map (Figure 5.6) are the key contributors to the formulation of a maturity model.	Objective 1—The maturity model and supporting guidelines can help assess an agency's use of digital information in project delivery and asset management.
Investment analysis (Stage II)	This stage focuses on the principal CIM tools identified from the CIP and provides general guidelines on the methodologies and requirements for benefit-cost analysis. While investment needs are identified for CIM tools, the anticipated benefits are mapped to the corresponding CIM functions. As such, benefits must be determined by modeling anticipated work process improvements within and across CIM functions. Case examples highlight agency's practices for selected CIM tools.	The specifications for this stage are drawn from multiple data collection efforts such as literature review, surveys (Chapter 5), and case studies (Chapter 6). While it was practically infeasible to quantify benefits of the system of CIM tools, literature and case studies provided information for some key components.	Objective 3—The expected costs and benefits have been identified for the noted CIM tools. The considerations for prioritizing these considerations have been identified to help agencies increase reliance on CIM.
Implementation considerations (Stage III)	This stage highlights the lessons learned and recommendations that state agencies obtained from executing projects and deploying CIM tools at their agency level. Albeit not necessarily quantifiable, these practices play an integral part, while dealing with contractual and governance-related issues.	The case studies of the projects that successfully demonstrated integration of major CIM practices and cross-case analysis (Chapter 6) supported the guidelines developed for this stage.	Objectives 2 and 4—The issues discussed herein highlight contractual, governance, and process-oriented strategies to enhance reliance on digital project delivery and asset management.

operations for AMG. This is an important and oftentimes costly step and should be highlighted in the document.

The team concurs that construction modeling is a significant function that transforms the 3D design deliverables to machine-readable formats for AMG. Simply put, this process involves incorporating required details (such as ensuring the addition of all surface elements in 3D, breaklines at necessary places, densification of points and grade lines, etc.) in the model that could enable machine automation and reliable quality control. The team believes that in a fully integrated CIM environment, agency designers and design consultants can take up this role while creating design deliverables and handover information for construction.

Accordingly, the team clarified the roles and responsibilities of designers in the CIM workflow (Chapter 3) in the Guidebook and provided suitable investments in training (Chapter 4, Section 4.2) for construction modeling.

7.1.b Reality Modeling and Digital Photography

Another expert suggested examining digital photography.

Reality modeling is an emerging term meant to describe the software that transforms digital photography taken by a drone into a 3D mesh model of current conditions. This is but one example of an array of data collection post-processing tools that likely should be recognized for their ability to create models of existing conditions.

The team agrees that the list of CIM tools, especially in the sensing technologies category, can be extended further with more options. With time, more technologies will penetrate the industry markets along with efficiency improvements to existing tools. It can be very challenging to present all of the known technologies—including foundational, advanced, and emerging technologies—in one guidebook. Considering their growing popularity and relevance for rapid data collection during project development and surveying, the team included digital photography and other relevant context-capture tools (for surveying) in CIM workflow (Chapter 3).

7.1.c Model-Based Quantity Take-Offs and Estimating

An expert recommended that QTOs from models for owners (such as DOTs) bid estimates be highlighted in CIM functions (possibly under design). Ideally, this data would end up in owner preconstruction and cost estimation packages such as AASHTOWare's Project Cost Estimation, Project Estimation, Project Estimator, and Project Preconstruction. It was also pointed out that owner-oriented construction supervision, such as AASHTOWare Site Manager, enables owners to examine contractor-earned value claims.

The team ensured that these suggestions were adopted and expanded current discussions on QTOs into the Guidebook to address these comments. The definitions for "5D estimating" under Project Management Function was expanded (Section 2.2.4) and details were added to the Construction Planning and Procurement Phase (Section 3.1.4) to highlight the role of 5D estimating or model-based QTO and estimating processes.

7.1.d Work Packaging and CIM Integration

Work packaging, as a project management principle, is gaining popularity among capital industry (such as power, oil, and gas processing etc.). It seeks to manage the daily project activities by "disaggregating into manageable parts and assigning responsibility for detailed management of each level and element. In the case of a construction project, the parts involve engineering, procurement, construction, and startup" (Construction Industry Institute IR 272 2013). Recent advancements also demonstrate that CIM and work packaging integration can also streamline the transition to model-based construction monitoring and operation. An expert asked the team to consider introducing the significance of the work packaging practice and exploring the potential of CIM integration for the highway infrastructure.

The team believes that work packaging is an emerging practice in the highway industry that can contribute in many ways to an agency's objective in terms of CIM workflow. Hence, the team included the definition of work packaging, along with brief explanations of its role for CIM in the Guidebook (Refer Section 4.3.1). In-depth investigations and implementation methodologies for CIM and work packaging integration were deferred for future research because this was not the primary objective of this project.

7.1.e Asset Modeling

With more agencies transitioning to CIM for project delivery and asset management, various requirements of assets maintenance need to be given due consideration. An expert member made the following comments during the validation process:

> *Asset management consists of both asset information management and asset modeling—modeling the degradation of an asset over time and the effects of various treatments. For example, a pavement management system has to manage information of the characteristics and condition of thousands of roadway segments. But it also has to forecast the degradation of the roadway due to time and traffic, be able to analyze the effects of different treatments such as minor resurfacing, reconditioning, or reconstruction, compare the C/B of the treatments and provide recommendations across the system.*

The team concurs that asset modeling plays an integral role in efficient management of assets, specifically pavements and structures. It has to be noted that deploying sophisticated performance and degradation prediction models need not directly reflect a CIM-related capability (or a function); CIM functions include only those that are positively affected by the enumerated CIM tools. Nonetheless, using state-of-the-art models reflects the maturity of the agency for pavement maintenance. Thus, the team included this capability under the operations and maintenance phase of the maturity model (Figure 3.2) in the Guidebook.

7.1.f Miscellaneous Comments and Modifications

- The learning curve for transitioning to 3D design and modeling and the system benefits after widespread adoption were highlighted for beginners. An expert member made the following comments to clarify this situation:

> *In any change, the initial transition may take some time to regain production performance, but once the new system or process is learned there are substantial productivity gained. For example:*

quantities become faster, changes are seen and performed quicker in a modeling environment, inter-disciplinary decisions and conflicts are easier to determine in a model environment, deliverables for management and public hearings are a by-product of the modeling process and not another process.

- An expert stated that the identified standards (Section 3.1.7 in the Guidebook) for model-based information exchange were representative examples. More work needs to be done to overcome their current limitations and adequately cover the scope of modeling all entities for highway infrastructure. The expert elaborated as follows:

Current examples (such as LandXML, TransXML, IFC, and COBIE, among others) are 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.

- A new CIM function (Contracts) has been added to the Guidebook under Project Management to account for activities such as construction project administration, Requests for Information, contract administration, and change order management (Section 2.2.4).

CHAPTER 8

Conclusion

CIM encompasses the set of foundational and emerging technologies that assist in digital workflow that includes data collection, design, construction, and asset management activities. This report documented the research objectives, methodologies, and principal research findings of NCHRP Project 10-96. An extensive literature review was conducted to understand the contemporary CIM tools and the functions they influence in the project delivery process. A synthesis of worldwide trends and initiatives was also presented to underline the pertinent strategies of other major countries deploying CIM for project delivery. The results of the two national surveys—agency and project surveys—were summarized along with basic statistical analysis that provided important insights into the current state of practice across U.S. agencies. The seven case studies, identified from the surveys, helped elicit several lessons learned and best practices for CIM integration with project work processes.

The key research findings were then used to develop the Guidebook, which consists of a three-stage implementation framework to help agencies assess their current capabilities, determine the investment requirements and process benefits of new technologies and functions, and make decisions after accounting for implementation of best practices. The Guidebook was then validated through online meetings with TxDOT, CDOT, and Bentley Systems, Inc. All the major comments and recommendations from the meetings were incorporated in the Guidebook. The Guidebook will act as a foundational guideline that facilitates widespread integration of CIM tools (and functions) and supplements existing specifications at agencies. Future research should focus on development of objective decision support systems that can help agencies plan, select, and prioritize the investment decisions about CIM technologies. Such tools can provide the agencies the decision-making capabilities for coordinated implementation of CIM tools.

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Acronyms

ABC	Accelerated Bridge Construction
ABP	Accelerated Bridge Program
AMG	Automated Machine Guidance
ATC	Alternative Technical Concepts
BCA	Building & Construction Authority
BEP	Building Information Modeling Execution Plan
BiDWG	Building Information Modeling in Delivery Working Group
BIM	Building Information Modeling
BYOD	Bring Your Own Device
CAD	Computer Aided Design
Caltrans	California Department of Transportation
CDE	Central Data Environment
CDOT	Colorado Department of Transportation
CIM	Civil Integrated Management
CIP	CIM Implementation Plan
CM/GC	Construction Manager/General Contractor
COBie	Construction Operations Building Information Exchange
CORENET	Construction Real Estate NETwork
CORS	Continually Operating Reference Stations
CRL	Crossrail
CTDOT	Connecticut Department of Transportation
CTR	Center of Transportation Research
D-B	Design-Build
D-B-B	Design-Bid-Build
DOT	Department of Transportation
DTM	Digital Terrain Model
ECMS	Electronic CAD Management System
EDC-3	Every Day Counts
EDMS	Electronic Document Management System
EED	Electronic Engineered Data
EIR	Employer’s Information Requirements
e-submission	Electronic Submission
ERP	Energy Resource Planning
FHWA	Federal Highway Administration
FPP	Field-Based Project Planning
GIS	Geographic Information Systems
GNSS	Global Navigation Satellite Systems

GPR	Ground Penetrating Radar
GPS	Global Positioning System
HDB	Housing and Development Board
HMA	Hot-Mix Asphalt
i-BIM	Integrated Building Information Modeling
IC	Intelligent Compaction
IFC	Industry Foundation Classes
IGN	National Institute of Geographic and Forest Information
ITS	Intelligent Transportation Systems
KYTC	Kentucky Transportation Cabinet
LiDAR	Light Detection and Ranging
LOD	Level of Development
MassDOT	Massachusetts Department of Transportation
MDOT	Michigan Department of Transportation
MEP	Mechanical, Electrical, and Plumbing
MIDP	Master Information Delivery Plan
nD	n-Dimensional
NPV	Net Present Value
NYSDOT	New York State Department of Transportation
O&M	Operations and Maintenance
ODOT	Oregon Department of Transportation
P3	Public-Private Partnership
PAF	Performance Assurance Framework
PL&G	Preliminary Line & Grade
PS&E	Plans, Specifications, and Estimates
PWF	Project Work Functions
PWP	Project Work Processes
QA/QC	Quality Assurance/Quality Control
QTO	Quantity Take-Off
RFI	Request for Information
RFID	Radio Frequency Identification
RID	Reference Information Documents
ROI	Return on Investment
ROW	Right of Way
RTN	Real Time Network
RTS	Robotic Total Stations
SME	Subject Matter Expert
SPMT	Self-Propelled Modular Transporters
SUE	Subsurface Utility Engineering
TCP	Traffic Control Plan
TIP	Technology Implementation Planning
TxDOT	Texas Department of Transportation
UAV	Unmanned Aerial Vehicle
UCM	Utility Conflict Matrix
WIP	Work in Progress
WisDOT	Wisconsin Department of Transportation
XML	Extensible Markup Language

APPENDIX A

Agency 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, "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

- **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

- **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

As you can see CIM encompasses a very wide range of technologies and applications; therefore, it is important that we obtain different user perspectives. If you feel that there are additional people in your agency, or the agency you work with that could participate in this survey, please forward this survey on and/or list the contacts below.

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

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

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

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

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

In addition to this survey, we are conducting a separate survey regarding projects' use of CIM. Are there any specific 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)?
   - ☐ Planning and Programming
   - ☐ 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. Agency Characteristics

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

4. Which methods of project delivery does your agency, or the agency you work with, utilize (check all that apply)?
   - ☐ Design Bid Build:
   - ☐ CM/GC:
   - ☐ Design Build:
   - ☐ Public Private Partnerships (P3)/Concessions:
   - ☐ Other, please describe: Click here to enter text.

5. Does your agency, or the agency you work with, keep and publish bid tab data?
   - ☐ Yes
     How and where is that documentation stored? Click here to enter text.
   - ☐ No

6. Does your agency, or the agency you work with, utilize an electronic/online project controls system (e.g., AASHTOWare Project, Primavera Expedition, etc.)?
   - ☐ Yes
   - ☐ No

7. Does your agency, or the agency you work with, utilize an electronic/online Enterprise Resource Planning (ERP) System?
   - ☐ Yes
   - ☐ No
   - ☐ Don't know

   If yes, please answer parts a, b, c, and d.

   a. Is the project controls system integrated with the ERP system?
      - ☐ Yes
      - ☐ No

   b. Are both or either systems integrated with CIM technologies/software utilized by the agency?
      - ☐ Yes
      - ☐ No

   c. Is the information in any way provided to an outside agency?
      - ☐ Yes
      - ☐ No

   d. Are there any security concerns regarding sharing data between agencies?

☐ Yes
☐ No

8. Does your agency, or the agency you work with, have or plan to add contractual language regarding the use of CIM technologies?
   ☐ Yes
   ☐ No

9. Does your agency, or the agency you work with, have any documentation that helps provide guidance on the implementation of CIM during design?
   ☐ Yes
   ☐ No

10. Does your agency, or the agency you work with, have any documentation that helps provide guidance on the implementation of CIM or any related technology on projects?
   ☐ Yes
   ☐ No

11. Does your agency, or the agency you work with, have a specific plan in place for archiving of digital information?
   ☐ Yes
   How is archiving of such information done today? Click here to enter text.
   ☐ No

12. Please check all of the technologies that your agency, or the agency you work with, utilizes.
   - **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.

13. 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 & Operations
2D	☐	☐	☐	☐	☐	☐	☐	☐
3D/nD	☐	☐	☐	☐	☐	☐	☐	☐
Sensing	☐	☐	☐	☐	☐	☐	☐	☐
Data Management	☐	☐	☐	☐	☐	☐	☐	☐

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

III. Technology Governance

a. Regulatory Issues

14. Do Federal regulations impact CIM implementation?
   ☐ Yes
   ☐ No

15. Are there any State statues, laws or regulations that impact CIM implementation within your agency or the agency you work with?
   ☐ Yes
   Please list the statues, laws or regulations. Click here to enter text.
   ☐ No

16. Does your agency, or the agency you work with, have any dispute resolution clauses in place to solve potential issues that may arise due to the implementation of CIM?
   ☐ Yes
   ☐ No

17. Does your agency, or the agency you work with, have a policy/guidelines regarding ownership of digital information?
   ☐ Yes
   ☐ No

b. Implementation and Best Practices

18. What are lessons learned (if any) related to deployment of specific technologies? Click here to enter text.
19. What are lessons learned (if any) with respect to training of personnel on the use of CIM technologies? Click here to enter text.
20. What are lessons learned (if any) with respect to contractual requirements related to CIM? Click here to enter text.
21. In your view, what are the primary benefits derived from the utilization of CIM related technologies and methods? Click here to enter text.
22. What are the primary challenges to the utilization and implementation of CIM? Click here to enter text.
23. If there was a guide for implementation, what do you think should be included? Click here to enter text.

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, "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 Programming
   - ☐ 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 contract 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. In 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 Program-ming	Survey and Mapping	Environ-mental Assessments	Design	Bidding & Procure-ment	Construc-tion	Manage-ment of Traffic/ Traffic Safety	Maintenance & Operations
2D	☐	☐	☐	☐	☐	☐	☐	☐
3D/nD	☐	☐	☐	☐	☐	☐	☐	☐
Sensing	☐	☐	☐	☐	☐	☐	☐	☐
Data Manage-ment	☐	☐	☐	☐	☐	☐	☐	☐

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 of 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

Interview Guide for Case Studies

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 is not limited to) techniques such as Intelligent Compaction (IC), Stringless Paving for Concrete/asphalt

Mobile devices for onsite applications: Technologies that include (but are 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 life cycle

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 deliverables can be found at the project website.
http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3648

APPENDIX D

Case Study Questions Format_V1

III. Introduction

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 machine guidance for the construction cycle of pavements – clearing and grubbing, excavating, grading operations, paving, compacting and inspection. Specifically for CIM, this includes (but is not limited to) techniques such as Intelligent Compaction (IC), Stringless Paving etc.
Mobile devices for onsite applications: Technologies that include (but are 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)
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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

IV. Questions

Topic 1: Organization, Contracts and Governance

(Agency-level influences measurement)

1. Can you describe the implementation measures for CIM at organizational level?
   - ⇒ Vision and mission statements, goals, task teams
   - ⇒ Workforce training and motivation of the project functional groups (ask for specific PWFs also)
   - ⇒ Are there any initiatives for integrating ERP system with Project Controls and CIM tools? How?
   - ⇒ Significant Investment costs and benefits (ask for specific PWFs also)
2. What CIM technologies would you use on a "typical" project – New construction/renovation, roadways/bridges? (Explain typical)
   - ⇒ What not? Why? What do you plan to use in future and why?
3. Could you describe the standards/guidelines for CIM specific to your agency and projects?
   - ⇒ CIM tools covered and CIM tools not covered, any areas require improvement?
   - ⇒ Ability for customized application to projects
4. How have application of CIM technologies impacted your contractual/legal provisions?
   - ⇒ Defining software usage to avoid interoperability issues and information loss
   - ⇒ Ascertaining pertinent Federal/State agency laws impacting usage of digital intellectual property on the project
   - ⇒ Apportion of responsibilities for maintaining and updating models
   - ⇒ Ownership and copyright issues of 3D models
   - ⇒ Protection of collaborators on models. "Read-only" files. Access control. Disclaimer clauses
   - ⇒ Conflicts and dispute resolution mechanisms. (Ex: If discrepancies between 3D model and plan sets, priority?)
   - ⇒ Public information and disclosure issues
   - ⇒ Digital signatures and their utility on projects
5. Which project delivery method do you think is best suited for CIM?
   - ⇒ D-B, D-B-B, CM/GC. Why? Are you allowed to use collaborative methods like DB?
6. What are your performance objectives/goals specific to CIM at organizational level?
   - ⇒ Have you achieved them or in transition?
7. Are there any additional contractual/legal concerns about implementing CIM technologies that need to be addressed?

Topic 2: CIM integration with the Project Work Functions (PWF)

(Project-level influences measurement)

PWF 0: General project characteristics

8. **Can you describe the project's characteristics?**
   - ⇒ **Project delivery method, Contract payment type, and primary driver for CIM implementation?**
   - ⇒ **Pilot project implementing CIM? Cost-driven or schedule-driven? (Any other unique features, if any)**

PWF 1: Planning and Surveying

9. (How) did you incorporate CIM tools in your planning and surveying process?
   - ⇒ Usage of LiDAR (type, processing of data, intended support for the project)
   - ⇒ Usage of GIS tools (Ex: UPlan) for ascertaining project impacts and making decisions
   - ⇒ Aerial imagery (Purpose, source of information)
   - ⇒ GPS Technology (for Roadway Surface mapping? How did you manage vertical elevation issues?)
10. (How) did you incorporate CIM tools for identifying project scope and objectives?
   - ⇒ Risk assessment, preliminary estimate and schedule, technology and vendor selection/review, ROW acquisition planning

PWF 2: Bidding and Contracting

11. (How) was CIM used during bidding and contracting process?
    - ⇒ What Reference Information Documents (RID) survey information provided to contractor (pre-bid and post-bid)?
    - ⇒ Were online tools used (Ex: ProjectWise) for sharing this information? 3-D model provided?

PWF 3: Design

12. (How) was 3D technology used during design process? 3D "Design" or "3D" modeling?
    - ⇒ Input data for the 3D model - Project Development Surveys, Existing as-built database (2D/3D)
    - ⇒ Process: Software and hardware used? Exchange format and Deliverables?
    - ⇒ How is the level of detail (LOD) defined and followed? - Accuracy level? Modeling detail (2D/3D)?
    - ⇒ Any other CIM tools used during design phase (Ex: GIS)?
13. (How) was CIM applied in bridge design?
    - ⇒ Type of bridge – Steel/Concrete? Fabrication process involved?
    - ⇒ Were bridges designed/modeled in 3D? Software used? LOD?
    - ⇒ How was integration done with roadway model? In a common software platform?
    - ⇒ (How) was the construction model generated and used for 4D/5D?
14. (How) did CIM assist in review and approval processes?
    - ⇒ Design reviews: Who participates (engineering, construction, safety, quality…)? Which communication tools do you use? Are they 3D- or 2D-based? Is it done in conjunction with constructability analysis?
    - ⇒ How was the approval and review done for shop drawings? Did you use online tools/electronic signatures?

PWF 4: Utility Coordination and management

15. (How) did CIM assist in collecting, organizing and managing utility data?
    - ⇒ Data collection process: Use of RFID, GIS, GPR, EMI, etc. to collect utility data? (How) did you share information with utility companies?
    - ⇒ Data organization and integration process with project information: Locational accuracy, current way of storage (Ex: UCM, SQL database, GIS based database etc.)
    - ⇒ Were they modeled in 3-D for the project? Was it used for clash detection?

PWF 5: Construction

16. (How) was nD modeling used to plan for construction and traffic management?
    - ⇒ 4D modeling: How was the process of attaching schedule activities to model elements (automated, semi-automated or manual)? Issues of LOD between model and schedule? Software tools used? Deliverables?
    - ⇒ 5D modeling: What is the need? Software tools used? Deliverables?
    - ⇒ (How) was traffic analysis done? Was microsimulation performed – how was traffic data collected?
    - ⇒ Intelligent Transportation Systems (ITS) for traffic management? What tools and why?
    - ⇒ How did you communicate Traffic Control measures to public? Used social media, 3D models?
17. (How) did CIM impact materials and equipment procurement for construction?
    - ⇒ Tracking, QA/QC records, supply to the site? Did you use advanced software tools/equipment for this?
18. (How) was CIM used during construction of roadways?
    - ⇒ Automated Machine Guidance (AMG): How Construction Quality Control was performed – rovers-based, Virtual Reference Station System, actual vs design model, design tolerance? Operators training?
    - ⇒ (How) were Intelligent Compaction and/or Stringless Concrete Paving used?
    - ⇒ Mobile devices and applications: Which communication tools do you use for field work, QA/QC checks, daily work report? What were formats of file used in the field (Ex: 2D plans, 3D pdfs, 3D models)?
19. (How) was CIM used during construction of bridges and major other structures?
    - ⇒ Understanding construction sequences? Any field automation activities?

PWF 6: Project Controls and Project Management

20. (How) did CIM impact functions of project controls?
    - ⇒ Estimating and budgeting, scheduling

⇒ How do you determine quantities for contractor payments? Did you use advanced tools for this (SiteManager)?
⇒ Forecasting and change management: RFIs, Change order generation and approval process. Advanced tools used for the purpose? (Ex: ProjectWise)
⇒ (How) Did you use advanced work packaging tools (Ex: Bentley ConstructSim) for scheduling your work?

PWF 7: Operations and Maintenance

21. (How) do you manage asset information?
    ⇒ Technologies and tools used (Ex: LiDAR)
    ⇒ How do you archive and update the as-built data? Is the process digital/electronic/paper-based?
    ⇒ What can you say regarding the utility of as-built information for new project development?
    ⇒ Is your asset management database integrated with GIS or cloud-based systems (Ex: UPlan)? If yes, are you frequently updating it?

Topic – 3: Other Factors

(External influences measurement)

22. (How) do you think there are any other external factors influencing CIM apart from agency and project-level issues discussed
    ⇒ Vendor-side inadequacies for software and hardware?
    ⇒ Other Management and policy issues?

Topic- 4: CIM Lessons learned and best practices

(**Qualitative indicators of performance)**

23. What are lessons learned through CIM usage on projects?
    ⇒ Deployment of specific technologies, contractual requirements, workforce training etc.
    ⇒ (How) do you manage the lessons learned database and share the knowledge for CIM?
24. In your opinion. Designate the CIM technologies to “Conventional”, “advanced” and “Innovative” practice level (Please refer to Page 1 for list of CIM technologies). (Why?)
    (Note:
    - Conventional – Well-established techniques that are used in industries quite common. Guidelines/specs for implementation are thoroughly documented
    - Advanced - Sophisticated technologies used in most of the contemporary hig hway projects. Guidelines/specs are available.
    - Innovative – Emerging technologies. Guidelines/specs. are not available in public)
25. Are there any other specific benefits or challenges to application of CIM on projects?

Topic – 5: CIM Performance goals and measurements

(**Quantitative indicators of performance)**

26. (How) do you assess performance measures specific to CIM for projects?
    ⇒ Cost, schedule, productivity, safety, quality, construction inspection, change management, reduced claims, worker satisfaction, any other measures?
    ⇒ For this project, how did you compare overall benefits to investment for CIM? Results can be based on qualitative/quantitative ideas

APPENDIX E

Validation Survey Questionnaire

As part of NCHRP Project 10-96, the Center of Transportation Research (CTR) of the University of Texas at Austin and the Construction Engineering and Management Program at the University of Colorado at Boulder are conducting research to develop a guide for Civil Integrated Management (CIM) implementation at DOTs. This guide will help the agencies assess their use of digital project delivery and asset management, identify practical benefits and costs, and determine methodologies and areas for increasing their adoption of CIM. The research team has developed a draft of the Guidebook for review and comments.

The purpose of this questionnaire is to validate the structure and content of the Guidebook draft by gathering feedback and/or suggestions from subject matter experts and stakeholders whom NCHRP has approved for review. The questionnaire consists of seven questions designed to capture the effectiveness of the Guidebook.

With the approval of NCHRP, the research team would like to invite you to participate in this early review process and provide comments to help us enhance the overall quality and usability of the Guidebook. If there are (any) important issues not adequately addressed by the seven questions, please do not hesitate to include them. Your input is valuable to the research. Thank you for participating.

General questions (Format)

1. Do you have any high-level comments on the overall appearance/readability of the Guidebook? Are there any text or figures which are not clear and easy to read? Do you have any suggestions on improving the visual appearance and readability of the Guidebook?
2. Are there any portions of the structure and/or organization of the Guidebook that are difficult to follow? Did you have difficulty locating specific sections in the document?

Subject area (Content)

1. CIM encapsulates numerous tools and practices that enable the transition to digital project delivery. Chapter 2 provides the definitions of CIM tools and functions that warrant attention for understanding their benefits and help develop systematic guidelines. Does Chapter 2 adequately cover the key topics related to CIM? Are there any descriptions that need clarification? Do you have any other suggestions to improve Chapter 2?

2. Chapter 3 demonstrates how different CIM functions rely on the information generated through a general workflow model. Are any of the explanations lacking clarity and consistency with the project delivery processes in your agency or in your general experience? Are we missing any critical CIM-related functions or project phases? Do you have any other suggestions to improve Chapter 3?
3. Chapter 4 proposes a three-step implementation framework to help agencies enhance their reliance on digital project delivery and asset management. Please answer the questions in the following five sub-categories:

    a. Assessment (Stage I): Does the three-level maturity model address the key CIM practices in a highway facility's life cycle (from scoping to asset management)? Are the CIM capabilities of each phase adequately described? Can you comment on the potential utility of this model in developing detailed guidelines for your agency?
    b. Investment analysis (Stage II): Are the investment requirements and benefits presented in a clear and understandable manner? Do you agree with the parameters chosen for prioritizing CIM investments?
    c. Implementation considerations (Stage III): Are the lessons learned and recommendations properly organized? Are all the major issues covered in this section?
    d. Illustration examples are provided to demonstrate the utility of the framework. Are they easy to read? Do they assist in practical understanding of the implementation process?
    e. Case examples provide empirical data on benefit-cost analysis and implementation issues. Is each of them adequately described? Are they helpful in terms of contextualizing analyses described in the Guidebook?

4. Chapter 5 provides a synthesis of supplemental information from the literature review, case studies, and surveys. Can you suggest any improvement to the content organization and/or presentation? Do you think we should include/delete/modify any topics in this chapter?
5. Appendix section provides a catalog of CIM resources. Do you think there are any other important references/resources that have to be presented here? Do you think the team should share any other information?

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

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