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MODEL DEVELOPMENT STANDARDS IN THE CONSTRUCTION INDUSTRY AND BEYOND

Prepared For:

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Research & Innovation Division

Final Report

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16. Abstract

UDOT has made investments in formalizing its approach to digital delivery during the design phase. UDOT has published and updated a guideline for model development and defined standards for model development. The guidelines and standard apply to the design phase and prepare digital data for use in construction and handing over asset information post-construction. The objective of this research is to determine how UDOT's approach to formalizing digital delivery aligns with the trajectory of national and international developments and to capture insights from how other industries manage and exchange digital information.

Internationally, there is a consistent approach to construction information management using Building Information Modeling and Industry Foundation Classes (IFC); the approach is published as International Organization for Standardization consensus standards. The consensus standards address management, technical, and commercial elements of Organizational Information Requirements (OIR). Interoperability challenges are not unique to the highway construction industry. While interoperability is a key requirement for durable and accessible information, the IFC extensions intended to support bridges and roads are still being developed.

UDOT's model development standards and digital delivery guidelines, as well as other pre-construction manuals, address most—but not all—of the elements in the OIR. Some of the detailed OIR elements—such as object-based information requirements—are immature for highways and lack consensus standards. Through piloting the new standard and updated guidelines, as well as collaborating with the American Association of State Highway Transportation Officials (AASHTO) committees, UDOT can refine the detailed requirements and remain aligned to evolving and emerging consensus standards.

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TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

LIST OF TABLES

LIST OF FIGURES

		TEMPERATURE (exact degree	
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Ce
		ILLUMINATION	
fc	foot-candles	10.76	lu
fl	foot-Lamberts	3.426	ca
		FORCE and PRESSURE or STRE	
lbf	poundforce	4.45	ne
lbf/in^2	poundforce per square inch	6.89	kil

APPROXIMATE CONVERSIONS FRO

Symbol	When You Know	Multiply By	T
		LENGTH	
mm	millimeters	0.039	in
m	meters	3.28	fe
m	meters	1.09	ya
km	kilometers	0.621	m
		AREA	
mm^2	square millimeters	0.0016	sq
m^2	square meters	10.764	sq
m^2	square meters	1.195	sq
ha	hectares	2.47	ac
km^2	square kilometers	0.386	sq
		VOLUME	
mL	milliliters	0.034	flu
L	liters	0.264	ga
m^3	cubic meters	35.314	cu
m^3	cubic meters	1.307	cu
		MASS	
g	grams	0.035	ou
kg	kilograms	2.202	po
Mg (or "t")	megagrams (or "metric ton")	1.103	sh
		TEMPERATURE (exact degree	
°C	Celsius	1.8C+32	Fa
		ILLUMINATION	
lx	lux	0.0929	fo
cd/m^2	candela/m^2	0.2919	fo
		FORCE and PRESSURE or STRE	
N	newtons	0.225	po
kPa	kilopascals	0.145	po

*SI is the symbol for the International System of Units. (Adapted from FHWA report template, Re

LIST OF ACRONYMS

AASHTO	American Association of State Highway Transportation Officials
AEC	Architecture Engineering and Construction
AIR	Asset Information Requirements
BIM	Building Information Modeling
bSI	buildingSMART International
CAD	Computer-Aided Design
CADD	Computer-Aided Design and Drafting
CAM	Computer-Aided Manufacturing
CATIA	Computer-Graphics Aided Three-Dimensional Interactive Application
COINS	Constructive Objects Integration of Processes and Systems
CNC	Computer Numeric Controller
DOT	Department of Transportation
DPD	Digital Product Definition
FHWA	Federal Highway Administration
GIS	Geographic Information System
IFC	Industry Foundation Classes
LOD	Level of Development
LOI	Level of Information
MBD	Model-Based Definition
MDSM	Model Development Standards Manual
OIR	Organizational Information Requirements
PAS	Publicly Available Specifications
PDF	Portable Document Format
PIR	Project Information Requirements
PLM	Product Lifecycle Management
STEP	Standard for the Exchange of Product
TPF	Transportation Pooled Fund
UDOT	Utah Department of Transportation
UML	Unified Modeling Language

EXECUTIVE SUMMARY

UDOT has conducted several digital delivery pilots, in particular with 3D model-based information forming the primary medium for the construction contract documents. Subsequently, UDOT has made investments in formalizing its approach to digital delivery: publishing and updating a guideline for executing digital delivery on projects and a Model Development Standards Manual (MDSM). The objectives of this research were to determine how UDOT's approach to digital delivery aligns with the trajectory of national and international standards and to capture insights from other industries related to managing and exchanging digital information.

The research focused on standardization and interoperability for digital delivery in the highways industry, the broader construction industry, and other related industries. The literature review identified that there is international consensus for the approach to construction information management using Building Information Modeling (BIM) and Industry Foundation Classes (IFC). There are consensus standards for both that are published as International Organization for Standardization (ISO) standards. The consensus standards address management, technical, and commercial elements of Organizational Information Requirements (OIR). While interoperability is a key requirement for durable and accessible information, the IFC extensions to support bridges and roads are still being developed. Other industries experience the same issues of data exchange, which they manage by documenting processes in detail.

UDOT's MDSM and digital delivery guidelines, as well as other manuals, address nearly all the elements of OIR. Some of the detailed OIR elements, such as object-based information requirements that qualitatively describe the geometry and information for highway assets lack consensus standards. UDOT can refine the detailed requirements through piloting the MDSM and guidelines. UDOT can monitor emerging consensus standards by continuing to participate in American Association of State Highway Transportation Officials (AASHTO) committees and the Transportation Pooled Fund (TPF) study for BIM for bridges. It may take several years for the IFC extensions to be viable for project delivery due to the lag of software development to support IFC and industry adoption of the new releases. The technical limitations of digital delivery are manageable, but the human factors will affect the behavioral economics of user acceptance and the ability for industry to embrace and scale digital delivery.

1.0 INTRODUCTION

1.1 Problem Statement

Digital delivery for project development means delivering the design intent for construction and receiving an as-built record of the facility in a 3D, digital format. UDOT's definition of digital delivery is broader; for UDOT, digital delivery encompasses the availability of digital project and asset information to all UDOT departments. Since 2014, UDOT has pursued digital delivery for the design and construction of roads and bridges. UDOT's goals for digital delivery include removing the inherent inefficiency of 2D plan-based workflows and to create a repeatable, digital process to communicate data through the construction lifecycle from design to asset management. (Utah Department of Transportation, 2019)

UDOT has had many notable successes with digital delivery and is one of the states leading process development for the nation. UDOT now wishes to formalize the digital delivery processes in order to scale the practice to statewide standard practice. Given UDOT's national leadership, it is important that UDOT standardize processes that align to the less mature, emerging consensus standards. This research will document new developments of Industry Foundation Classes (IFC) for roads and bridges, examine other emerging and ongoing research and development by peer agencies, as well as look at other building industries to provide insights that relate to UDOT's creation of a Model Development Standards Manual (MDSM).

1.2 Objectives

The objectives of this research are to:

- Determine whether UDOT's approach to digital delivery aligns with the trajectory of national and international developments.
- Provide insights from the approaches other industries take to managing and exchanging digital information.

1.3 Scope

This research involved a desktop search and literature review, followed by analysis to align the findings to UDOT's goals and objectives.

1.4 Outline of Report

The report includes the following chapters:

- Introduction, which provides an orientation to the report,
- Research Methods, which describes the approach to conducting the research in each of the content areas,
- Literature Review, which summarizes the collected information,
- Discussion, which relates the collected information to UDOT's MDSM,
- Conclusions, which summarize the lessons learned from the literature search as related to UDOT's MDSM, and
- Recommendations, which describes potential next steps for UDOT to:
    - Refine the MDSM and guidelines,
    - Monitor the alignment to national and international consensus standards,
    - Support the development of missing detailed consensus standards for highways, and
    - Support workforce development to scale the capability and capacity for digital delivery in Utah.

2.0 RESEARCH METHODS

2.1 Overview

The data that drives highway construction automation, like Automated Machine Guidance (AMG) is surprisingly simple. Concrete paving automation like continuous slipform paving has been in use since the early 2000s. The data used to drive these systems—simple three-dimensional (3D) line strings—has not changed in two decades. In that time, Computer-Aided Design and Drafting (CADD) software has become more sophisticated, making it easier to generate 3D roadway designs and produce the data required for construction automation systems. Why is it, then, that digital delivery is still nascent in the highway construction industry?

This research examines current approaches to digital delivery in highway and bridge construction to identify challenges and successful methods to resolve them. It explores whether or not the current issues are unique to highway and bridge construction and seeks potential solutions from within the highway and bridge construction realm and from related industries.

The research will:

- Explore emerging digital delivery practices in the highway and bridge construction industry to identify the framework and thrust for digital delivery. It will answer questions like: *Why are we going this way, what are our touchstones, which paths are we currently exploring?*
- Identify where the paths align with more mature practices in the general Architecture-Engineering-Construction (AEC) industry (e.g., buildings). It will answer questions like: *What are the strategies and approaches and are they valid for UDOT?*
- Examine other related industries to identify potential solutions to common issues. It will answer questions like: *Do other industries experience these problems and how do they resolve them?*

2.2 Digital Delivery Framework

The AASHTO executive board signed an Administrative Resolution (AR-1-19) in 2019, which noted that transportation agencies are progressing toward Building Information Models (BIM) as the successor to the standard plan set for highway infrastructure projects. The resolution also noted that transportation agencies need the ability to exchange data seamlessly to implement asset management more efficiently throughout the lifecycle of the asset. (American Association of State Highway Transportation Officials, 2019) The migration to BIM as a replacement for a centuries-long practice of communicating design intent through sets of plans, as well as the need to exchange digital asset information across phases of the asset lifecycle, both represent a significant disruption to how transportation agencies conduct the business of project development. “Digital delivery” is the term used to describe the end state of this disruption.

While the efficiencies of exchanging digital information are compelling, it is important not to take for granted the simplicity and accessibility of two-dimensional (2D) paper plans. Leonardo da Vinci conceived of machines that were impossible to fabricate 500 years ago, but his drawings are now available to download as 3D printing files (STLFinder, 2020) because the conventions of creating 2D plans have endured, making his designs readily interpretable. The transition to digital delivery—using BIM—will create opportunities for efficiency, but it must also preserve the accessibility and durability of plan-based delivery while addressing the challenges that digital media introduce.

The framework for digital delivery begins with establishing the requirements for delivering plan information digitally. Construction plans serve a variety of audiences, including less technically proficient and less resourced stakeholders, such as the general public, small utility owners, and, occasionally, legal personnel. Once the regulatory and policy requirements are defined, the information delivery requirements can be established. This provides a means by which potential digital solutions may be evaluated to identify and close gaps.

Figure 2.1 describes desirable attributes of the digital delivery framework as a Venn diagram. The diagram uses four foundational attribute sets: interoperable, secure, standardized, and open. In the diagram, “open” means that the information is publicly available. The various intersections of sets are labeled with other attributes. For example, the intersection of the “standardized,” “open,” and “secure” sets is “predictable.” The intersection of the “secure” and “interoperable” sets is “durable.”

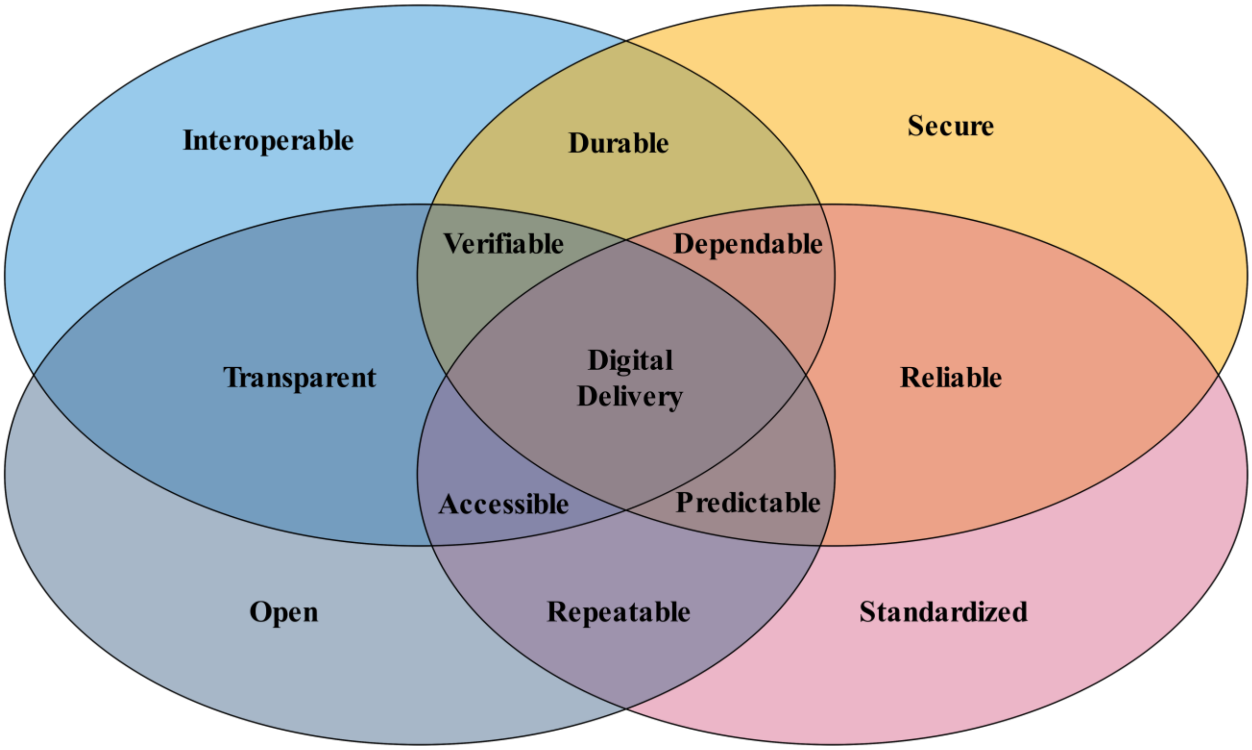

Figure 2.1 Digital Delivery Requirements Described as a Venn Diagram

The policy and procedures for publishing information and securing electronic information are relatively mature. For example, UDOT has had an active online open-data portal for many years that discloses project and geospatial information to the public. Most state transportation agencies, including UDOT, use a digital plan room which, in UDOT's case (Project Explorer) requires a login issued by UDOT. This research will focus on the two more dynamic areas of policy and procedure development: standardization and interoperability.

2.2.1 Standardization

The National Institute of Building Sciences (NIBS) maintains the National BIM Standard-United States® (NBIMS-US™), which is developed by committee. Now in its third version with the fourth in development, the NBIMS-US™ is a compendium of consensus-based standards created by referencing existing standards, in particular to document information exchanges for the entire built environment. (National Institute of Building Sciences, 2015) Another key focus area of the NBIMS-US™ is a compendium of practice documents that cover practices such as for establishing minimum BIM requirements, for managing the execution of BIM on projects, and for developing practical BIM contract requirements. (National Institute of

Building Sciences, 2019) Many of the referenced standards have undergone further development since the NBIMS-US™ V3 was published, including:

- The BIM Project Execution Planning Guide – Version 2.1 of 2011 was updated and Version 2.2 was published in 2019. (Messner, et al., 2019)
- The BIMForum Level of Development Specification of 2013 enjoyed annual updates until 2019. (BIMForum, 2019)
- The United States Army Corps of Engineers (USACE) continues to develop their approach to defining BIM model element grades and deliverable requirements. (CAD/BIM Technology Center for Facilities, Infrastructure, and Environment, 2019)

This research conducted a desktop study to identify approaches to standardize the following:

- Information specifications, in particular, for design and construction submittals,
- Information management in design and construction, and
- Collaboration using shared data.

Sources included published standards and requirements documented in policies, guidance documents, standard contract templates, and other relevant official documents. The search began within the highway and bridge market and expanded to the broader AEC industry, and then to other related disciplines such as aerospace, manufacturing, industrial engineering, chemical processing, and electrical distribution.

2.2.2 Interoperability

The AASHTO AR-1-19 resolved to adopt the IFC Schema as the national standard for AASHTO states to exchange information. (American Association of State Highway Transportation Officials, 2019) This resolution followed years of work to develop data standards within the state highway domain and especially focused on bridges. Early data standardization efforts with LandXML and TransXML foundered due in part to a lack of stewardship. By the time a workshop was convened to discuss the future of TransXML, buildingSMART International (bSI) had already initiated a conversation on expanding IFC to cover roads, bridges, and other horizontal infrastructure. (Turnbull, 2014) Mlynarski & Hu (2016) evaluated a range of standard data formats for bridges, performed a gap analysis, and recommended IFC. AASHTO members subsequently formed a TPF study to provide a funding mechanism for AASHTO to govern and steward standardization of BIM for bridges and structures in the United States. (National Cooperative Highway Research Program, 2017)

At the time of writing, the IFC schema is still being developed to provide foundational support for highways and bridges. (Moon, et al., 2018) (Borrmann, et al., 2019) This research explored interoperability with an emphasis on:

- Describing the status of IFC standards for roadway and bridge elements,
- Describing the future development of IFC, and
- Establishing realistic expectations for the practical application of IFC on roadway and bridge projects.

Primary sources were:

- Documents developed as part of the projects to extend the IFC schema to accommodate roads, bridges, and other linear infrastructure,
- Other documents developed by the bSI InfraRoom,
- Published papers and other documents describing IFC infrastructure projects, and
- Documents describing dependent standards.

2.3 Summary

The primary areas of development to implement digital delivery for highway and bridge construction are interoperability and standardization. These will be explored looking within state transportation policy and guidance documents, ongoing industry developments nationally and internationally, and in external, related industries such as manufacturing and aerospace.

The pertinent research question is: *Does UDOT's current approach to digital delivery align with the nascent approach of the US transportation industry?* To fully answer, it is necessary to capture insights on how other industries experience and resolve similar problems of interoperability and standardization for the exchange of digital data.

3.0 LITERATURE REVIEW

3.1 Overview

Data is an enterprise asset, but using that data to disrupt an organization is an artifact of performing analytics with the data. Henke, et al. (2016) examined how data and analytics cause disruption. The biggest barrier they identified to realizing value from data is people: Are they open to incorporating data-driven insights and does the organization have the right talent to generate those insights? Consequently, they concluded, most companies are still underachieving in terms of realizing value from their data assets.

Data marketplaces connect data users to the providers of that data. (Henke, et al., 2016) Streetlight Data is an example of a data aggregation and analytics provider in the transportation operations domain. Streetlight Data collects, indexes, and processes smartphone location information and analyzes it in the context of publicly-available spatial datasets like roadway, sidewalk, and bike-lane inventories. Streetlight Data then performs analytics as a service for public and private clients. (StreetLight Data, Inc., 2020) This is an example of what Henke et al. (2016) describe as an "orthogonal dataset," which provides value by aggregating data across siloes to disrupt, in this case, the transportation planning industry. Digital delivery for construction will bring new datasets to UDOT and with standards and interoperability, UDOT may use those datasets across the agency in ways that create new value.

In Europe, public sector organizations from twenty-one countries came together to form the EU BIM Task Group to produce a European-wide cohesive, strategic approach for BIM. The resulting EU BIM handbook establishes a common performance definition of BIM that is consistent with existing and developing standards. (EU BIM Task Group, 2017) The handbook makes a number of action recommendations—both strategic and specific to implementing four performance-level capabilities, namely: Policy, Technical, Process, and People and Skills.

Table 3.1 Recommended Strategic Actions to Implement BIM in the EU.

Action	**Motivation**
Define compelling drivers, a vision and goals	Builds support and alignment among stakeholders with a focus on the expected outcomes from action.
Document the value proposition and strategy	Justifies the resources necessary for investment and builds buy-in from stakeholders.
Identify sponsor, funding, and stewardship team	Enables provision of funds and action to be taken.
Engage early with industry	Builds buy-in, alerts industry to prepare for change, identifies champions who can help lead the change.
Create networks	Disseminates information. Enables communities of practice to interpret the program for their specific context.
Use mass communication, events, media, web, and social media	Uses a variety of channels to reach dispersed stakeholders with a clear message.
Develop the legal and regulatory framework	Clarifies the process and requirements to overcome barriers to the digital information exchange.
Reference or develop technical and process standards	Provides a consistent language and common understanding of the required BIM outputs.
Build skills, tools, and guidance	Creates capacity in the effective and consistent use of BIM to meet the requirements.
Promote industry pilot projects	Builds confidence among stakeholders, provides feedback for improvement, and examples of effective practices.
Increasing use of a strategic lever to grow capacity	Provides industry certainty and confidence to begin investing in the transition and workforce development.
Measure and monitor progress and embed change	Inspires and continues to build support from industry for the transition.

Figure 3.1 further describes the four defined areas of the EU performance level for BIM implementation. Table 3.2 lists the implementation action recommendations. Figure 3.1 and Table 3.2 are reproduced according to the usage requirements from the *Handbook for the Introduction of Building Information Modelling by the European Public Sector* (EU BIM Task Group, 2017).

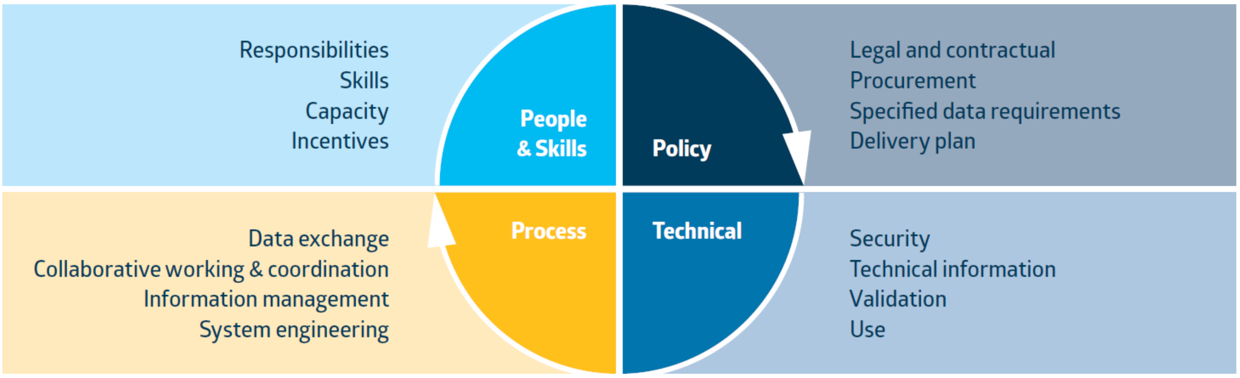

Figure 3.1 Common EU Performance Level for the Implementation of BIM

Table 3.2 Recommended Actions to Implement BIM in the EU.

Category	Action	Motivation
Policy	Contractual requirements	Supports effective collaboration, improves compliance with standards for producing and delivering models and data, and establishes rights for digital data use.
	Establish information requirements	Establishes clear technical, process, and deliverable requirements for digital data so that submittals meet the owner's needs and expectations.
	BIM capability criteria	Clarify the BIM capability and capacity needed to meet the requirements and optionally include in best-value awards.
	BIM execution plan requirement	Plan the information delivery to ensure all parties understand their responsibilities and are prepared.
Technical	Vendor-neutral data exchange	Increases interoperability, supports diversity in the supply chain, and supports retrieval of archived data.
	Object-oriented organization of information	Provides the capability to define the context within which the object is used. It enables classification systems a common referencing framework.
Process	Container-based collaborative working per ISO 19650.[1]	Container-based collaboration (one editor at a time) is a step towards collaborative centralized databases with multiple concurrent editors.
	Common data environment	Provides the ability to communicate, re-use, and share data efficiently without loss, contradiction, or misinterpretation.
People & Skills	Assign responsibility for data and information management	Projects generate a vast amount of data that needs stewardship and governance.

[1] A container is typically called a "file," and may contain a 3D model, a drawing, a document, table, or schedule. Containers are categorized as document containers, graphical information containers, or non-graphical information containers. (EU BIM Task Group, 2017)

3.2 Standards

The NBIMS-US™ provides a framework for collaborating and exchanging digital data about built assets. Initial work on the NBIMS-US™ began in 2005 and a committee is currently working on an updated, fourth version. As noted in the previous chapter, NBIMS-US™ V3 references existing standards and practice documents, some of which have been revised since NIBS published NBIMS-US™ V3. This review used the most recent version of the referenced standards. The NBIMS-US™ has a broad scope; it encompasses the whole lifecycle of building assets, including the design of heating, cooling, ventilation, water, fire prevention and electrical systems, and energy performance analysis. (National Institute of Building Sciences, 2015) The referenced practice documents are based on the use of BIM on projects. The practice documents cover the processes and templates used to establish favorable uses of BIM, describe the model requirements to support those uses, define how and when the models will be used for collaboration, and define the contract requirements for delivering the model-based information.

The British Standards Institution published BS 1192, which is a code of practice for the collaborative production of AEC information in the United Kingdom (UK). (The British Standards Institution, 2016) The UK government considers BIM to be essential to achieve the objectives of digitizing the built environment, which includes buildings and civil works. The UK government has mandated the use of BIM on all design and construction projects since April 2016. (Ashworth, et al., 2017) Over the past several years, a number of Publicly Available Specifications (PAS) were developed to build on and extend BS 1192.

The series of five PAS 1192 documents, beginning with PAS 1192-2:2013, provide standards, specifications, codes of practice or guidelines to implement the UK BIM mandate. The framework created by the last version of BS 1192 (i.e. BS 1192:2007 + A2:2016) and the various PAS 1192 documents establish the requirements for BIM Level 2, as mandated since 2016. (McPartland, 2017) The BS/PAS 1192 documents are in the process of being formalized as ISO standards (ISO 19650), beginning with BS 1192:2007 + A2:2016 and PAS 1192-2:2013, which have been replaced by ISO 19650-1:2018 and ISO 19650-2:2018, respectively. ISO 19650-1:2018 establishes the concepts and principles for business processes to support creating and managing BIM-based information at any stage in the asset lifecycle. (International Organization for Standardization, 2018)

ISO 19650-1:2018 establishes a framework that includes:

- Perspectives of project and asset information management,
- Definition of information requirements and the resulting asset and project information models,
- The information delivery cycle and its alignment to the asset lifecycle,
- Project and asset information management functions,
- Delivery team capability and capacity,
- Information container-based collaboration,
- Information delivery planning, including timing, responsibility, and defining a federation strategy and breakdown structure for information containers,
- Managing collaborative information production, including level of information and information quality, and
- The Common Data Environment solution and workflow. (International Standard for Organization, 2018)

ISO 19650-2:2018 specifies information management processes at each step in the project delivery process, i.e. pre-procurement, advertising (“invitation to tender”), letting (“tender response”), award (“appointment”), mobilization, construction (“collaborative production of information”), acceptance (“information model delivery”), and close-out. The contractor provides their BIM execution plan at award. The BIM execution plan documents how the contractor proposes to manage information and describes the contractor’s information management capability and capacity. (International Organization for Standardization, 2018)

One of the core features of PAS 1192-2 was establishing “Employer’s Information Requirements,” where the “employer” is the facility owner. ISO 19650-1:2018 revised the term to Organizational Information Requirements (OIR). Per ISO 19650-1:2018, the owner develops OIR, which are used to generate Asset Information Requirements (AIR) that specify an Asset Information Model (AIM). The AIR informs the Project Information Requirements (PIR) that specify a Project Information Model (PIM) for design and construction. Figure 3.2 illustrates the BS/PAS 1192/ISO 19650 framework as described above. The PAS 1192 framework has additional documents that are not illustrated.

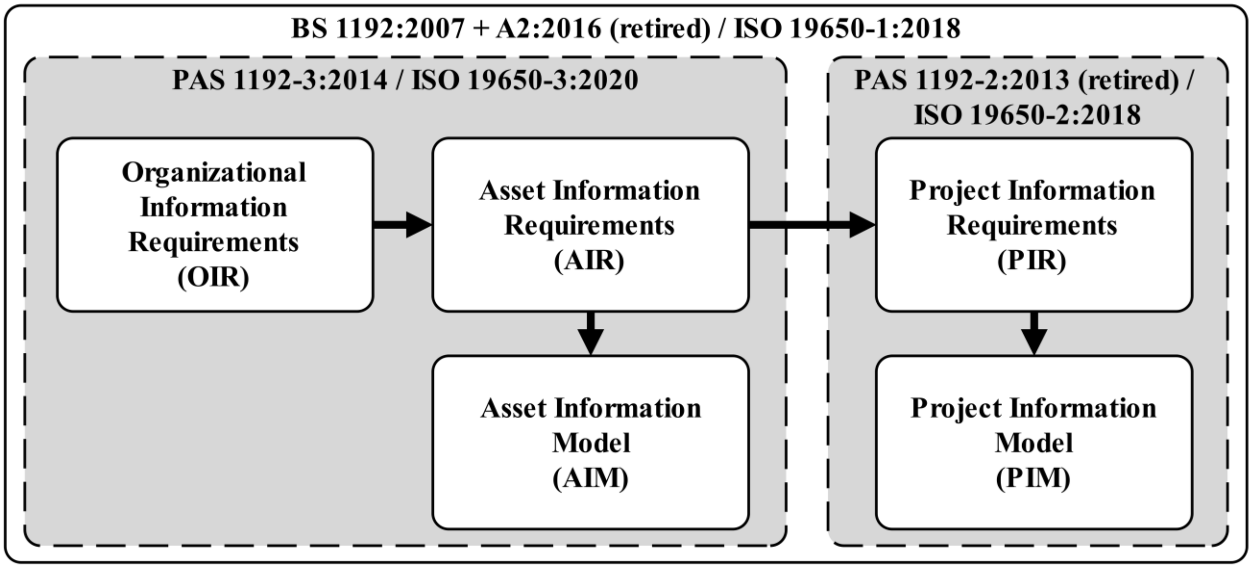

Figure 3.2 A Subset of the BS/PAS 1192/ISO 19650 Framework

Employer's Information Requirements, or OIR (per ISO 19650-2:2018), are a key part of EU BIM Handbook. Ashworth, et al. (2017) conducted a literature search, focus group interviews, case study interviews, and expert peer reviews and interviews to examine the effectiveness of OIR to meet owners' and facility managers' needs. They found three factors that contributed to positive value capture in operations: (Ashworth, et al., 2017)

- Having a good understanding of BIM standards,
- Early and active engagement in the BIM process, and
- Understanding how to use OIR at the start of the BIM process.

As Figure 3.2 shows, the OIR drive the AIR and inform the PIR that the contractor must satisfy through BIM. PAS 1192-2:2013 (now ISO 19650-2:2018) begin with the owner defining the OIR and the Common Data Environment (CDE) requirements, as well as the information management processes (i.e., BIM execution plan). When these are defined clearly up front, it streamlines the development of the PIR and the PIM during design and construction. Ashworth & Tucker (2017) developed a template and guidance for developing the OIR. This guide focuses specifically on the information to be delivered to the owner so that the minimum BIM requirements are established at the start of the project. The template guides owners through documenting basic project and contact information before establishing the information delivery requirements in three categories: management, technical, and commercial. Table 3.3 lists the content of the OIR in each of these three categories.

Table 3.3 Structure and Content of OIR. (Ashworth & Tucker, 2017)

Management Requirements	Technical Requirements	Commercial Requirements
• Standards and guidelines • Contract terms and conditions • Roles and responsibilities for project delivery • Enterprise asset management systems • Model authoring and management protocols	• Software • IT and system performance constraints • Data exchange formats • Common coordinate systems • Levels of definition • Specified data formats • Specified attribute data model	• Information deliverables aligned to project delivery milestones • BIM capability and capacity evaluation criteria for business partners • BIM evaluation criteria for awards

3.2.1 Collaboration

Collaboration standards provide the framework for creating, sharing, using, and delivering digital data on a project. PAS 1192-2: 2013 established the framework, roles and responsibilities for collaborative use of BIM in a Common Data Environment. (McPartland, 2017) ISO 19650-2:2018, which replaces PAS 1192-2:2013, specifies process requirements for information management during project delivery (i.e., design and construction). The details of the OIR for collaboration fall under both management and technical requirements. The management requirements define the processes and obligations for managing collaboration needed to produce and use data, while the technical requirements define the consistent technical infrastructure to facilitate the collaboration, data production, and use. The contractor addresses how they will meet these requirements within their BIM execution plan. (Ashworth & Tucker, 2017)

The project execution planning guide and project execution plan content sections of the NBIMS-US™ V3 reference the superseded versions of the guides. A more recent version of these guides was published in 2019. (Messner, et al., 2019) The project execution planning guide is narrower in scope than ISO 19650-1 in that it focuses only on the project development phase of the asset lifecycle. While ISO19650-1 considers asset information requirements and an asset information model, the project execution planning guide assumes an asset management system and its information requirements are pre-defined. Figure 3.3 shows the four-step process defined by the project execution planning guide. (Messner, et al., 2019)

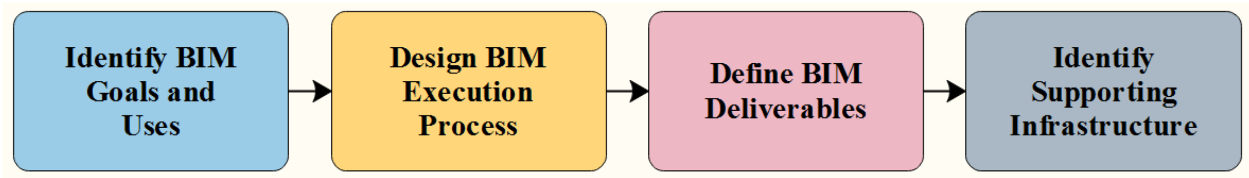

Figure 3.3 A Four-Step Process to Develop a BIM Project Execution Plan

According to Messner et al. (2019), the objective of creating a BIM project execution plan according to their guide is to provide a project document that brings value by:

- Clearly communicating the strategic goals to create consistent understanding across the project delivery team,
- Enabling team members to understand their roles and responsibilities,
- Enabling team members to design a process to execute the project that is consistent with their business practices and workflows,
- Proactively identifying any need for additional resources, training, and competencies,
- Documenting the plan to aid new team members to join effectively,
- Providing a resource to purchasing staff to draft contract requirements, and
- Providing a baseline from which to measure progress.

3.2.1.1 Identify BIM Goals and Uses

The purpose of defining BIM goals and uses is to identify how BIM will add value to the project. The Messner et al. (2019) guide has a catalog of twenty-four discrete BIM uses that are defined in terms of their potential value, necessary resources, required competencies, and references to further information. Some of the BIM uses defined by Messner et al. (2019) apply directly to highway and bridge projects (e.g., design authoring, design review), but many are specific to buildings (e.g., building system analysis, sustainability analysis, energy analysis). Many (e.g., code validation, structural analysis, digital fabrication, cost estimation, lighting analysis) could be applicable but need to be defined for highways and bridges because there are differences in approach to design and construction that alter the value proposition and resource needs. Messner et al. (2019) note that capability development and testing/illustrating information exchanges are also valid project goals for BIM.

3.2.1.2 Design BIM Execution Processes

The purpose of designing BIM execution processes is to identify where team members' work overlaps. For example, to design a waterway crossing, a bridge engineer needs roadway geometrics from the roadway designer, right-of-way limits from the surveyor, and hydraulic information from the drainage designer. High-level process design would identify the sequencing of these information exchanges. Each functional area could then create more detailed process maps to support the defined BIM uses within their control.

3.2.1.3 Define BIM Deliverables

The purpose of defining BIM deliverables is to ensure that the team members creating and receiving information at each exchange clearly understand the information content and how it may be used reliably. The approach uses a five-step process to define the digital deliverables. Figure 3.4 shows the five steps, which are: identify each exchange, select a breakdown structure to inventory the model, identify exchange requirements, assign responsibility for developing the information to be exchanged, and compare the input and output after exchange.

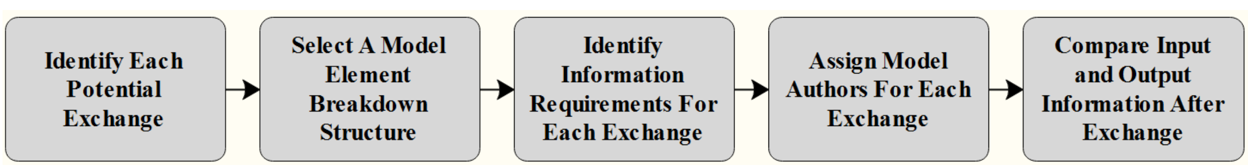

Figure 3.4 A Five-Step Process to Define BIM Deliverables

The third step, identifying information requirements, involves creating a specification for the information with a data quality measure called the Level of Development (LOD). The guide provides a simplistic specification for the data quality with grades A through C, where A represents accurate size and location with other attribute information, B represents accurate size and location and some parameters, and C represents schematic size and location. (Messner, et al., 2019) The next section, Data Quality Specifications, describes rigorous LOD specifications in more detail.

Messner et al. (2019) provide a template spreadsheet that organizes building model content according to the Uniclass™ classification system developed by the Construction Specifications Institute (CSI). For each defined use (e.g., 3D coordination), the spreadsheet documents the general information required, responsible party, and additional notes. The spreadsheet uses three grades of information and defines responsible parties by discipline. Each use is defined by the timing of the exchange (e.g., design development, construction), recipient of the information, recipient file format, and the specific version of the software application. Figure 3.5 shows a snapshot from the template spreadsheet with the columns for the design authoring, existing conditions modeling, and cost estimation uses visible, along with rows for part of the substructure model elements organized according to the Uniclass™ specification and disciplines defined according to OmniClass® Table 33.

INFORMATION EXCHANGE (IE)

	Information
A	Accurate Size & Location, include materials and object parameters
B	General Size & Location, include parameter data
C	Schematic Size & Location

Disciplines (OmniClass Table 33)	
11	Planning
21	Design
25	Project Management
31	Surveying
41	Construction
55	Facility Use Disciplines
81	Support Disciplines
99	Other Disciplines

BIM Use Title	Design Authoring			Existing Conditions Modeling			Cost Estimation		
Project Stage	Design			Design			Design		
Time of Exchange (SD, DD, CD, Construction)									
Responsible Party (Information Receiver)									
Receiver File Format									
Application & Version									
Model Element Breakdown	Info	Resp Party	Notes	Info	Resp Party	Notes	Info	Resp Party	Notes
01 SUBSTRUCTURE									
01 10 Foundations									
01 10 10 Standard Foundations									
01 10 20 Special Foundations									
01 20 Subgrade Enclosures									
01 20 10 Walls for Subgrade Enclosures									

Figure 3.5 A Snapshot of the Information Exchange Spreadsheet

3.2.1.4 Identify Supporting Infrastructure

The purpose of this step is to define and document the details of how to execute the collaboration with digital data for the project. This includes creating contract language, defining communication procedures, specifying the technology infrastructure, and defining the quality control measures. There are document templates, and the guide outlines a sequence of meetings to complete them. The guide recommends embedding the overarching project execution plan (for which there is a template) into contracts. (Messner, et al., 2019)

3.2.2 Data Quality Specifications

Data quality specifications provide context to the information requirements. It is possible to share two instances of an object with the same content, format, coordinate system, and attribute data that are still different in definition and thus provide different outcomes when used for the same purpose. Roadway models use graphical data to communicate the design intent. Alignments may be geometrically defined with complex curvature, but the corridor modeling process used to define the roadway prism and side slopes in three dimensions computes the typical section at defined stations only. The geometry is linearly interpolated in between the defined stations. The corridor geometry exactly matches the design intent at each location that the typical section is computed, but all other locations are approximations. (Maier, et al., 2016) Figure 3.6 illustrates how the density of points along a line string affects the accuracy with which curvature is approximated. The top line has twice as many points as the middle line, and the bottom line has half as many points as the middle line. Circles highlight the points on each line. The light gray background is a line with true curvature.

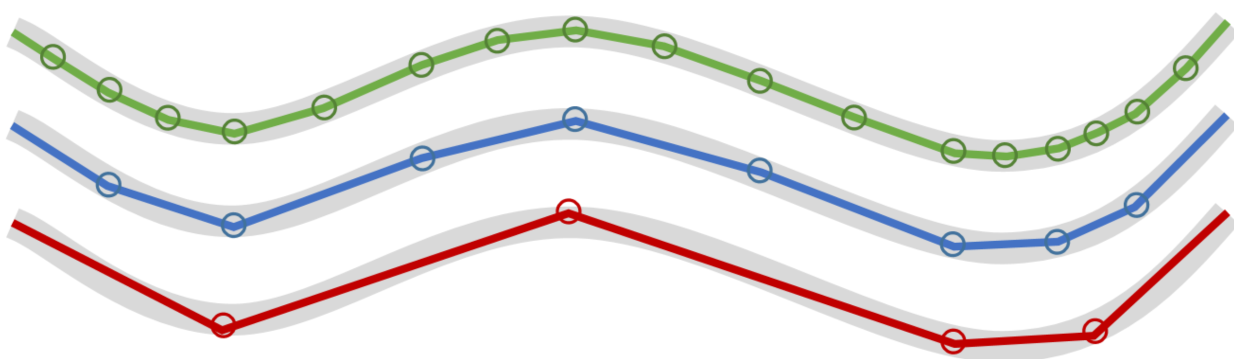

Figure 3.6 Comparison of Curve Approximation Using Different Point Densities

The completeness of a model for highway construction is not necessarily correlated with the sophistication of the software used to produce it. Catchings et al. (2020) analyzed 3D model files from twelve projects located in Kentucky. The projects were initiated between five and twenty-six years prior to the letting. The most complete models were from projects initiated in 1998. Designers expressed in interviews that they were willing to provide any digital data for construction that the owner desired, but they needed clear information on the data needs. (Catchings, et al., 2020)

Consultant designers in Michigan felt comfortable providing digital data as the primary means of communicating design requirements for alignments and profiles, but were reluctant to use digital surface or line-string data to convey the design intent unless the data quality could be described. They also had concerns about the duplicate effort created by the design process focus on plans and not 3D models. (Mitchell, et al., 2019)

Data quality specifications are also needed for bridge construction, where the use of parametric modeling is becoming more common. A designer may begin a design model by inserting model elements from a template with the intention that the geometry and attribute information will be updated later as the design matures. All of the information may be available, but it does not reflect the design intent. Data quality specifications provide a means to communicate the maturity of the information and the specific uses that it supports reliably. Data quality specifications also enable model managers to systematically review the quality and sufficiency of a model. (Brenner, et al., 2020)

3.2.2.1 Level of Development

In 2008, the American Institute of Architects (AIA) published standard contract language for BIM, which introduced the concept of LOD. (American Institute of Architects, 2008) The initial definition of LOD related to the completeness of the model element, but it was later revised to be a descriptor of "the minimum dimensional, spatial, quantitative, qualitative, and other data included in a model element to support the authorized uses associated with such LOD." (American Institute of Architects, 2013) There are five recognized levels for the AIA LOD definitions, numbered 100 through 500. LOD 100 represents the least maturity, where a model element may be represented merely by a symbol. LOD 500 represents the most maturity, where the geometry and location of the model element has been field verified. The accompanying BIM protocol exhibit document explicitly defines minimum model content requirements and associated authorized uses for each LOD level. Uses are analysis, cost-estimating, scheduling, and coordination. (American Institute of Architects, 2013)

Messner *et al.* (2019) provided a simplistic data specification that differentiated between accurate and schematic geometry and positioning, and whether or not additional attributes were present. They reference two other data specifications in their project execution planning guide:

the BIMForum LOD specification and the USACE Minimum Modeling Matrix (M3). The technical requirements component of the OIR template and guidance uses Levels of Definition from the NBS BIM Toolkit. (Ashworth & Tucker, 2017)

The BIMForum LOD specification introduces a sixth level, LOD 350, and does not explicitly associate the foundational LOD-level definitions with authorized uses. Instead, it provides explicit content requirements, at different LOD levels, for dozens of objects that are classified according to the Uniclass™ and Omniclass® specifications. (BIMForum, 2019) While some of the objects included in the BIMForum LOD specification can be applied to bridge projects (e.g., foundations, slabs on grade), the definitions are intended for use with building projects and some definitions (e.g., for roadways) are inadequate for highway construction.

The NBS BIM Toolkit is a web-based tool to build information requirements for projects consistent with ISO 19650. (RIBA Enterprises Limited, 2015) The toolkit has a library of over 5700 objects classified according to Uniclass 2015, a unified classification system for the UK construction industry. Each object has two-dimensional Levels of Definition that describe requirements for Level of Detail and Level of Information (LOI) specific to the object. For each Level of Detail there is an example image, a description of the requirements, and a description of the purpose. The Levels of Detail are 2 through 5, which correspond to the second through fifth stages of the Royal Institute of British Architects (RIBA) Plan of Work, which is a formal process for designing and constructing buildings. Stages 2, 3, and 4 represent conceptual, developed, and technical design, respectively. Stage 5 is construction, and stage 6 is hand-over of the constructed facility. (RIBA, 2020)

3.2.2.2 Level of Information

The second dimension of the model element definitions developed by the NBS BIM Toolkit is LOI. For each object-oriented LOI level, there is a general description of the information requirements and a list of attributes and the information they should contain. (RIBA Enterprises Limited, 2015) The LOIs are 2 through 6, which align to the RIBA Plan of Work stages for conceptual design through hand-over.

The USACE also uses LOI as one of the four dimensions of its object specifications. Unlike the NBS BIM Toolkit, where the LOI levels are defined discretely for each object, the

USACE has a universal definition of LOI levels 0 through 3. Designated Quality Levels I-0 through I-3, they range from no attached information (I-0) through geometric information only (I-1) and geometric information in addition to some data to automate the production of schedules (e.g., reinforcement schedules) for contract documents (I-2), to all data required to identify a real-world object from a manufacturer that is represented by the modeled object (I-3). (CAD/BIM Technology Center for Facilities, Infrastructure, and Environment, 2019)

USACE uses the same 0-3 scale for the other three dimensions of their data quality specification. These three dimensions are: (CAD/BIM Technology Center for Facilities, Infrastructure, and Environment, 2019)

- Geometry–the spatial, geometric and dimensional accuracy,
- Function–parametric behavior and connectivity to other objects to form a system, and
- Extension–attribute information attached to the object (e.g., material properties).

The new, four-dimensional data-quality specification replaces the previous LOD and element-grade definitions found in the M3. In the past, a single element-grade designation conveyed whether the element was 2D or 3D and whether facility data were attached to the model elements. The USACE uses the object-oriented organization of model elements.

3.2.2.3 CI/ASCE 38-02

Existing subsurface utilities create risks on projects that are difficult to manage due to the incomplete, inaccurate, or missing records of their location. CI/ASCE 38-02 is a consensus standard for defining the quality of subsurface utility location and attribute information that is placed on plans. Quality levels A through D are designated by a subsurface utility engineer to communicate a professional opinion of the quality and reliability of the information on the plans. (American Society of Civil Engineers, 2002)

3.2.2.4 Confidence Level and Model Density

Existing consensus standards for data-quality specifications do not cover roadway assets well. For example, the BIMForum LOD specification has only four entries for bridge objects.

There are two factors that affect the reliability of 3D digital-design data for contractors wishing to use that data for highway construction, in particular using AMG. The first is the density of points used to approximate curvature within the model elements, and the second is the amount of uncertainty in the existing ground survey that formed the basis of the design. (Maier, et al., 2017) In Michigan, consultant designers expressed that they felt that the most risk to their firms from providing digital design data occurred where their assumptions regarding the existing ground conditions were flawed. (Mitchell, et al., 2019) In Kentucky, out-of-date or erroneous existing survey information were the cause of problems with the roadway design at tie-in points and on side slopes. (Catchings, et al., 2020)

Maier et al. (2017) proposed a two-dimensional data-quality specification that communicated the uncertainty and risk in the roadway design files delivered to the contractor. The first dimension, Model Density, described how much detail (in terms of point density) was in the model. The second dimension, Confidence Level (CL), was a qualitative statement of the uncertainty associated with the original ground depiction. When model density is high and uncertainty is low, there is a high probability that the digital design data can be used directly in construction—particularly for AMG. However, no amount of model density can compensate for the existing ground model not matching field conditions. If the primary control from which the existing ground survey was completed is insufficient for construction (i.e., CL-C or CL-D), then earthwork quantity changes are likely. However, if the primary control is sufficient for construction and features were collected with necessary accuracy (CL-A or CL-B), then it is likely that change orders and design revisions can be avoided. (Maier, et al., 2017)

Michigan Department of Transportation (DOT) has been working with a digital-delivery working group comprised of DOT staff, consultants, and contractors, to develop a LOD framework for their digital roadway files that are provided to contractors as reference information. Michigan DOT's business partners believe that an LOD framework is a prerequisite to having selected digital design data provide the primary contract document to communicate design intent. Michigan DOT's digital-delivery working group is moving towards adapting a similar two-dimensional data-quality specification to that proposed by Maier et al. (2017) and is working towards piloting it on projects in 2021. (Federal Highway Administration, 2019)

3.2.3 Data Quality Management

Michigan DOT has used a formal process to review the digital data that they provide to contractors as reference information since 2015. Nevertheless, many of their consultant designers were not aware of the process. (Mitchell, et al., 2019) The process uses a spreadsheet that the design manager maintains through the design development phase of the project. The spreadsheet tracks the design manager's quality control checks and the quality assurance reviewer's comments at each milestone. The review process includes: (Michigan Department of Transportation, 2015)

- File naming conventions,
- File format requirements,
- Presence of required files,
- Use of referencing within the files,
- Visual review of the alignment and profile files in native and open formats,
- Tie-in geometry for alignments, profiles, and side slopes,
- Visual review of various discipline design files (e.g., signing, lighting),
- Visual review of 3D model files (both line strings and surfaces),
- Concurrence between digital files and contract PDF plans,
- Visual review of surfaces and drainage files,
- Geospatial metadata (i.e., units, coordinate zones, vertical datum), and
- Additional criteria for construction layout data.

In their review of twelve letting data sets, Catchings, *et al*. (2020) had issues with hardware and software. Some of the files they attempted to review were corrupted. Incompatible software versions were another challenge. When they were able to access all the files, they reviewed:

- Inclusion of all required files,
- Adherence to CAD standards for line styles, colors, and levels,
- Whether the perimeter of the proposed surface is within the right-of-way,
- Whether the boundary of the proposed surface matches the triangle file,
- The quality of the triangulation on slopes, transitions, and tie-ins,
- Consistency and appropriateness of the point density,
- Contiguity in the proposed drainage model, and
- Contiguity in the proposed pavement features model.

The USACE works with its business partners in a BIM consortium to develop their BIM standards and guidance. The consortium developed a submittal review checklist and a guidance document to define the methods and criteria for a technical specialist to review submittals. The process was intended to improve the acceptance rate of submittals and to improve the consistency of the review process. The first submittal is a review and approval of the BIM project execution plan. The BIM execution plan must be approved before any further submittals can be made. The second submittal is a content inventory review. In this submittal, the model content is reviewed for consistency with the BIM execution plan and the contract requirements. Once the submittal is accepted as complete, the third stage of the review is to verify the content by ensuring that the files open in the software version specified in the BIM execution plan. The final stage of the review is content validation. In this review, the contents of the model are validated against the requirements in the BIM execution plan and the contract requirements. (USACE/Industry BIM and CIM Consortia, 2016)

The USACE has also incorporated a section on quality control into its BIM execution-plan template. The plan must describe a strategy for quality control for each model file in the project. The template also has a table where the plan must identify the responsible party for several checks, provides the reference documentation to execute these checks, and the frequency with which the checks must occur. (US Army Corps of Engineers, 2020)

3.3 Interoperability

The Integrated Digital Built Environment is a joint working group of the Open Geospatial Consortium and bSI. The Integrated Digital Built Environment conducted an analysis of three data standards that separately and collectively serve the built environment. These data standards were: IFC, LandInfra, and CityGML. The objective was to identify problems that hold back the integration of these standards and to propose actions to overcome those obstacles. They found disparities that hinder integrating the three standards. For example, there are disparities in the spatial representation (geometric versus geographic) and in the intended general purpose and practical applications of the standards. (Gilbert, et al., 2020)

The Netherlands has invested in open standards for the Dutch construction industry. The BIM Loket is a website that provides a centralized source for all BIM-related standards maintained in the Netherlands. BIM Loket maintains a Dutch open standard for a semantic data model and exchange format called Constructive Objects Integration of Processes and Systems (COINS). COINS facilitates the exchange of BIM, Geographic Information Systems (GIS) and Systems Engineering data, and linked digital documents, enabling different types of information to be recorded in one database. ISO 21597, "Information Container for Data Delivery," is partly based on COINS 2.0. (BIM Loket, n.d.) ISO 21597-1:2020 defines an open and stable container format. ISO 21597-1:2020 supports exchanging files to deliver, store, and archive documents that describe an asset throughout its entire lifecycle. (International Organization for Standardization, 2020)

bSI has a formal process to develop the IFC standard and publish it through the International Organization for Standardization (ISO). While the first version of the standard dates back to the mid-1990s, the first version that became widely used was IFC 2x3 (ISO/PAS 16739:2005). IFC 2x3 primarily supports architecture and building elements. IFC 4 (ISO 16739:2013) has been available since 2013 and it forms the basis of the schema extensions to support linear infrastructure (including roads, bridges, tunnels, railways, and waterways). The first extension was to support common elements for linear infrastructure, including geospatial coordinates and linear referencing and alignments. This work built off the LandXML schema and was performed in cooperation with the Open Geospatial Consortium. (Liebich, 2013)

3.3.1 Roadway

In 2012, the Korean chapter of bSI began working to extend the IFC standard to roads. bSI sanctioned development of IFC Road through the InfraRoom in 2014. IFC 4.1 (ISO 16739-1:2018) includes support for Alignment, but other common definitions (e.g., terrain modeling) were not completed when the IFC Road project began, so the projects were developed concurrently and collaboratively. The IFC extension process has several sequential work points (WPs). These include drafting a project execution plan (WP-0), analyzing requirements (WP-2), extending the schema (WP-3), seeking international consensus (WP-4), software deployment

(WP-5), and project management (WP-6). For IFC Road, WP-1 involved collaborating with the project to develop the common definitions. (buildingSMART InfraRoom, 2017)

The IFC Common Schema project conducted a use case analysis to coordinate the outcomes of the requirements analyses conducted by the Road, Rail, and Bridge schema extension projects. The various use cases were prioritized as “must have,” “should have,” “could have,” and “won’t have.” “Must have” use cases for roads were: (Plume, 2019)

- Initial State modeling (i.e., existing conditions model),
- Design to Design (reference model),
- Coordination / collision detection,
- Quantity take-off,
- Handover to asset management,
- Visualization,
- Handover to GIS for spatial analysis,
- Machine control and machine guidance (during construction),
- Geotechnical investigations,
- Geotechnical constructions (e.g., piling systems), and
- Earthworks cut and fill design.

The IFC Road project reached WP-4 in March 2020 when the candidate standard became available for testing. A new project has been proposed to deploy the infrastructure extensions as IFC 4.3, which would ideally become ISO 16739-1:2021. (Anderson, 2020)

3.3.2 Bridges

bSI sanctioned development of IFC Bridge through the InfraRoom in 2016. An international working group had proposed an IFC model for bridges in 2006, but the lack of IFC support for alignment definitions, amongst other reasons, prevented its adoption. (Castaing, et al., 2017) Work supported by the Federal Highway Administration (FHWA) in 2015 reviewed a range of schemas (including IFC and LandXML) and produced requirements for delivering “workhorse” bridge information from design to construction for bidding and construction. The work identified that further schema extensions were still necessary. (Chipman, et al., 2016)

The IFC Bridge project followed the bSI guidelines and was executed similarly to the IFC Road project, with WPs for requirements analysis, taxonomy analysis, conceptual model development, draft proposed IFC schema extensions, validation, final proposed schema extensions, and adoption as a candidate standard. The schema extensions focused on "workhorse" bridge types, i.e., slab, girder, slab-girder, box-girder, frame, and rigid-frame bridges, as well as culverts. Truss, arch, cantilever, cable-stayed, and suspension bridges are likely also supported by the proposed schema extensions, but were not directly addressed. (Borrmann, et al., 2019) The "must have" use cases for bridges were: (Plume, 2019)

- Initial state modeling (i.e., existing conditions),
- Design to design (reference model)
- Coordination / collision detection
- Quantity take-off
- Handover to asset management
- Visualization
- Handover to GIS for spatial analysis
- 4D construction-sequence modeling
- Progress monitoring
- As-built vs. as-planned comparison
- Design-to-Construction hand-over
- Import of major road / railway parameters

Design-to-construction hand-over was not completed in the fast-tracked project, (Borrmann, et al., 2019) but it is in scope for the TPF study [TPF-5(372)]. (National Cooperative Highway Research Program, 2017) The IFC Bridge project concluded in March 2019 when the candidate standard became available for testing. After successful testing, the proposed extensions can proceed through the bSI standardization process to become the official IFC 4.2 candidate standard. (Borrmann, et al., 2019) The infrastructure extensions project would harmonize the changes from IFC 4.2 to IFC 4.3 and enable IFC 4.3 to move from a candidate standard to a formal standard (ISO 16739-1:2021) with ongoing support. (Ouellette & Liebich, 2020)

3.3.3 Future Development of IFC

bSI has developed a roadmap to modernize IFC to meet future needs, such as digital twins, smart buildings, and big data analyzed with machine learning. The technology base of IFC is not sufficiently scalable to meet these future needs. In particular, technical components of the IFC standard such as IfcDOC, mvdXML, Information Delivery Manuals, and the buildingSMART Data Dictionary are bespoke and difficult to scale. More scalable technical solutions include the Unified Modeling Language (UML), BIM Collaboration Format (BCF), XML, JavaScript Object Notation (JSON), and application programming interfaces (APIs).

The technical roadmap focuses on migrating towards more generic technology bases, for example by uncoupling the IFC schema from the STEP modeling language and file format. The technical roadmap is for the period 2020-2023. One of the key features of the modernization is that it would make the schema more modular and less monolithic. Currently, software vendors only implement subsets of the schema, called Model View Definitions (MVDs). Users are unaware that the software only supports part of the schema, which can lead to unexpected results. (buildingSMART International, 2020) A modular schema would address this issue.

3.4 Other Building Industries

Product Lifecycle Management (PLM) is a strategy to use digital product information to achieve positive outcomes across the product lifecycle. PLM involves information technology and process management to improve access to the product information and communication between stakeholders. A wide array of manufacturing industries use PLM, including aerospace, automotive, electronics, pharmaceuticals, and more. PLM often integrates CAD/CAM data with other product design data (such as structural analysis, bill of materials) and testing, quality, and compliance information. (Smartsheet, 2020) Sophisticated product data inventories are sometimes known as Digital Twins. (Hauck, 2018)

The literature search considered aerospace, chemical processing, electrical distribution (Smart Grid), industrial, and manufacturing practices for data standards and data management. Other than Smart Manufacturing and Aerospace, it was difficult to relate the practices to Highways. One notable detail from Smart Grid (electrical distribution) is that the data standards are based on UML, one of the languages being considered for modernizing IFC.

3.4.1 Smart Manufacturing

In 2011, McKinsey Global Institute (MGI) had high expectations for how data and analytics would transform the manufacturing industry. Projections were for declines of up to

50% in product development costs, as well as 25% for operating costs. Five years later, MGI estimated that only 20-30% of the expected value was captured, mostly by a small number of industry leaders, such as automakers. The major barriers were siloed data in legacy IT systems and leadership skeptical of the potential of data and analytics. Successful applications of data and analytics involved digital models of the entire production process, also called "digital factories," and integrating sensors to reduce operating costs by 5-15%. (Henke, et al., 2016)

3.4.1.1 Industry 4.0

Discrete manufacturing makes parts that are often components to a larger product, e.g., a car or a computer. Discrete manufacturing may be focused on a low mix of parts produced at high volume (such as computer components), or a high mix of products that are created at low volume (such as creating individual parts and small orders). The latter demands high agility when switching between products. Thus, it is the type of manufacturing that is of interest for so-called Industry 4.0, which aims to improve agility through analyzing data that is generated from sensors on the equipment, referred to as the Industrial Internet of Things (IIoT). (Sobel, 2018)

IIoT produces vast batches of data that need to be reduced through machine learning techniques. However, discrete manufacturing data is highly complex and a lack of semantic interoperability between manufacturing systems (such as general-purpose Computer Numeric Controller [CNC] machines) makes it difficult to glean meaningful insights from the data. Proprietary protocols and data structures on equipment like CNC machines and a historical interest in only developing the control systems to support a human-machine interface, makes it extremely challenging to automate the extraction and meaningful analysis of data. (Sobel, 2018)

MTConnect is a standard for IIoT data that includes semantic content and context related to the components of the equipment. This means that the extracted data has a well-defined meaning and numerical data has defined units and formats. This enables the aggregation of data from machines from different vendors. However, low-volume product datasets are often not sufficiently large to train machine-learning algorithms. (Sobel, 2018)

Product definitions are typically defined using CAD and Computer-Aided Manufacturing (CAM) tools, which lack standardization. The standards that exist support digital models of the geometry with tolerances and annotations. However, the standards focus on human readability, not computer automation. The information that is loaded on the manufacturing equipment (in a proprietary format) is reduced to a series of tool selections and motion control actions. Effective analytics would require product information to be delivered in a standardized, machine-accessible, information model that enables an automated comparison of product outcomes to the design intent. (Sobel, 2018) This would streamline the quality assurance process.

3.4.1.2 Data Standards

Proprietary CAD systems continue to dominate the manufacturing industry. Software vendors seem unmotivated to adopt open data standards. There is a disconnect between designers' desire for enhanced design features and the business needs of effective information exchange. CAD data exchange happens as a matter of course in an industry with multi-tiered suppliers who rarely use the same CAD products (or product versions) throughout the supply chain. Information exchange typically occurs through either two-way exchange (proprietary format → neutral format → proprietary format) or direct exchange from one proprietary format to another, where available as a software feature. CAD translation is such a problem for the manufacturing industry that third-party translations services have emerged. (Letelier, 2019)

STEP is currently the foundation of manufacturing data standards. Formally known as "Standard for the Exchange of Product model data," STEP is a comprehensive standard for electronically exchanging product data between PLM systems. Initially published as ISO 10303 in 1994, STEP expanded the scope of information exchange beyond CAD data to include product data that is useful over the product lifecycle. (Pratt, 2001) STEP is effective at exchanging CAD data for design, assembly, and manufacturing. STEP can exchange geometry definitions and tolerances, as well as attributes like color, topology, texture and material specifications, finish requirements, process notes, and welding symbols. (Letelier, 2019)

The Object Management Group (OMG) is a non-profit membership organization that develops technology standards for several industries, including manufacturing, space, and government. OMG maintains a specification for PLM services that is used to interact with CAD data on a platform-neutral service. Specific use cases include importing and exporting assembly data, uploading and downloading product data and metadata, viewing change management information, and querying objects. (Object Management Group, 2011) The information model is derived from ISO 10303-214, the part of the STEP standard concerned with the core data for automotive mechanical design processes. ISO 10303:214 has been withdrawn and revised by ISO 10303:242, the part of the STEP standard concerned with managed model-based 3D engineering. (International Organization for Standardization, 2014)

Most major CAD/CAM systems now read and write STEP data. What remains is widespread adoption within industry. 3D CAD graphics could be used in multi-party critical design reviews and technicians could use CAD models and non-destructive inspection techniques like augmented reality. (Letelier, 2019)

3.4.2 Aerospace

Initially, the aerospace industry used two military standards, MIL-Q-9858A and MIL-I-45208A, as *de facto* industry standards. These two standards, respectively, covered quality program requirements and inspection system requirements. (American Society for Quality, 2016) The industry then adopted the ISO 9001 consensus standard, but later developed its own derivative standard to better serve its needs. The G-14 Americas Aerospace Quality Standards Committee of SAE International maintains the AS 9100 family of consensus standards for quality management systems. (SAE International, n.d.)

The terms that describe BIM-like processes in the aerospace industry are Digital Product Definition (DPD) and Model-Based Definition (MBD). Boeing subsequently developed its own specification for DPD that applies to all suppliers and sub-tier suppliers. MBD is one possible format of DPD. An MBD is a dataset containing 3D geometry and annotations of dimensions and tolerances (possibly also notes and parts lists), sufficient to provide a complete product definition. An MBD is a DPD that does not include any 2D drawings. (Boeing, 2019)

Boeing developed a digital data-quality specification, Boeing document D6-51991 “Quality Assurance Standard for Digital Product Definition at Boeing Suppliers.” D6-51991, a supplement to the quality-management system requirements for suppliers, is intended to streamline technical coordination between Boeing, its supplier, and any sub-tier suppliers. Suppliers are contractually required to adhere to the digital data-quality specification if they receive, download, or use Boeing DPD or MBD in any way. D6-51991 establishes requirements for suppliers to create and implement plans, user-level procedures, and process documentation for using DPD. (Boeing, 2019)

Boeing uses DPD for suppliers to create products and inspection media for the supplier's quality representative to verify conformance with quality requirements. There are ten elements to the Boeing D6-51991 specification:

1. Comprehensive documented processes and/or procedures related to DPD, including a graphical flow diagram depicting the flow of data throughout the product lifecycle.
2. Configuration management and media security to ensure data integrity and security.
3. Product-acceptance software, which may be proprietary and even bespoke.
4. Internal quality audits, including a plan with procedures to audit all operations that affect DPD data and related documentation.
5. Procurement control to ensure that all requirements related to DPD flow down from supplier to sub-tier suppliers.
6. Control of measurement equipment, including calibration and coordinate-measurement-systems procedures.
7. Inspection media, such as 2D drawings, digitally-defined surfaces or features within 3D models, reduced content drawings (a 2D drawing with additional information in a 3D model), MBD datasets to be loaded onto manufacturing equipment, and more.
8. Data exchange methods, which place the onus on the supplier to maintain hardware and software configuration to maintain compatibility with Boeing-supplied datasets and/or data exchange formats. Suppliers are also responsible for clearly documenting the process for all translations, such as from native CAD formats to CATIA or STEP formats. The process must also document how to verify the accuracy of the translation. Suppliers are required to demonstrate the CAD translation process.
9. Special tooling design, traceability, and inspection.
10. Training to assure competence for all DPD system users (e.g., Quality, IT, planning, purchasing, tooling, contract review, and manufacturing).

3.5 Summary

There is international consensus and collaboration on lifecycle asset management in the built environment using BIM. The approach in Europe and in the US buildings and military construction industry is founded on defining clear, detailed, and explicit object-oriented (or asset-oriented) information requirements documented in BIM execution plans that also manage the development and use of model information during project delivery. Organizational information requirements encompass the entire framework for developing and delivering asset information digitally. The framework includes management, technical, and commercial requirements that define the processes, content, format, and organization of the project information so that it is ultimately compatible with the receiving asset information systems. The current best format for data interoperability is IFC. However, IFC is still being developed and deployed for infrastructure, meaning it is not yet available as an option to read or write data in commercial software. The roadmap for the future of IFC involves modernization to a broader technical foundation that is more scalable.

Other industries experience similar issues with standardization and interoperability. There are promising uses of product models in manufacturing and DPD in aerospace, both for manufacturing and for tolerance checks for quality assurance. Interoperability is a challenge in all industries. The aerospace industry pays particular attention to quality management processes, including for DPD. Boeing suppliers must also provide detailed DPD process documentation that addresses how to exchange the DPD information to be compatible with Boeing's systems.

4.0 DISCUSSION

4.1 Overview

Digital data holds the potential to bring value to project delivery and beyond. To be useful, data needs to be of predictable and reliable quality, consistent, fit for the purpose, and accessible. Nationally and internationally, public agencies in the AEC industry are taking a consistent approach to systematically procuring digital data in project delivery that is useful for operations, maintenance, and asset management.

There is international collaboration to produce open standards for both the procedures and the underlying technical infrastructure for digital delivery through the ISO. In the US, the NBIMS-US™ is a compilation of consensus standards that includes some of these international standards, along with US-based standards—in particular for BIM execution planning and describing PIRs. Implementation efforts involve strategic actions and actions that advance the policy, process, technology, and workforce development capabilities.

4.2 The Path to Digital Delivery

The path to digital delivery in the AEC domain distills down to five elements. Insights from other industries—in particular smart manufacturing and aerospace—reinforce the effectiveness of these elements and provide novel approaches to some ongoing challenges. The five elements are:

- Organizational information requirements
- Object-oriented data requirements describing data quality
- Process management
- Open standards, and
- Container-based data management.

Creating detailed, specific OIR and governing the processes for creating and using BIM data through BIM execution plans are important steps for UDOT to realize value from their design and construction data later in the asset lifecycle.

4.2.1 Organizational Information Requirements

In general, US highway infrastructure owners have not defined OIR as comprehensively or broadly as envisioned in Europe and the broader US AEC industry. The highway industry has defined the PIR for road and earthwork construction using AMG. (Maier, et al., 2016) The FHWA and the TPF study for BIM for bridges and structures support research into defining the PIR for bridges. (Chipman, et al., 2016) (Brenner, et al., 2020) (National Cooperative Highway Research Program, 2017) These requirements are generally specified in terms of content and file format. In some cases, there are additional criteria such as CADD standards, file naming conventions, and modeling conventions. These comprise a small set of the technical component to OIR as described in ISO 19650. There are a handful of US examples where highway and bridge projects have included a sub-set of the management and commercial elements of OIR, including some in Utah.

The Boeing DPD requirements, documented in D6-51991, have evolved over many years to manage the details of governing digital data. The purpose of the DPD requirements is to ensure that all parties can access the information they need to ensure the quality of the product. This specifically includes product design, tooling, manufacturing, and inspection. The Boeing DPD requirements do not prescribe specific software or hardware, but they place the onus on the supplier to demonstrate and document detailed processes to make the DPD compatible with Boeing's enterprise data.

The USACE OIR include commercial and managerial elements, such as the BIM project execution plan, M3, and submittal requirements. Still, the BIM execution planning process—used by the USACE and the AEC industry in general—is largely an organic approach to developing PIR, in particular, for information exchanges that support defined use cases. Construction inspection is not one of the use cases identified by Messner et al. (2019) for the AEC industry, nor by the USACE in their BIM execution planning template. However, it is of interest for roadway construction and a focus for manufacturing and aerospace industries.

Through UGate, UDOT has a mature, industry-leading asset information model and realizes substantial value and efficiency through analytical tools that join orthogonal datasets. For example, the Project Design App creates efficiency with scoping and estimating resurfacing projects. UDOT has experimented with embedding asset information in project models, for example the structure identity number on the Blackrock bridge replacement project, (Brenner, et al., 2020) and UDOT's digital delivery guidelines provide guidance on the minimum attributes to embed for a range of asset classes. UDOT is well-placed to define comprehensive OIR that address the managerial, technical, and commercial elements described in the EU BIM Handbook.

In Europe, there is a particular focus on using an object-oriented approach to organizing information, including through a classification system. This allows information to be contextualized and referenced through a common framework. (EU BIM Task Group, 2017) When a common classification system is used, it is easier to connect information. For example, if the model elements, construction specification, and measurement and payment items all share a classification system, it is much easier to embed the construction tolerance and pay-item reference within the model elements. This would make the model elements more useful to inspectors and they would spend less time cross-referencing information in the field. Currently, highway and bridge models do not embed the construction tolerances. However, it is a common practice in manufacturing that the tolerance is embedded within the product definitions.

The manufacturing supplier fulfills the joint roles of the designer and the contractor in AEC procurement modes. Sub-tier suppliers—analogous to the designer in a design-build relationship or sub-contractors—are held to the same DPD requirements. Like a designer, the supplier is obligated to develop the information needed to manufacture (or build) the product, as well as to inspect it. However, the typical highway and bridge design process does not differentiate between these two consumers of the design information. While highway and bridge plans aim to serve both, Boeing's DPD requirements clearly differentiate these two applications.

Construction is most like low-volume, high-mix manufacturing. Many constructed features are bespoke to the project, especially fabricated components like bridge girders. IIoT is unlikely to be meaningful for UDOT, though contractors may see value in implementing IoT devices for fleet management. The most relevant IoT for UDOT is for e-ticketing, but that is outside the scope of this research.

4.2.2 Object-Oriented Data Quality Definitions

Despite over a decade of experience delivering 3D data to contractors, Kentucky contractors continue to note that the quality of the 3D models they receive is variable. (Catchings, et al., 2020) Contractors lack a framework to describe the data quality aspects of PIR for construction; contractors in Michigan feel that a measure of data quality is essential if the design intent is to be delivered digitally using 3D models. (Mitchell, et al., 2019)

The core data-quality descriptors for bridges are geometric accuracy and information, while subsurface utilities and roadway models (especially for AMG) need a third dimension to describe uncertainty, or confidence. CI/ASCE 38-02 is the standard that used to communicate uncertainty in subsurface utility records. The designated quality level could be appended to 3D model elements as an attribute. For roadways, the existing conditions need to be defined with control that has construction-level accuracy and with much more enhanced accuracy in key areas where the design ties into immovable features. (Maier, et al., 2016)

Information requirements flow down from the OIR and are unique to each asset class. The geometric needs are variable, depending on the context and construction acceptance tolerances. For example, the location tolerance of a pile footer is often +/- four inches, but the alignment tolerance is ¼ inch per foot of length. The appetite for uncertainty is also context-sensitive. For example, a tie-in to a gentle grassy slope can readily be adapted in the field, but a tie-in to an existing lane has no room for error. Object-oriented definitions can differentiate minimum modeling requirements by phase; for example, a paving lot may be defined by breaklines and depth in construction, but by area, width, depth, cross-slope, and smoothness at handover.

Defining object-oriented data-quality definitions, like the BIMForum LOD Specification for building elements or the NBS BIM Toolkit definitions is a large, but important step. It is dependent upon a classification system and foundational definitions for Level of Information, Level of Geometry (or detail, or development), and Level of Confidence (or uncertainty). This is an issue of national interest and national alignment would be beneficial for the industry. For example, the NBS BIM Toolkit provides a user-friendly tool to define PIR from a library of 5,700 objects that are defined in terms of level of detail and level of information.

4.2.3 Process Management

Process management is a critical quality management tool. Boeing places a heavy emphasis on documenting processes and procedures, and the supplier is ultimately responsible for ensuring that the digital information is valid, even when it has been transformed from native CAD to other formats. The DPD requirements do not place any constraints on the processes and tools that a supplier may use. Instead, the supplier is responsible for ensuring data is secure and accessible. This requires thorough documentation of hardware and software configurations, lifecycle data flow processes, and data translation procedures. The supplier is required to document translation procedures and also to demonstrate them. Suppliers must also identify training requirements to ensure that all parties have the skills necessary to access the DPD information. Finally, the supplier is responsible for generating inspection media, that is, the media that inspectors will use to validate the quality of the manufactured product.

There is a greater probability of consistency and predictable project outcomes when the OIR includes requirements to manage the production and use of digital data on a project through BIM execution planning. The BIM execution planning processes used in the AEC industry have been refined in over a decade of practice. These processes are mature, but the highway and bridge specific use cases need to be developed. While some uses defined by Messner et al. (2016) transfer directly, others need to be tailored to highways and bridges and new uses, such as construction inspection, need to be defined. This is another issue of national interest where alignment would be beneficial for the industry.

4.2.4 Open Data Standards

There is national and international consensus and collaboration to move forward with the IFC standard for infrastructure. However, the IFC development process is long, and the software deployment and adoption phases lag considerably. IFC 4.0 was adopted as an international standard in 2013, but it was not available in commercial products to test on UDOT’s Blackrock project in 2017-2018. (Brenner, et al., 2020) It may take sustained pressure from the national and international highway community before IFC 4.3, once adopted, is supported by enough commercial software products—which in turn need to be adopted by owners, consultants, and contractors—to make IFC 4.3 feasible as the primary format for digital delivery. (It would still have value as an archival format once the model-authoring software supports it.)

In the meantime, digital delivery is constrained to proprietary data formats and LandXML version 1.2, which has not been supported since 2008. Currently, data in proprietary formats are unreliable when retrieved from archives (Catchings, et al., 2020) and data exchange between proprietary systems is an onerous process that is often unreliable. (Maier, et al., 2017) Nevertheless, industry needs to begin developing and using 3D models in order to build capability and capacity in the workforce for 3D modeling skills and workflows.

The same vendors serve the manufacturing and civil infrastructure CAD market, in some cases with the same CAD products. It is unsurprising, therefore, that geometric data standards have a common origin for both industries in STEP (ISO 10303). It is equally unsurprising, however, that interoperability is a persistent problem for the manufacturing industry. The Boeing DPD requirements for data exchange described above ensure that the DPD is reliably accessible by the end users: the owner, inspector, and manufacturer. This is an approach that UDOT could consider for design-build projects where the designer and contractor cooperate closely.

4.2.5 Container-Based Data Management

Project delivery documentation—contractual and contextual—comprise an array of files that contain document-based information (e.g., geotechnical reports, inspection daily reports), non-graphical data (e.g., schedules of quantities), raster images (e.g., photographs), and graphical information (e.g., 3D models) that is compartmentalized into individual files that are referenced together. Machine learning is an emerging approach to extract information from document-based and raster information, though geolocating (i.e., appending a geospatial reference frame to) the extracted information will remain a challenge. ISO 21597-1:2020, which is based in part on COINS 2.0, was developed because the construction industry needs to be able to handle multiple documents as one information deliverable. (International Organization for Standardization, 2020)

The container-based data management intended by ISO 19650 segregates information into files (which serve as the container) that one user can edit at a time. Some BIM software creates a centralized database that multiple users can edit concurrently. ISO 19650 specifies a

CDE, which manages the file "containers" so that users can share and reuse data efficiently. Document management systems are managed solutions that provide password-protected access and read-write file protections. Commercial managed solutions like ProjectWise and Bluebeam Studio often fulfill the role of a Common Data Environment. However, data organization during project delivery is usually based on the project identification number, which makes it difficult to locate asset information after the project is complete.

Container-based management envisioned by ISO 21597 uses "wrapper" that binds multiple files into one with associated metadata. The "ZIP file" is such a container format that also supports lossless compression. The construction industry already uses containers, such as ZIP files, for a variety of information exchanges in project delivery. Some proprietary tools, like Autodesk's e-Transmit, are designed to preserve the complex relationships between referenced CADD files when creating the container. Once the digital data is downloaded from the managed environment, the relationships between reference files can be severed. Container files can help to preserve those relationships.

ISO 21597-1:2020 defines an open and stable container format to exchange, store and archive the various documents that describe an asset throughout its entire lifecycle. Use cases include bidding, submittals, approval packages, and file versioning to track changes. (International Organization for Standardization, 2020) Container-based data management as envisioned by ISO 21597 is an issue of international interest.

4.3 Digital Delivery at UDOT

UDOT is in the process of developing a *Model Development Standards Manual* (MDSM) (Utah Department of Transporatation, 2020) and updating the *Model-Based Design and Construction Guidelines for Digital Delivery*. (Utah Department of Transportation, 2019) The manual will apply to projects where the primary controlling contract document is a digital 3D model. This section compares the manual and guidelines content with the framework for digital delivery described above.

4.3.1 Organizational Information Requirements

The MDSM describes minimum modeling requirements, LOD definitions, Model Element Breakdown (MEB) structure, and specific digital delivery use cases supported by the minimum modeling requirements. In addition, the MDSM provides standards for establishing project management strategies, such as the use of project execution plans (UDOT uses a different term for the plan). The MDSM links to other relevant standards, such as the Survey/Geomatics Manual, Structures Design and Detailing Manual, and standard drawings series.

The British Institute of Facilities Management guide for OIR defines management, technical, and commercial elements of OIR. Table 3.3 breaks these elements down further by content. UDOT's MDSM and guidelines cover all the management elements except contract terms and conditions and enterprise asset management systems, which UDOT defines outside of the digital delivery documents. The roles and responsibilities are defined at the project-level in the BIM execution plan, which is required by the MDSM. The MDSM defines the minimum modeling requirements for the contractual deliverables for digital delivery projects. Together, the guidelines and MDSM define the PIR, which UDOT could reference in existing contract language.

UDOT's MDSM and guidelines cover all the technical elements except IT and system performance constraints. These constraints would include things like maximum file sizes. The OIR intends for LOD to be defined for each element, rather than just a foundational definition. The MDSM includes detailed element-level minimum modeling requirements that define the LOD and information for one or two specific levels. These requirements are defined to support the use cases that have been developed. UDOT could expand the library of element-specific LOD and attribute standards when piloting and implementing the MDSM.

The commercial requirements include information deliverables aligned to project milestones. These would be defined explicitly in the BIM execution plan, but the final submittal requirements are also identified in the guidelines. The two commercial requirements that UDOT does not yet fulfill are the BIM capability and capacity evaluation criteria.

4.3.2 Object-Oriented Data Quality Definitions

UDOT's LOD definition describes the degree of engineering intent on the basis of size, location, quantity, orientation, geospatial coordinates, and attribute information. Table 4.1 contains the UDOT foundational LOD definition. (Utah Department of Transporatation, 2020)

Table 4.1 UDOT Foundational LOD Definitions.

Level of Development Basis	LOD A	LOD B	LOD C	LOD D
Physical Shape	X			
Size	X			
Location	X	X	X	
Quantity	X	X	X	
Orientation	X	X		
Project Coordinate System	X	X	X	
Data Attribution	X	X	X	

The UDOT definition includes geometry (i.e., shape, size, location, quantity, orientation, and geospatial coordinates) and information (i.e., data attribution), but does not address the uncertainty or confidence that relates to subsurface utility and roadway models. UDOT could include the CI/ASCE 38-02 quality level as an attribute requirement for existing subsurface utility elements. The uncertainty or confidence in roadway models is dependent on the existing ground survey. UDOT updated the survey manual to bring the survey accuracy requirements up to a level with low uncertainty. (Utah Department of Transportation, 2017) The project delivery network includes a survey/mapping quality-control checklist to identify if the level of accuracy is correct. (Utah Department of Transportation, 2014)

UDOT's model element breakdown structure uses high-level object definitions at the first level, where model elements are broken down by design discipline (e.g., roadway, structures, drainage, utilities). At the second level, UDOT's breakdown is grouped in some cases by object and in other cases by pay item. The pay-item grouping serves immediate construction needs, but it groups together objects that are different asset classes (e.g., "Untreated Base Course, Hot-Mix Asphalt, HMA Bicycle and Pedestrian Paths, Stone Matrix Asphalt, and Portland Cement

Concrete Pavement" is a single category), it groups objects from different locations, and it separates co-located objects (e.g., Untreated Base Course is separate from the other pavement layers). Another approach could be to group pavement objects at the second level and differentiate by pay item at the third level.

4.3.3 Process Management

UDOT's MDSM includes comprehensive requirements for BIM execution planning; the MDSM uses the term "Model Development and Delivery Implementation Plan" for a BIM execution plan, but functionally, they are equivalent.

4.3.4 Open Data Standards

There is not currently an available open data standard that adequately supports bridge and roadway information for design and construction. UDOT participates actively on the AASHTO Joint Technical Committee for Electronic Engineering Standards and in the TPF study that is advancing the IFC standard for bridges. UDOT's digital delivery guidelines specify a mix of proprietary file formats unique to specific versions of one vendor's products (e.g., ITL, ALG), proprietary file formats that are readable by a range of software (e.g., DGN), human-readable file formats (e.g., XML), and PDF. The submittal requirements in the guidelines are specified by content and file type, e.g., summary tables in XLSX or PDF format.

4.3.5 Container-Based Data Management

The MDSM does not specify how to segment data into file "containers" or to package the submittals, but there are instructions in the guidelines for file-based data management consistent with ISO 19650. UDOT uses Bentley® ProjectWise, a managed solution for document management that functions as a common data environment. The submittal process involves multiple steps, including:

- adding a metadata attribute to the files,
- copying to a designated folder,
- restoring the referencing relationships between files,
- bulk editing the file names to append an advertising reference to the file name, and
- checking that file name change did not sever the referencing relationships.

The next step involves Construction Advertising staff moving the files to another folder that is accessible to bidding contractors.

It is possible that using containers (e.g., ZIP files) could help with this process, but the referencing relationships between CADD files are complex and easily severed. If the vendor does not provide a container packaging tool within the software that manages these relationships, using, e.g., a ZIP container may not work as intended. The UDOT Digital Delivery website (and the guidance housed there) is a reference to assist all users with the current process.

4.4 Summary

Data collection continues to get cheaper. New types of data are becoming available through tools such as sensors and smart phones. As the cost of new data collection declines, it is important to contemplate the value of legacy data in relation to the costs of storage and governance. There is a strong desire to repurpose data across the asset lifecycle, but it is important to isolate the data that is worth keeping and managing. According to MGI, data holds its value when data collection is expensive or when physical barriers limit access to collect that data. MGI also found that aggregating data from different sources adds value when it is technically difficult or organizationally challenging, such as when it has to be coordinated from diverse sources. (Henke, et al., 2016)

Highway design and construction data easily meets these criteria for adding value through data retention and data aggregation. In design, highly skilled individuals generate the data and perform quality assurance processes. There are high external costs (e.g., from lane closures) and safety issues associated with data collection in construction, maintenance, and operations. UDOT is on a path to generate high-value data through digital delivery in project development. The durability of the data is a concern, due to a lack of available open data formats. However, it takes time to build capability and capacity for digital delivery across the industry; meanwhile, the current formats are being used effectively in construction.

There is much work still to do internationally and nationally to define the consensus standards that underpin digital delivery for highways. UDOT is participating in that work through AASHTO committees and a TPF study. In the meantime, the most fruitful investments seem to be in defining the OIR, both the priority asset information requirements, in the context of project delivery, and the process management requirements. UDOT's recent investments in an MDSM and updating the digital delivery guidelines has made significant progress in these areas.

5.0 CONCLUSIONS

5.1 Summary

UDOT has made investments in formalizing its approach to digital delivery. In particular, UDOT has defined the requirements to generate consistent, 3D model-based information that forms the primary medium for the construction contract documents. The objectives of this research were to determine how UDOT's approach aligns with the trajectory of national and international developments and to capture insights from other industries related to managing and exchanging digital information.

The necessary traits of digital delivery information were identified to be secure, interoperable, open, and standardized. Combinations of these traits provide the other essential characteristics of digital delivery information, including: accessible, durable, predictable, reliable, transparent, etc. Recognizing that UDOT's policies for security and open information are relatively mature and relevant to digital delivery, the literature search focused on developments in interoperability and standardization for digital delivery in the highways industry and more broadly.

An extensive literature search gathered information on national and international efforts to advance digital delivery, in particular through consensus standards. The discussion described a five-step approach to digital delivery based on international consensus standards and practices that are applicable to highway and bridge construction. UDOT's products from its recent work to create standards and digital delivery guidelines were reviewed and compared to findings of the literature review.

The conclusions will address the original research questions:

- *What is the motivation for the current approach and what are the touchstones?*
- *Does the UDOT approach align with national and international efforts?*
- *Do other industries experience the same problems and how do they resolve them?*

5.2 Findings

UDOT has undertaken many strategic and specific actions to increase the capacity and capability for digital delivery within UDOT and its business partners. The European community has united behind the ISO 19650 approach to construction information management and the international community is collaborating to extend the IFC standard to linear infrastructure for data interoperability. UDOT's approach, in particular recent work to draft an MDSM, is consistent with the ISO 19650 approach. UDOT is participating in the efforts to expand the IFC standard to highways and bridges through AASHTO committees and a TPF study.

5.2.1 Motivation and Touchstones

Digital models have approximations and limitations that are necessary for efficiency. Specific use cases of models tolerate different amounts of approximation. For example, a structural analysis model may ignore minor horizontal curvature that is inconsequential to the analysis. Using a model for unintended purposes may result in costly errors. Extending the example, if the analysis model were used to fabricate girders, the girders would not fit between the abutments. Context is important to understand model limitations. An object-oriented (i.e., asset-focused) organization for model elements enables contextualizing the information.

Engineers have used models for decades, but with digital delivery they need to share their models for others to use in ways they cannot control. To avoid misuse, the end user needs to determine if their intended use is appropriate given the limitations of the model. In order to make that determination, the limitations of the model need to be defined clearly. The corollary is that future users need to define the acceptable limitations to the model authors as requirements. Despite over a decade of trying, the roadway models delivered to contractors who intend to use them for AMG still usually fall short of the mark. (Catchings, et al., 2020) (Maier, et al., 2017) The resolution involves creating a common language to describe models so that contractors can describe their requirements and designers can communicate limitations.

Developing OIR using consensus standards provides a common language and approach that is transferable between regions and disciplines. This enables the industry to increase capability and capacity more nimbly. International consensus standards for open data provide a single standard for software vendors to support, accelerating a broad inclusion of the open standard within the software products used across the industry. The consensus standards that are framing the approach to digital delivery for the AEC industry are:

- ISO 19650 *Organization and digitization of information about buildings and civil engineering works, including building information modeling (BIM) — Information management using building information modeling*
- NBIMS-US™ *National BIM Standard-United States®*
- *BIM Project Execution Planning Guide*
- ISO 16739 *Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries*

5.2.2 Alignment to National and International Efforts

UDOT's approach to developing model development standards aligns with the overarching framework of the AEC consensus standards for digital delivery. There are areas where these consensus standards are not yet mature for highways and bridges. These are:

- Classification of highway and bridge model elements,
- Asset information requirements for maintenance, operations, and asset management,
- Construction inspection information requirements,
- Practices for developing and organizing models for bridges and structures,
- Use cases and detailed object-oriented data quality requirements,
- Open data standards, and
- Procedures for model-based design reviews and 3D-model quality management.

A variety of *ad hoc* classification systems organize highway and bridge elements, such as those used in asset and maintenance management systems, construction specifications, construction pay-item schedules, and software data models. There is not yet a consensus standard that unifies the classification of highway and bridge elements. This limits the ability to align data collected and used at different times in the asset lifecycle. UDOT's Bridge 3D catalog aligns bridge model elements to the CADD level, specification, pay item, and national bridge inventory classifications. This is a practical solution that meets UDOT's immediate business needs.

The issue of aligning classification systems is broad; a change to the classification system could make it challenging to use legacy datasets. There are opportunities for national and international collaboration, for example, the alignment of AASHTOWare data models to the IFC standard and the broader agency business needs. The area of model element classification is where UDOT runs the greatest risk of falling out of alignment with the US highway industry and international development of the IFC schema. Aligning classification systems using an object-oriented (or asset-focused) approach is the foundation of context-sensitive lifecycle asset data.

UDOT's digital delivery guidelines—for model authoring and review—are among the most detailed available for bridge modeling. The software is relatively immature, and UDOT will likely continue to refine these procedures through further piloting. Contractors can adapt to different model organization as long as it is documented and consistent within a project dataset. The same applies to UDOT's defined use cases and element-level minimum modeling requirement definitions, as well as UDOT's approach to providing the most accessible and durable digital information while the industry develops and implements the IFC infrastructure extensions. Procedures for conducting model-based design reviews and for quality management for 3D modeling are still emerging. The AASHTO Joint Technical Committee for Electronic Engineering Standards and the TPF study for BIM for bridges are two forums UDOT participates in where DOTs could exchange emerging notable practices.

5.2.3 Insights from Other Industries

The most significant insights from how other industries manage digital information were:

- Paying careful attention to documented processes for DPD,
- Allowing the supplier to select software products and file formats for product development, but requiring the supplier to provide *and demonstrate* a detailed plan for how to exchange information and verify the exchanged information,
- Making quality management a priority use case for the digital product definition, and
- Embedding quality assurance tolerances in the digital product definition.

5.3 Limitations and Challenges

People were the biggest barrier to realizing value from data that Henke, et al. (2016) identified. While people are usually open to new ways of working that are easier or that solve a particular problem, the sunk-cost fallacy often makes people unwilling to give up approaches that they have invested a lot of time, money, or effort into. The 2D plan-based approach to project development was refined and standardized over centuries. Digital delivery and lifecycle asset information management are comparatively new. There are technical limitations that are manageable, but the human factors of the new approach will affect the behavioral economics of user acceptance and the ability for industry to embrace these new procedures and scale them.

The consensus standards that have matured and formalized are either specific to buildings or remain at a high level. Detailed consensus standards tailored to the highway industry are still in development, or development has not yet begun. Many will not be available for some years—certainly from the project development user's perspective. For example, IFC 4.3 is likely to be published as an international standard in 2021, but it will not be a practical solution for project delivery for some years. First, software vendors will need to create new versions of their products to support IFC 4.3; then, users have to adopt those new software versions. The lag in widespread adoption throughout the supply chain may last a decade or more.

6.0 RECOMMENDATIONS AND IMPLEMENTATION

6.1 Recommendations

The next logical step for UDOT is to pilot the MDSM and updated digital delivery guidelines. Piloting would introduce industry to the approach and enable UDOT to receive feedback on the usability, human factors, effectiveness of the detailed element-level data quality requirements, and usability of the element information attributes in construction and beyond. When UDOT is ready to expand on the current OIR, consideration should be given to:

- Defining the construction inspection information requirements,
- Prioritizing the specific asset information to capture in construction,
- Formalizing model-based design review procedures,
- Expanding the model use cases and associated modeling requirements, and
- Formalizing 3D-model quality management procedures.

UDOT should remain informed of the national and international activities to develop consensus standards. This would enable UDOT to continuously monitor the alignment of its digital delivery approach to evolving industry practices, as well as to take advantage of new approaches or consensus standards that may be beneficial to UDOT's program. The AASHTO Joint Technical Committee on Electronic Engineering Standards and the TPF study for BIM for bridges and structures are the two primary collaboration platforms for digital delivery in highways and UDOT participates actively in both.

UDOT could work with the National Highway Cooperative Research Program to participate on panels or submit problem statements of national interest for funding. Potential topics include:

- Model-based design reviews and 3D-model quality management procedures,
- Classification systems for highway and bridges that support lifecycle data,
- Comprehensive construction inspection information requirements, and
- A library of object-oriented data definitions that include LOD and information,

Finally, UDOT could develop resources that support workforce development across their business partners. These include clearly defined capability and capacity measures for digital delivery so that industry partners can prioritize their workforce development investments. For example, what BIM-related capabilities do subcontractors need to use digital delivery to install structural reinforcement? UDOT could also provide sample datasets for business partners to use to create and deliver training.

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