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Digital As-Builts: Getting Started How-to Reference

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16. Abstract

This Getting Started How-To Reference serves as a practical primer to implementing Digital As-Builts (DABs) in transportation agencies. It covers the current state of practice for agency as-builts/DABs, key components and frameworks, essential use cases, data requirements, modeling, data exchanges, repositories, and tools and technologies. It also outlines implementation methods for agency pilots and projects, strategic approaches, capability maturity considerations, and critical success factors for successful DAB adoption.

The guide is designed to support agencies in their initial transition to DAB workflows, with a focus on essential use cases and piloting steps. It introduces two primary methods for implementing DABs: a simplified approach and an integrated approach.

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FORWARD: WHY ARE THEY IMPORTANT?

As-built drawings are nothing new; they have long been a vital component of construction projects. They serve as the documentation that captures how a project was actually built, noting deviations from the original plans and any changes made during construction. What is exciting and different, is the use of these drawings beyond the construction phase to provide asset-specific information essential for efficient operations and maintenance (O&M) of infrastructure facilities. However, to effectively use as-built drawings throughout an asset's lifecycle means relying on something more than the traditional e drawings presented as two-dimensional (2D) paper sheets, image scans, and document-based PDFs.

Today, technological advancements have led to the use of three-dimensional (3D) digital as-built (DAB) models. These as-builts are more than just drawings; they are data-rich with project and asset information. They serve as a key link between project design, survey, and construction data, connecting them to ongoing operations and asset management. Many transportation agencies have made significant advancements in digital delivery and tailored their approach to their specific project delivery and asset management needs. This document serves as a reference for getting started with implementing DABs in a transportation agency. It provides detailed how-to information with insights and real-world examples from peer agencies for successful adoption of DABs.

1. IMPLEMENTING DIGITAL AS-BUILTS: OBJECTIVES, SCOPE, AND ORGANIZATION

1.1 What is a Digital As-Built?

In contrast to traditional 2D paper, image scans, or PDF plan markups, DABs are, as the name implies, digital, dynamic, data-rich geospatial information models that document the as-constructed state of the physical infrastructure. They are initially created during construction to document design changes between letting and final construction close-out and then continue to be updated during post-construction (O&M) activities. DABs are a digital as-constructed record of all relevant data of the physical built infrastructure—a "digital twin" replica involving a project information model (PIM) for use as an asset information model (AIM) for lifecycle infrastructure facilities management. DABs provide a key link in connecting project design-survey-construction data to operations-maintenance-asset management. A glossary of relevant terms is provided at the end of this document.

Digital as-builts are living records of as-constructed and asset data, continuously updated throughout the construction process and over the asset's lifecycle, to support effective asset and performance management. By streamlining data collection through digital means, agencies can collect data once and reuse it often.

Digital as-builts, also known as "living records," are a dynamic form of documentation that captures accurate, up-to-date, and comprehensive information about transportation system assets throughout their lifecycle. These records are not static; they are continuously updated during construction to document design changes that occur between the initial project letting and the final construction close-out, and they continue to be updated when changes happen during the O&M phase of the infrastructure assets. DABs serve as both a historical record and a current snapshot of the built facility. This continuous process of updates supports effective asset and performance management and future asset maintenance and rehabilitation. By streamlining data collection through digital means, agencies can collect data once and reuse it often.

DABs also provide valuable data to support enterprise asset inventories, data-driven decision-making, capital planning, maintenance, conditions assessment, improvements programming, operations, federal reporting, and automation needs for lifecycle infrastructure information management. DABs support data reuse with extractable geolocated information for built assets. Lifecycle data in a DAB typically comprises geometric graphical design data (computer-aided design [CAD]/survey/geographic information system [GIS]), nongraphical data (attributes), documentation data (inspection/materials/condition), and metadata (data about data). Unlike current as-built approaches using PDF files, DABs data are searchable and accessible, geospatial and contextual, reliable and durable, human and machine readable, and extractable and interoperable for use across the infrastructure lifecycle.

Lifecycle transportation infrastructure asset information in a DAB can include data about:

- Roadways/Railways – highways/roadways, interchanges/ramps, intersections/junctions, pavement/shoulders, rumble strips, curb and gutter, surfaces, drainage/culverts, railways, alignments/ center lines, rights-of-way (ROW), and easements.
- Structures – bridges, retaining/noise walls, tunnels, large culverts, sign bridges, and geotechnical foundations.
- Traffic – intelligent transportation systems (ITS), advanced traffic management systems (ATMS), ramp meters, traffic signals, message signs, automatic traffic recorders, and sensors/cameras.
- Safety – traffic signs, lighting, guiderails/guardrails/barriers, pavement marking, Americans with Disability Act (ADA)-compliant curb ramps, sidewalks/paths, and road gates.
- Utility Data within the ROW – electrical, communication, telephone, gas, steam, lighting, water, and sanitary sewer.
- Facilities/Buildings – maintenance facilities, tollway facilities, rail/transit stations, airports/terminals, transit/multi-modal stations, rest areas, and park and rides.

1.2 Objectives and Scope Involving DABs and Digital Delivery

In the context of highway infrastructure, digital delivery refers to a modernized approach that uses digital technologies, processes, and data to design, construct, operate, and maintain transportation assets throughout their lifecycle. This approach encompasses a wide range of digital tools and methodologies, including DABs, 3D modeling, BIM, GIS, and various survey techniques. Collectively, these tools and methodologies create a comprehensive digital ecosystem for the lifecycle management of highway infrastructure.

While BIM serves as the foundation of this digital ecosystem by providing a framework for creating and managing digital asset data, DAB's dynamic, data-rich geospatial information models capture a wealth of information about the assets and the project. As noted above, in addition to creating an as-constructed record of the infrastructure, DABs are maintained and updated throughout the asset's lifecycle, to incorporate data collected through various sources.

This Getting Started How-To Reference is intended to aid State DOT staff in implementing DABs as part of a digital delivery roadmap. The primary target audience includes transportation agency executives, program managers, technical experts/champions, practitioners, and information technology staff.

This document was undertaken under the Federal Highway Administration (FHWA) Every Day Counts Round 6 (EDC-6) initiative. FHWA goals and objectives through EDC initiatives and state-based efforts are to improve highway transportation in the United States, deploy proven but underutilized innovations, shorten the project delivery process, enhance roadway safety, reduce traffic congestion, integrate automation, and improve lifecycle transportation facilities management.

This Getting Started How-To Reference builds on the 2020–2023 FHWA Transition to DABs research and pilot implementations, which included background research on the state of practice around as-builts and DABs; summaries from literature reviews/industry reviews, interviews/surveys, and case studies/examples; "real-world" implementation DAB pilot projects; and an assessment of the state of practice related to a DAB framework and capability maturity levels.

The scope of this reference guide includes agency as-builts/DABs state of practice, DAB components and framework, essential DAB use cases, data requirements, modeling, exchanges and repositories, tools/technologies used, DAB implementation methods for agency pilots and projects, agency implementation strategies, capability maturity, and critical success factors.

The focus of the reference guide for agencies is limited to the initial transition to DAB workflows, essential use cases, and piloting steps involving two key DAB methods: a simplified approach and an integrated approach.

1.3 Organization of this Guide

This reference guide is organized into the following chapters:

- Chapter 1 defines DABs, objectives, and scope.
- Chapter 2 presents a current state of practice of agency as-builts and DABs and describes the stakeholders involved, processes, practices, storage, key benefits and opportunities, key barriers and challenges, and DAB implementation methods.
- Chapter 3 outlines the two primary DAB implementation workflows and provides brief case examples from State DOTs that used these workflows. Detailed descriptions of these primary workflows are provided in two standalone reference documents produced as part of the EDC-6 Digital As-Builts Initiative: *Guide for Digital As-Builts—Using Simplified Digital Workflows, and Digital As-Builts—Using Integrated Digital Workflows*.
- Chapter 4 summarizes the implementation strategies, capability maturity, and critical success factors in getting started with DABs at agencies transitioning to, advancing, and implementing DABs and presents the critical success factors for implementation of DABs and digital delivery.

2. BACKGROUND AND CURRENT STATE OF PRACTICE FOR AGENCY AS-BUILTS

2.1 National State of Practice for As-Builts with DOT Agencies

Two recent research studies involve the state of practice around DABs: the 2017–2020 NCHRP 548 Synthesis, *Development and Use of As-Built Plans by State Departments of Transportation (DOTs)* (Taylor et al., 2020), and the 2020–2023 FHWA research on transitioning to DABs. The objectives of the 2020–2023 study were to investigate the needs, gaps, benefits, barriers, and practices for State DOTs to make the transition from paper-based markup plans to model-based DABs; identify asset information requirements and business process changes for implementation; establish a connection between the asset data captured in the digital model during construction and the asset data repository intended for use during the O&M phase; and establish a current state of practice for as-builts. Additionally, two pilot studies during construction of DABs by State DOTs were advanced to evaluate the framework of the benefits, barriers, and solutions and to provide an implementation guide as part of the research study. The research results, findings, and conclusions provided support to the 2022–2023 EDC-6 DABs implementation initiatives. The key results, findings, and conclusions of the research are provided in the following sections.

As part of the FHWA DAB research project, a review of academic literature and publicly available State DOT documentation (e.g., manuals, specifications, policies) was conducted in 2021 and updated in 2022–2023. This review documented the current state of the practice of construction as-builts and use of DABs for the 50 State DOTs, the District of Columbia Department of Transportation (DDOT), and FHWA Federal Lands Highway Management Agencies and Tribes. Follow-up questionnaires, structured interviews of more than 20 State DOTs, and virtual workshops/forums/webinars were also conducted in 2021 to validate and supplement the available information on construction as-built processes and to provide in-depth evaluations and maturity level assessments of DAB practices at State DOTs. Six State DOTs (Minnesota, Iowa, Colorado, Connecticut, New York, and Wisconsin) that were piloting and transitioning to DABs participated in structured case study interviews. These case studies provide a cross section of advanced as-built practices, innovative approaches, and tools/technologies deployed to enable other State DOTs to evaluate and improve their as-built processes and advance DABs. As agency as-built practices and policies and industry technologies and standards involving digital project delivery are continually evolving, this research also highlights innovative documented approaches, applied strategies, and best practices to support asset management, operations, maintenance, and PIM to AIM data management.

For many State DOTs, significant changes in advancing to digital practices appear to have been accelerated the evolution of e-construction technologies. The findings of the state of practice for DABs for State DOT agencies showed maturity levels that varied based on entities/stakeholders involved, information required/delivered, methods/processes used, tools/technologies implemented, and uses/functions deployed in advancing the as-built program and transitioning to DABs. State DOT practices varied in capturing, verifying, recording, updating, approving, storing, and using as-built data.

State DOTs exhibit a diverse range of practice maturity levels in relation to DABs. Comparatively, from the 2021 research findings of as-built primary methods used by State DOTs of information collected from 50 State DOTs, DDOT, and Federal Lands as shown in Figure 2-1, 10 percent developed as-builts using hard-copy paper-based/mylar-based markups (5 DOTs), 10 percent used paperless image-based scanned markups (5 DOTs), 56 percent used PDF-based markups (28 DOTs), and 24 percent used/piloted digital object-based model methods (12 DOTs). Information provided during the 2022–2023 DAB peer exchanges, regional workshops, and survey responses revealed that 9 percent of agencies developed as-builts using hard-copy paper-based/mylar-based markups, 8 percent used paperless image-based scanned markups, 59 percent used PDF-based markups, and 24 percent used/piloted digital object-based model methods.

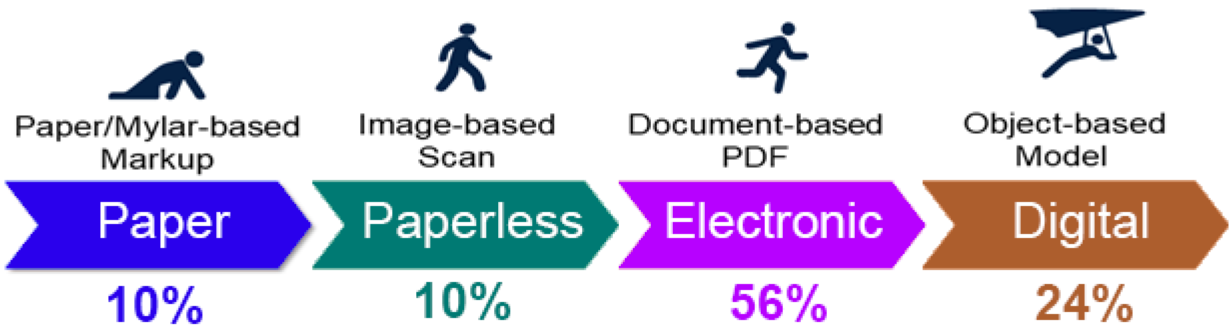

Figure 2-1. State DOT primary as-built methods state of practice research (2021–2022).

A key focus of the 2020–2023 research was on connecting project delivery design from construction to asset management O&M for transportation facilities lifecycle information management, and the DAB was established as a key link from the PIM to the AIM for State DOTs.

The 2020–2023 research identified the benefits/opportunities of transitioning to DABs:

- Streamlines digital workflows and dataflows.
- Connects business area silos within the organization.
- Integrates and links 2D/3D model data and production.
- Offers scalable digital data delivery for lifecycle use.
- Provides a CDE that allow better access for decision-making.
- Improves quantities delivery (estimates/pay).
- Offers a living record that enhances updating with post-construction data collection.
- Has the potential to reduce costs, shorten schedules, and reduce claims and risks.

These benefits are described in more detail in Section 2.5.

The research also identified barriers to overcome in the transition:

- Executive support and champions.
- Digital processes, policies, and practices.
- Agency resources and funding.
- Technical training for the workforce.
- Enterprise integration and interoperability of software applications/platforms.
- CDE and Intelligent Construction Technologies (ICT) for cloud/hybrid technologies.
- Data standards, legacy data integration, and governance.
- Change management to implementation.

More information about the barriers is provided in Section 2.6.

State DOTs highlighted the following needs that are key to making the transition to DABs:

- Digital delivery strategic and tactical plans.
- Digital processes, policies, and best practices.
- Data standards, framework, and governance.
- Advanced survey data collection tools.
- Advanced CAD-GIS-survey modeling tools.
- Cloud-based and hybrid on-premises technologies.
- Funding for the paradigm shift to digital transformation.

Additional information about State DOT practices is presented in the case study briefs and webinar recordings from the EDC-6 DABs initiative.

Finally, State DOTs and others making the transition to DABs identified gaps in the transition:

- Technology solutions tailored to agency needs.
- Integrations with applications/platforms.
- Field and automated solutions.
- Data connecting to legacy and database systems.
- Data governance and schema needs.
- Open data standards and architecture.
- Federated CDE databases.

2.2 Stakeholders Involved in Delivering DABs

Numerous stakeholders are involved in advancing DABs, both internally across the State DOT and externally (e.g., contractors and consultants). The traditional as-built delivery process from markup plans previously involved construction resident engineers, inspectors, surveyors, and contractors. With a model-based process to deliver DABs, stakeholders are expanded to include designers, surveyors, construction staff, inspectors, maintenance staff, operations staff, asset managers, planners, information technology staff, consultants/subconsultants, contractors/subcontractors, and industry technology solution providers/vendors. Delivering and advancing DABs involves integrating staff from the delivery phases, including programming and planning, survey and environmental, preliminary and final design, bidding and construction, maintenance and operations, and asset and facilities management.

2.3 Developing, Capturing, Preserving and Updating DABs

The DABs process begins by establishing information requirements. As a first step, an agency needs to determine the information about a highway facility's lifecycle that needs to be captured and recorded in the DAB. This information includes asset attributes, contract administration data, and construction-related changes and deviations. Guided by the digital delivery strategic plan and implementation roadmap, the agency develops a prioritized list of use cases for which data requirements are developed. Finally, the requirements are formalized in a policy, practice, and specifications document. The agency then develops data collection templates for assets of interest, either standalone templates (e.g., spreadsheets or fillable documents), or as a part of a digital design model. Key asset data include: bridges, roads, pavements, drainage, retaining/noise walls, sign bridges, geotechnical foundations, alignments/center lines, ROW, lighting, traffic signals, ITS, ATMS, traffic barriers (guardrails/guiderails), signs, rumble strips, pavement marking, sidewalks, curb ramps/ADA compliance, surfaces, landscaping, aboveground and subsurface utilities, and facilities/buildings. The agency proceeds with the design phase, producing either 2D plan sets, digital models for informational purposes, or digital models as legal documents.

Data collection also becomes an essential part of the construction phase. Resident construction engineers, inspectors, surveyors, and contractors collect, field-verify, and validate asset data. Because DABs are asset-centric, various tools are used to capture as-constructed information and asset class data (e.g., surveys, inspection daily reports, quality assurance/quality control [QA/QC] tests) and incorporate them in inventories and databases for upstream and downstream users.

Survey hardware and software tools for field verifying assets include: global navigation satellite system (GNSS) rovers, Light Detection and Ranging (LiDAR)-static terrestrial/mobile/uncrewed aerial systems (UAS), mobile devices, handheld survey devices, and robotics total stations in conjunction with electronic PDF editing tools. Bluebeam/Adobe, Esri collector, Infotech Mobile Inspector, and CAD are more frequently used than traditional survey methods of level/rod, wheel/measuring tape, and manual inspection supplementing aerial photogrammetry.

The data, which are georeferenced to state plane coordinate/geodetic systems with projections, are exchangeable and can be readily migrated and extracted from various survey, CAD design, construction, GIS, and asset management systems (AMS). Further changes to as-constructed data are updated from maintenance, operations, design, and survey and asset management statewide survey LiDAR data collection, making them useful for mining by an extract, transform, and load (ETL) process.

Upon project handoff, the extracted as-built data, including geospatial and asset-specific data, can be leveraged to support various use cases, particularly for asset management. At a minimum, agencies use this information to build an asset inventory for asset management and federal reporting purposes. This inventory serves as a comprehensive record of all assets, including location, asset-specific details, and condition data for forecasting future needs, capital planning, and federal reporting (e.g., Highway Performance Monitoring System [HPMS], Model Inventory of Roadway Elements [MIRE], and National Bridge Inventory [NBI]).

2.4 Data Management for DABs and Digital Delivery

As-built data have been and are still frequently stored as paper, scans, or PDF markups in file cabinets or electronically in non-integrated data systems where data are neither readily accessible nor extractable. The data sets for as-built data are often locked in disconnected functional area or legacy system data silos. DABs overcome these shortcomings by introducing a more efficient and effective approach to managing as-built data.

Digital data for DAB assets are collected, inspected/survey verified, preserved, and updated primarily in databases and preferably in structured sequential query language (SQL) databases and stored in cloud and hybrid on-premises/cloud data repositories.

When implementing DABs, several key considerations should be considered:

- Information Requirements: It is necessary to define what data needs to be collected. This includes identifying the necessary data elements and their attributes to meet the data requirements for PIM and AIM.
- Understanding Data Types: The collected data may come in many forms, including structured, semi-structured, and unstructured data. Understanding these data types is essential for effective data collection, storage, and utilization.
- Data Standards: Implementing data standards ensures that the collected data is consistent, high-quality, and usable.
- Interoperability: Enabling data to be more interchangeable, integrated, and interoperable is essential for converting and exchanging data between different file types and schemas to enable their use across various systems and applications.
- Shared Repository: A shared repository, such as a CDE, is vital for managing the collected data. It provides a centralized platform for the collecting, inspecting, verifying, preserving data in a manner that improves its accessibility and use.

2.4.1 Digital Data

The digital data of assets within a DAB exist in various formats:

- Structured Data: This refers to data that are well organized as defined in a schema. These data are typically stored in relational databases (e.g., SQL databases), where they are organized into tables with predefined keys, rows, columns, rules, and relationships.
- Semi-Structured Data: Semi-structured data are a form of data that have some level of organization. They contain tags or metadata that provide a level of structure, but the data are not as well structured as they are using a predefined schema. A flexible schema can accommodate varied data types and structures. Examples of semi-structured data include XML (eXtensible Markup Language) documents and JSON (JavaScript Object Notation) files.
- Unstructured Data: Unstructured data refers to data that do not have a predefined model or are not organized in a predefined manner. These data are often free-form and cannot be easily categorized or structured into tables or schemas. Examples of unstructured data include text documents, images, sensor data, and videos. Unstructured data are typically stored in large files and often require conversions from raster (grid cell or pixels, 3D image clouds) to vector (points, lines, polygons/areas, 3D point clouds), machine to text, and streaming dynamic real-time to static data.

In addition, metadata are necessary for all data formats to provide additional information, such as the file type, keywords, geolocation and data last updated, for improving the organization, searchability, and usability of the data.

Data for DABs often reside in proprietary applications. Example of such databases include Bentley and Autodesk for CAD data and Trimble, Topcon, Leica, and CAE applications for survey data. The proprietary databases have their own unique structures and formats for data, which makes exchanging data between two different applications challenging. Middleware (e.g., Safe Software Feature Manipulation Engine [FME], Esri Data Interoperability Extension) and application programming interfaces (APIs) or connectors are often required to enable data exchange between different databases, applications, or systems.

Middleware facilitates data validation and/or conversion to another format. APIs set the rules for how different software applications should interact with each other, while connectors transform the data into a format for further processing. For instance, the digital model is enhanced with tagged attributes and metadata and often exported in an XML format to a GIS system directly using APIs. Together, they facilitate data exchange across different data structures and formats.

Data standards for information exchanges are key for interoperability from PIM to AIM involving DABs. Open source data standards, including international and Construction Specifications Institute and national standards make data more interchangeable, integrated, and interoperable. Relevant data standards, guidance, and specifications related to as-builts and DABs including FHWA, AASHTO, and the U.S. Army Corps of Engineers.

2.4.2 Common Data Environment

A CDE is an agreed-upon common source of information in a shared data environment from multiple sources for a program/project/enterprise. It facilitates collaboration among multidisciplinary teams by allowing them to collect, disseminate, exchange, evaluate, and manage from each information container (a structured set of data that represents a specific component of an asset or facility) through a managed process. CDE technology platforms host and manage various types of data that are collected throughout the lifecycle of a facility. They typically include all forms of data—geospatial, nonspatial, graphical, nongraphical, structured, semi-structured, unstructured data, open, and proprietary data.

The most commonly used CDE platforms are grouped as follows:

Model-based BIM collaboration platforms: Supporting graphical, geometric, parametric, geospatial data, nongraphical attributes, documentation data, and metadata. Examples include Bentley ProjectWise, Autodesk Construction Cloud/BIM 360, and Trimble Quadri/Trimble Business Center.

Geospatial data management and analysis platforms: Supporting graphical, geometric, geospatial data, nongraphical attributes, documentation data, and metadata data integration, aggregation, and analysis. Examples include Esri ArcGIS Online ArcGIS Pro/Desktop, ArcGIS Portal, and Enterprise Spatial Data Engine (SDE).

Data visualization and business intelligence platforms: Used primarily for nongraphical attribute/documentation data and metadata. Examples include Microsoft SharePoint, ProjectSolve, and Power BI.

Document and content management platforms: These platforms are primarily enterprise electronic document management systems (eDMS) and/or enterprise content services (ECS). They are typically used to manage and store project data, including as-builts, and usually are found on State DOT local area networks. Examples include Infotech DocExpress, Falcon DMS, Hummingbird, Box Enterprise, Highland OnBase, and Interchange.

Other platforms, including AMS databases and legacy Oracle database management systems, are also used.

Various CDE platforms have applications that are compliant with open data standard formats and ISO 19650 compliance. They may use middleware for data ETL and interoperability, such as Safe Software FME, Esri Data Interoperability Extension, or various connectors and APIs. In addition to on-premises information technology and communication (ITC) services, cloud and hybrid ITC services are typically used because CDEs use cloud infrastructure and platform as a service (IaaS/PaaS) services (e.g., Amazon Web Services, Microsoft Azure, Google Cloud, IBM Cloud) for connected data.

For model-based DABs, State DOTs are transitioning to and/or supplementing their enterprise data storage with CDEs (primarily at a project level); however, most State DOTs are still using enterprise eDMS to store their as-builts as 2D PDFs and maintaining a separate CAD/BIM database for model-based 2D/3D data, including parametric data. Additionally, most State DOTs have advanced their data from survey and CAD/BIM data to GIS systems while newer AMS supplement legacy AMS systems primarily in a 2D environment. Many State DOTs also lack comprehensive data dictionaries, attributes, and metadata but are looking to migrate to 3D GIS (e.g., ArcGIS Pro, enterprise SDE). Numerous State DOTs want to keep data in on-premises client-server systems and in other in-house systems; however, hybrid on-premises and connected CDEs are continually being advanced.

2.5 Key Benefits and Opportunities in Implementing DABs

Traditional as-builts are “marked up” plan sets that document deviations from the original plans and changes made during the construction process. They include 2D paper markups, image-based scans, and PDFs where changes made during construction were electronically redlined. Their primary purpose is to serve as final and detailed documentation of how a project was built. While traditional paper-based as-builts have fulfilled their basic purpose, DABs offer a new way of thinking about, doing, and using as-builts over the project lifecycle.

As noted above in the Forward and in Section 1.2 of this document, DABs leverage digital technologies to serve a broader range of purposes. The data-rich digital models enable agencies to make data-driven decisions relating to asset management, operations, maintenance, capital planning, traffic, and safety. This expanded purpose and need facilitate the adoption of a “digital twin” model-based approach to enable comprehensive data integration and management over the lifecycle of assets.

DABs serve as information repositories that store a wealth of high-granularity data unique to a specific project or the assets they comprise. DABs can facilitate the collection and integration of various types of data from different sources in various formats (structured, semi-structured, or unstructured). They encode a variety of asset-related information, such as material types, quality, and quantities, in addition to spatial information. This high-value information provides a comprehensive representation of the built infrastructure and serves as a key information management link, digitally connecting project and asset information throughout the entire project lifecycle.

The encoding of this high-value information in various digital formats enhances data accessibility and retrieval efficiency. These models can be updated and expanded to include the O&M updates throughout the asset lifecycle. Stored in a CDE in standardized formats, DAB data promotes interoperability and efficient data sharing among different systems and platforms. This facilitates easy extraction, transformation, and loading of data among various software applications and systems for further analysis and use.

Lastly, DABs benefit all stakeholders involved in the project lifecycle, from designers to asset managers, as everyone can access and use the data they need. The single source of truth, continued updates, accessibility, and shareability of the DAB data enable better collaboration and communication among stakeholders, which improves the overall efficiency of data management in the project lifecycle.

From State DOT surveys and web conference interviews involving as-builts in research, State DOTs observed the following major benefits and opportunities by implementing DABs:

- Improved lifecycle information management across all phases of the enterprise.

- Streamlined project delivery, repeatable processes, and efficiencies for construction/inspection staff, survey verification, and improved pay quantities to contractors.
- Improved, updated, and real-time data accessibility for better data-driven decision-making with data analytics for lifecycle capital planning, scoping, and O&M scheduling and work.
- Improved quality, accuracy, and reliability of assets inventory, geospatial location, and management.
- Improved and integrated advanced model-based tools/technologies/applications for design, survey and e-construction, maintenance, operations, and AMS/GIS.
- Improved enterprise cloud-based/hybrid CDE.
- Improved disciplinary data across the enterprise for data management, asset attributing, data mining, and extractable data.
- Reduced rework and reduced time spent searching for data and identified opportunities to leverage digital data for new purposes.
- Enhanced safety with reduced exposures and work zone safety for workforce and public and reduced risks.

As reported by the State DOTs, the top benefits and opportunities derived from moving to DABs were: processes, standards, and workflows (48 percent); followed by tools, technologies, and data (42 percent); and trained experienced staff/resources (10 percent).

2.6 Key Barriers and Challenges in Implementing DABs

From State DOT surveys and web conference interviews involving as-builts in research, major barriers/challenges and gaps encountered by State DOT to overcome in implementing DABs included:

- Lack of best practices guidance, data standards, clear policies/procedures, specifications, and contracts.
- Lack of asset lifecycle data governance/data governance plans, digital delivery strategic plans, and tactical plans.
- Lack of agency innovation, adapting to change/culture change, and collaboration in business functional areas.
- Lack of software interoperability/incompatibility and integrations for digital project delivery and lack of vendor technical support.
- Lack of information and geospatial survey, design, construction, and asset management tools/technologies.
- Lack of enterprise systems technologies/tools, cloud access, and CDE systems.
- Shortage of technical and experienced staff and training.

- Lack of available agency resources/funding, tangible cost-benefits, and management support.

The top identified barriers and gaps were: lack of processes, standards, and workflows (49.7 percent); followed by lack of tools, technologies, and data (27 percent); shortages of experienced staff and training (13.2 percent); and lack of funding/resources (10.1 percent).

2.7 The Transition to DABs

Implementation approaches, methods, and strategies for advancing DABs and digital delivery varied by State DOT and fall into two main categories: (1) Simplified Digital Workflows, and (2) Integrated Lifecycle Digital Workflow. Digital delivery and advancing DABs within a digital delivery framework affect all functional areas, delivery phases, and stakeholders at an agency, including external consultants, contractors, and other associated agencies. Strategies for short- and long-term success to advance digital delivery and DABs require agencies to evaluate everything from workflows and processes to staff capabilities and skills to resources and funding. Agencies getting started in transitioning to DABs and digital delivery employed various top-down and bottom-up approaches, including expert project delivery and asset management delivery teams, multidisciplinary functional areas, and change management strategies. Chapter 3 outlines key innovative and common best practices by State DOTs from the research, and Chapter 4 summarizes implementation strategies, change management strategies, capability maturity self-assessment evaluation/critical success factors, and best practices to enable interested agencies to transition to and advance DABs and digital delivery.

2.8 DAB Implementation Methods

This Getting Started Guide is focused on the two primary methodologies for deploying DAB processes: the Simplified Digital Workflow and the Integrated Lifecycle Digital Workflow, both of which are discussed in further detail in Chapter 3.

The Simplified Digital Workflow separates the normal design process and data collection into electronic format, with upstream phases involved in defining requirements, and downstream phases tasked with integrating information generated during construction. This approach is suited for simple to moderately complex projects with fewer assets and assets with less complexity.

The Integrated Lifecycle Digital Workflow employs information modeling and electronic processes to comprehensively transfer information across different project phases. Particularly suited for projects involving plan production, this approach emphasizes object-based data modeling, which organizes information into defined sections resembling building blocks to represent real-world entities or concepts. This structured approach facilitates the management and utilization of data throughout the project lifecycle in a structured and easily comprehensible manner.

2.9 DAB Use Cases

State DOTs are using or piloting five key essential/primary DAB use cases:

- 2D/3D models streamline the construction workflow through preconstruction visualization, early conflict detection, and design conformity checks. For example, New York State DOT (NYSDOT) uses 3D CAD models and digital data to communicate project details, such as saved views, thereby reducing the need for formal information requests. These models are also used to confirm elevations with GPS and enable clash detection with underground utilities to facilitate early conflict resolution.
- DABs streamline field surveys, verify field quantities, link pay items, and validate asset attributes during construction. Connecticut DOT embeds two types of data attributes into the CAD model: pay item related attributes (e.g., the item number, bid quantity, and total installed units), and asset-specific attributes (e.g., item description and model type). These attributes are verified, updated, or supplemented by construction field inspection. The verified quantities, which are linked to pay items, are used for payment processing.
- The system provides precise geospatial positioning of assets, both subsurface and aboveground, for use in various business applications throughout the asset's lifecycle. For example, Colorado DOT (CDOT) captures accurate geospatial information of subsurface utilities during the preliminary design phase. This information is subsequently integrated with digital design models to detect potential utility conflicts, and CDOT identifies mitigation strategies to minimize them. Furthermore, the agency records the as-constructed locations of these utilities in DABs, which then serve as the system of record for future utility work throughout their lifecycles.
- The DAB model, with its verified data and geospatial locations, is documented into the system of record, serving as a reliable data source for future reference during the O&M phase. Minnesota DOT requires contractors to collect and submit as-built data using data collection templates for various asset classes, which includes asset type attributes, location data, and/or redlined plans. Agency staff then further review these accepted as-built data,, process them, and integrate them into the agency's asset management system of record.
- Once integrated, the geospatial and asset data can be exchanged for future project planning, design, and asset management. Utah DOT integrates geospatial and asset data collected from field surveys and a propriety form-based field data collection application into the agency's enterprise database.

Five advanced/future DAB use cases are being piloted or are used that are outside the scope of this Getting Started Guide. These use cases include:

1. Update as-constructed model data with post-construction survey, LiDAR, and imagery data.

2. Link model data with inspection daily report, material certification, e-ticketing, and QA/QC test data.

3. Link model data with construction automated machine guidance (AMG)/automated machine control, intelligent compaction, subsurface utility engineering (SUE), geophysical ground penetrating radar, electromagnetic location (EML) survey, and horizontal directional drilling data.

4. Link model data with construction real-time asset monitoring sensors, internet-of-things, artificial intelligence, and machine learning data.

5. Link model data with conditions assessment, hazards and emergency response/repair data.

3. IMPLEMENTING DIGITAL AS-BUILTS: GETTING STARTED METHODS AND WORKFLOWS

Implementing DABs requires a systematic approach that involves addressing key requirements such as establishing strategic and technical working groups, undertaking process improvements, determining data and technology requirements, and engaging stakeholders. Meeting these requirements enables agencies to formulate effective workflows for DAB implementation.

State DOTs employ a range of practices that vary significantly based on their specific needs and capabilities. Despite the diversity, these practices can be broadly categorized into two main workflows: the Simplified Lifecycle Digital Workflow and the Integrated Digital Workflow. Both workflows aim to develop DABs, but they differ in their complexity and integration of design and data collection processes.

The Simplified Digital Workflow is a straightforward approach that separates the design process from the data collection process, which is undertaken using data templates during the construction phase. The Simplified Digital Workflow stands in contrast to the Integrated Digital Workflow, a more comprehensive approach that intertwines the design process and data collection, making asset data a core component of the digital design model. In both workflows, these as-built data are then transferred to information systems or to an enterprise data warehouse during the handover to the O&M phase for throughout the asset's lifecycle.

3.1 Simplified Digital Workflow

The Simplified Digital Workflow is suited for simple to moderately complex projects with fewer assets and assets with less complexity. In this workflow, after determining what data need to be collected, a data collection template is created for field data collection during construction. During the design phase, the agency proceeds with the normal design process, producing either 2D plan sets or models as legal documents. Asset data collection becomes an essential part of the construction phase, with construction inspectors or contractors collecting asset-specific data using data collection templates and documenting changes and any deviations from tolerances in the field. In the O&M phase, the information transferred from construction can be used and updated, creating dynamic, up-to-date recorded asset information throughout the asset's lifecycle.

Primary steps in the Simplified Digital Workflow include:

- Develop requirements to establish a clear understanding of the information needed throughout the asset's lifecycle. These information types can typically be grouped into four categories:
  - Asset information requirements.
  - Project information requirements.
  - Organization information requirements.
  - Exchange information requirements.

- Create data collection templates (in spreadsheet or fillable document format) for use by field inspection staff or contractors to facilitate efficient data in the field.
- Develop design files, similar to the traditional as-built approach. By separating data collection from the design model, the State DOT can opt for developing standard plans either 2D PDF or advanced 3D models, along with other design documents.
- Define contract requirements for 2D and 3D as-built plans as well as additional data collection needs in the construction procurement documents.
- Facilitate communication. Initiate communication during the preconstruction meeting to discuss the needs and challenges of meeting the contractual requirements relating to DABs to achieve buy-in from the contractor.
- Conduct field inspections to inspect the quality of materials and workmanship, measure and document pay quantities, record asset installation locations, maintain accurate records of construction activities, and ensure compliance.
- Record changes in the 2D plans using redlining or incorporate any changes into the 3D models after construction is complete to establish a system of record. If specified in the contract, the contractor can often provide DAB information more readily. However, the owner may need to ensure data accuracy through QA checks.
- Close-out the project by reviewing the markups and asset data submittals from the prior step. Once the change is reviewed and confirmed, the DABs can be accepted.
- Exchange asset-specific data from the completed data collection templates to an enterprise data warehouse for subsequent post-processing, reconciliation, quality checks, attribution, and integration into the system of record.
- Engage in periodic surveys during the O&M phase of the facility to update records throughout the asset's lifecycle.

Figure 3-1 provides a schematic flow diagram for the simplified workflow.

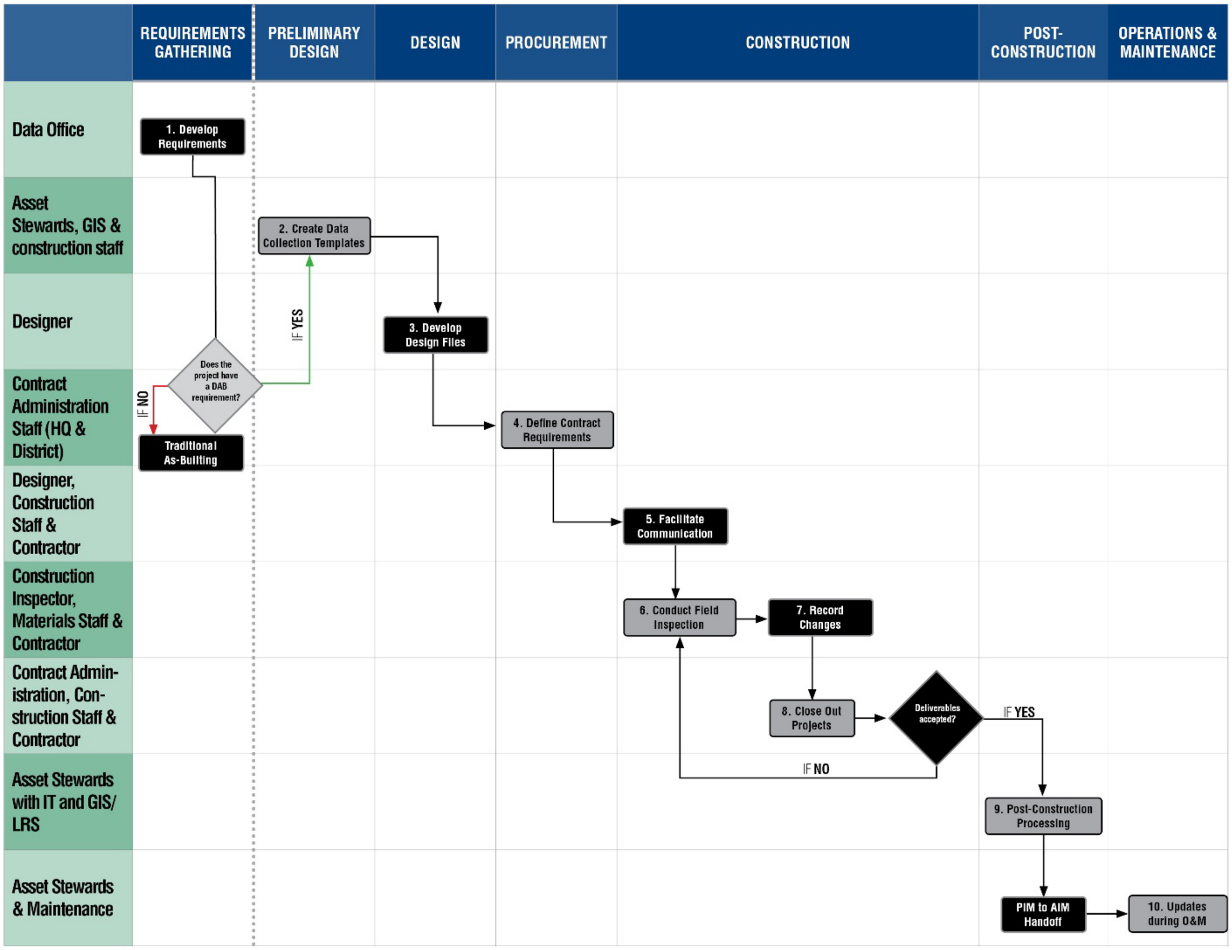

Figure 3-1. Simplified Workflow for DABs.

The adoption of a Simplified Digital Workflow for DAB development represents a significant advancement in modernizing project delivery processes within the construction industry. By streamlining data collection, enhancing communication, and facilitating real-time updates, this approach offers numerous benefits, including improved accuracy, reduced information loss, and enhanced project transparency. Moreover, the use of digital tools and standardized templates empowers stakeholders to effectively manage as-built information, leading to more informed decision-making and optimized asset management practices. As organizations continue to embrace digital transformation initiatives, the implementation of simplified digital workflows for DABs will undoubtedly play a pivotal role in driving efficiency, cost-effectiveness, and overall project success in the construction sector.

A detailed description of the Simplified Digital Workflow is provided in the *Guide for Digital As-Builts—Using Simplified Digital Workflows*, a companion document product produced as part of the EDC-6 Digital As-Builts Initiative. Two case studies following the Simplified Digital Workflow are described below.

3.1.1 Minnesota Department of Transportation Case Example

The Minnesota Department of Transportation (MnDOT) has developed digital delivery initiatives, model-based deployments, and as-built workflows triggered to meet key transportation business needs from an asset management approach in alignment with its Transportation Asset Management Plan (TAMP).

For MnDOT, the purpose of as-builts is to better enable planning, scoping, and maintenance by obtaining as-constructed data involving priority transportation facilities asset classes with the following objectives:

- Tracking assets owned within the MnDOT ROW.
- Geospatially locating assets.
- Using valuable data for planning, scoping, and design.
- Monitoring and inspecting the condition of the assets.
- Establishing the cost to maintain, inspect, and replace assets.
- Establishing the optimum maintenance, rehabilitation, and replacement schedules.
- Establishing strategies to lower risk and lifecycle costs.

Since 2011, MnDOT has required contractors to collect as-built data collection during construction, as outlined in a special provision (SPV) in its construction contracts. These data, which include geospatial information and asset inventory details for various asset classes, are used to populate an agency GIS database and enterprise systems. The SPV provides detailed specifications for over 13 asset types and mandates varying levels of location accuracy depending on the asset class (MnDOT, n.d.). Inspectors coordinate with contractors to verify and document asset data in the field, which are then submitted to the agency. Final payment is dependent on the agency's approval of the submitted data.

MnDOT developed an eight-step process for as-builts statewide and for its Metro District.

1. Project specifications – as-built inclusion.
2. Project letting.
3. Tracking as-built requirements in Microsoft Excel/Microsoft Access database.
4. As-built coordination – early stage communication.
5. As-built review for ancillary assets, rumble strips, pavement messages).
6. As-built coordination – communication nexus for construction and subject matter experts.
7. Project close-out.
8. Post-processing and import to system of record.

Over the last decade, MnDOT has advanced DAB processes and construction as-built data to GIS, maintenance, and enterprise AMS based on:

- Agency organization, project/program, and asset management information requirements (organization/owner information requirements, program information requirements, and asset information requirements).
- The as-built data collection approach during construction that was expanded by including a MnDOT SPV in construction contracts for contractors to collect geolocated information and provide asset inventory information for various asset classes to populate an agency-maintained GIS database repository and enterprise systems for downstream uses.
- Pavement asset class by automated data collection to data management using their agency pavement management system (PMS).
- Bridge asset class by national bridge inspection standards, AASHTO and agency requirements data collection to data management using their agency bridge management system (BMS).
- Ancillary asset classes including drainage, geotechnical systems, facility sites, lighting systems, noise walls, traffic barriers, rumble strips, pavement message systems, signal systems, signing and traffic management systems (TMS) by field data collection and verification during construction primarily by Contractor staffs using the MnDOT as-built SPV specification with e-construction mobile devices/applications and survey methods including handheld GPS survey devices, GNSS rovers and total stations to agency GIS database and AMS.

A key use case was to geospatially track priority assets. MnDOT initially started with 12 to 15 key priority assets for as-builts and has expanded to more than 78 asset classes. As part of a statewide LiDAR survey completed in 2017 to collect barrier data, as-built data were collected for the 12 priority asset classes to provide supplemental surface asset features baseline scans. These data were uploaded to TAMS. Statewide post-construction LiDAR mass data collection is proposed for subsequent data collections. Asset class information regarding subsurface underground asset features within the ROW are collected during construction.

After data are collected and received from contractor, they are converted and generated to SHP format for GIS, TXT for Logs and DGN for CAD, and by API automation to Oracle DB-TAMS, KMZ-Google Earth and DGN-CAD.

In addition to required as-built markup plans, the as-built SPV specification was generated in 2011 and is required for all eight districts since 2015 with current use in nearly all projects within the Minneapolis-St. Paul metropolitan area district and approximately half of the projects involving the other Minnesota districts. As-built requirements for assets describe asset class, data collection method, deliverable, data format, descriptive attributes and location information. The location of the specified assets requires geolocation to a geographic coordinate system and projection. Asset location accuracies required vary per asset class with higher survey-grade accuracy at sub-foot horizontal and +/- 0.1 foot vertical or better collected in the field for bridges, drainage and geotechnical assets, pond/basin bathymetry 0.5 foot contours and +/- 3 foot sub-meter for mapping-grade accuracy for facility site, lighting system, noise wall, traffic barrier, rumble strip, pavement message system, signal system, signing and TMS assets. Inspectors are required to coordinate with the contractor involving field verification, location and documenting asset data and submit required information per the as-built specification prior to the agency issuing of final payment.

For MnDOT, as-built asset classes that have been incorporated include pavement in its PMS, bridge structures in its BMS, and ancillary asset classes in its TAMS including:

- Data for the Tier 1 pavement asset class are defined by data formats required by the MnDOT PMS Oracle HPMA including automated machine and imagery data collected.
- Tier 1 bridges asset class are defined by data formats required by the national bridge inspection standards, AASHTO and MnDOT requirements using MnDOT BMS SIMS BrM DRIM/AssetWise (formerly Inspect Tech) including inspection text, spreadsheet CSV, Excel, PDF and photo images data.
- Ancillary assets data are defined by the MnDOT standard specification for as-built data collection with typical data formats of text, CSV, spreadsheet Excel (MS XLS), database (MS Access) and photo images data (see MnDOT As-Built specification).
- An Esri GIS platform is used as a geospatial repository for as-built data and the GIS data dictionary and metadata are under development for various ancillary structure asset classes.

3.1.2 Pennsylvania Department of Transportation Case Example

In 2020, the Pennsylvania Department of Transportation (PennDOT) embarked on a journey to redefine how highway and bridge projects are delivered in the Commonwealth. The Digital Delivery Directive 2025 five-year initiative was developed to transform PennDOT from a traditional 2D plan-centric environment to a full model-based digital project delivery environment, where the model becomes the single source of truth. In the five-year strategic roadmap, PennDOT developed activities and a timeline for planning, developing, and adopting the processes, standards, and technologies to enable digital delivery. Three major goals guided the strategic roadmap activities:

- Implement 3D technology.
- Advance the use of accessible digital processes and tools.
- Capture data-rich-asset models.

The digital technology associated with using digital models on a construction site created an opportunity to reform the as-built record documentation. Instead of marking up PDF plans, contractors collected digital as-built records that were format-ready for PennDOT's maintenance and asset management business systems to receive the information they need.

PennDOT's existing as-built practices are redlined paper markup plans, which are scanned and stored in PennDOT's electronic record document system. Various as-built records are redlined electronically using Adobe applications, but this is not the norm. PennDOT instituted paperless administration of contractual documents and construction inspection in 2003. PennDOT uses the Engineering and Construction Management System (ECMS) as its system of record for the project delivery process. PennDOT produces 2D plan sets, which are uploaded to ECMS. Contractors download contract documents to prepare their bids and submit their bids electronically through ECMS. Once a contract is executed, the ECMS continues to serve as the system of record for the project. ECMS is the backbone of many e-construction applications used by district construction personnel to administer the project. Construction applications with connection to ECMS include:

- PennDOT Project Collaboration Center (PPCC) –used during construction to access active project documents, including 2D plans.
- ECS – used as the archival system of project documents after close-out.
- Construction Document System (CDSv3) – used by field personnel to document project inspection, such as project site activities and contractor payments.
- Electronic Construction and Materials Management System (eCAMMS) – used to input and track key information about materials, such as samples and mix designs.

In addition, PennDOT developed a suite of mobile applications for Apple iOS. Construction personnel use these applications in the field to retrieve or input information from and to PennDOT computer systems. At the conclusion of a project, the Inspector in Charge provides all project records, including the final as-built plans showing construction field changes not shown on the original contract drawings, to the District's Finals Unit. The District's Finals Units upload all project records, including as-built plans to ECMS. *The as-built plans may be prepared by the contractor or PennDOT construction personnel and are delivered as PDF files via PPCC. The current process requires that all changes to the original contract plans are made with a red pen on printed sets (in which case are then scanned to PDF) or shown as markups on a PDF file. Electronic markups may be completed using any PDF editor available to the contractor.* PennDOT currently uses Adobe products. One of the challenges with the current process is that to retrieve as-built data, the user needs to know the ECMS project number, which can make it difficult to access information.

The Roadway Management System (RMS) is PennDOT's primary asset inventory system containing state-owned highway network information related to roadway features, conditions, and characteristics. The RMS is a legacy database that contains location referencing, pavement history, condition data, traffic information, and other administrative and inventory data. PennDOT collects data for one-quarter of the state-owned network on an annual basis for guide rail inventory and condition to update the information in the RMS. This information is used for decision-making, monitoring the performance of guide rail and end treatments, accessing future requirements, and allocating maintenance funds to county organizations. However, guide rail maintenance activities, such as repairs, replacements, and upgrades occur daily. Therefore, PennDOT created a mobile application to help maintenance crews enter information about the guide rail systems on via a GIS survey form (ArcGIS Mobile Collector/Field Maps). The information collected is automatically pushed to RMS in a text file format. In addition to survey data, photos can uploaded to the system. All survey data and photos may be accessed via ArcGIS Online and Maintenance IQ, which is a PennDOT custom GIS application. Bridge information is stored in the Bridge Management System 2 database or BMS2. BMS2 is a custom database that houses current and historical inspection data, as well as various plans and notes. PennDOT has also deployed the Infrastructure Asset Management System (IAM), which is a shareware solution. The IAM has been configured for bridges and pavements to produce future condition forecasting for PennDOT.

The pilot project process for DABs include: (1) identify pilot projects; (2) develop a special provision for data collection; (3) develop DAB data collection information requirements; (4) select an appropriate data collection method (e.g., spreadsheet, GIS form, or GPS survey codes); (5) conduct preconstruction meetings with pilot project contractors; (6) conduct pilot project; (7) collect feedback; and (8) create plan for transferring the data to PennDOT systems. Pennsylvania DOT selected five projects involving one asset class (guiderail upgrades/repairs) over 66 miles for its DAB pilots, which were completed in the 2021 construction season.

PennDOT developed a special provision to provide guidance for collecting and submitting guide rail digital inventory information for a select number of pilot projects. This provision lists the information requirements for the contractor to provide to PennDOT after construction, including general information, asset location, installation details, asset identification and properties, and inspection details. The measurement and payment for this pay item was set to DOLLAR and the project management team tracked the actual work being performed via a Force Account. The PennDOT Force Account permitted the contractor and subcontractors to document the actual day to day work performed under an extra work item where the work was to be paid on a Force Account basis. The Inspector in Charge recorded the daily actual labor usage and equipment usage to collect the guide rail as-built asset data. A Guide Rail and Barrier As-Built Information Requirements spreadsheet was developed for contractors to log as-built information for guide rail and barrier assets. The tools and software to collect the as-built data were not identified as part of the pilot project process. This allowed the contractors to use their own means and methods to collect the information needed for the spreadsheet. Geospatial coordinates were determined to be collected every 50 feet with curve placement at the beginning and ending of each curve. A 2D/3D CAD or GIS model was not required, as the spreadsheet became the information model to be imported to GIS. The requirements spreadsheet contained the following categories information using pick lists or key-in entry:

- Asset Location
- Installation Details
- Asset Identification and Properties
- Inspection Details.

The as-built data required by PennDOT during construction from PIM to AIM involving data collection and data handover linked to asset management fulfills: purpose (specific information needs), content (geometric graphical, nongraphical attribute and metadata information), form (how and when information is presented and delivered) and format (how information is encoded) for DAB use.

Pennsylvania DOT is a DOT transitioning to digital model-based 2D/3D CAD/BIM digital delivery, and the DAB pilot initiative was the first digital as-built data collected by contractors using an as-built SPV involving guiderail assets. The SPV specification was developed to provide an as-built asset specification for guide rails to the contractors which used Esri collector or other survey methods at +/- 3' accuracy. Data will be field collected and provided for use in conjunction with their data dictionary.

Gaps in DABs and digital delivery for PennDOT include:

- Construction as-built data may be imported to Esri GIS but may not readily import to ECMS as the system of record and RMS as the PennDOT's primary asset inventory system.
- Maintenance IQ/Guide Rail Mobile application will need to include additional fields currently not being collected and managed by the RMS and Maintenance IQ database.
- Bentley OpenRoads Designer (ORD) will need workspace geometric properties and attributes to incorporate guiderail as-built data.
- Digital delivery interim guidelines for model-based processes have been developed along with software tools/technologies and standards (e.g., model element breakdown-MEB) being piloted.

3.2 Integrated Lifecycle Digital Workflow

Instead of relying on simple data templates, as described above, the Integrated Lifecycle Digital Workflow adopts a comprehensive, more automated, and object-based data modeling approach to achieve the core objectives of DABs. This workflow is particularly suited for complex projects. Essentially, the integrated workflow intertwines, or integrates, the design process and data collection, and makes asset data a core component of the digital data-centric design model.

In this workflow, the design process and data collection are closely linked, with asset data being a key part of the digital design model from the start. The design model is organized into "objects" that represent physical features, such as a bridge, a road segment, or a traffic sign. Each object contains detailed information about that asset.

During the preliminary design phase, asset data in the proposed project area are extracted and enriched. This involves extracting data from enterprise systems and enhancing them with survey data. Subsequently, during the design phase, additional intelligence is incorporated into the asset information to facilitate field data collection and identify instruction-related information such as pay items. Attributes are created to document any field changes for potential reconciliation.

During construction, inspectors use digital tools to access the design model in the field. They can add more asset details, record any changes, and automatically track quantities for payment. At the end of construction, the design model is updated with all the as-built information. Finally, in the post-construction phase, the DAB pay item is settled, ensuring that all contained information complies with the contract requirements. When the project is handed over to O&M, all the asset data, including location, is transferred to the agency's information systems, where it can be updated and used throughout the asset's lifecycle.

Primary steps in the Integrated Lifecycle Digital Workflow are described below.

- Develop specifications for capturing and providing as-built data to fulfill diverse information requirements including the creation of as-built markups, materials quality records, quantity assessments, asset management, maintenance, and more. These requirements align with the standards outlined in ISO 19650 and may encompass organizational needs, data exchange specifications, or project-specific asset information requirements.
- Extract asset data from the enterprise systems.
- Conduct additional survey to provide accurate measurements and locations of features to support design and construction inspection.
- Develop design plans to communicate the project's design requirements.
- Detail the contract requirements for DAB deliverables and identify any additional survey and data collection needs.
- Initiate communication during preconstruction to discuss the needs and challenges of meeting the contractual requirements relating to DABs.
- Prepare for field data collection by converting the data from CAD models into a format suitable for location-based data collection.
- Conduct field data collection to verify and incorporate as-built conditions in the digital design models.
- Reconcile any deviations in the field-recorded data.
- Enrich the asset data model by incorporating findings from inspections and surveys.
- Update the design model to a complete clean digital model to incorporate changes that occurred during construction.
- Close-out the project by reviewing the markups and asset data submittals and recording changes resulting from construction. Once the record change is reviewed and confirmed, the DAB deliverables are accepted.
- Exchange asset-specific data from DABs to an enterprise data warehouse for further post-processing, reconciliation, quality checks, additional attribution, and integration into systems of record.
- Engage in periodic surveys during the O&M phase of the facility to update records throughout the asset's lifecycle.

Figure 3-2 provides a schematic flow diagram for the integrated workflow.

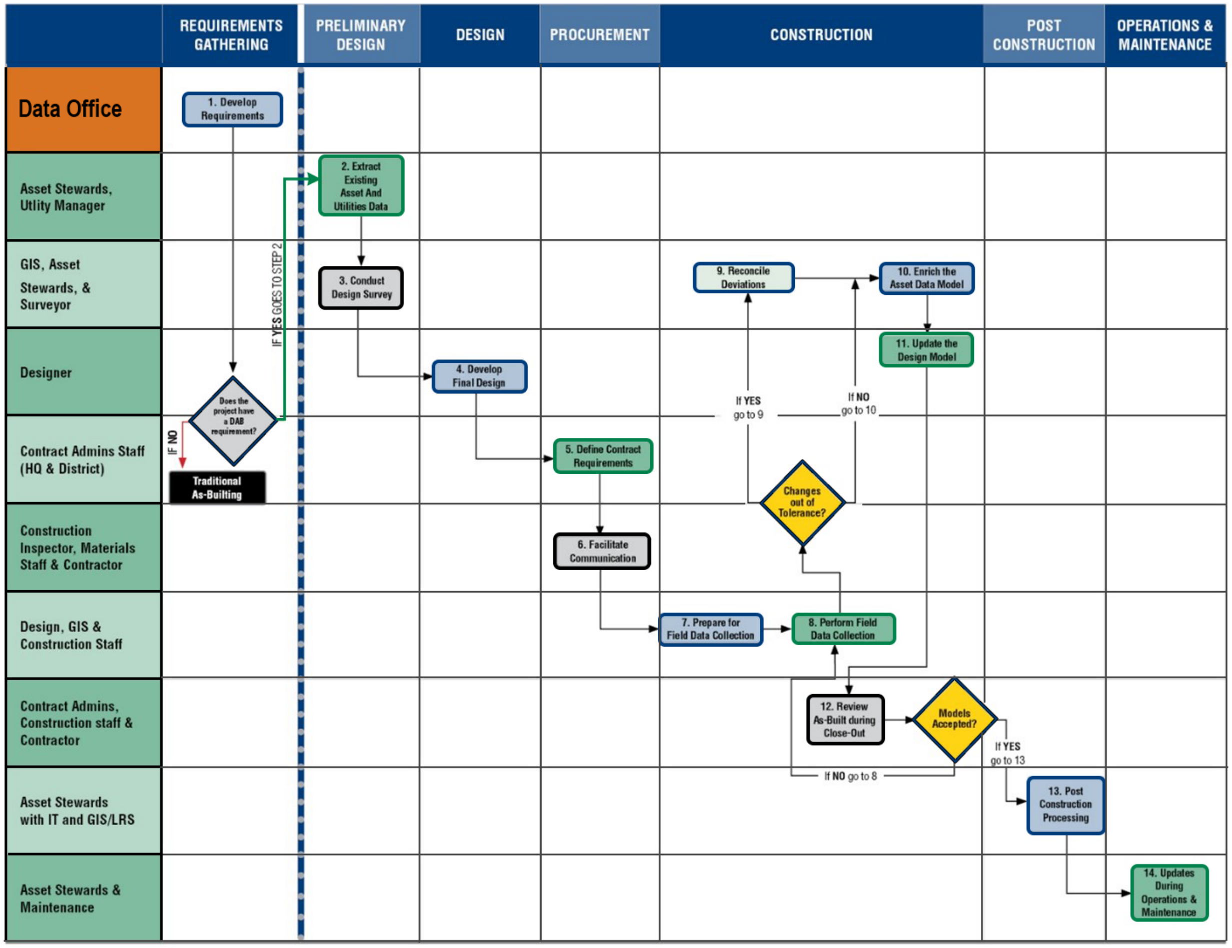

Figure 3-2. Integrated Workflow for DABs.

The Integrated Lifecycle Digital Workflow presents a comprehensive, more automated, and object-based approach to project management, bridging the gap between different phases seamlessly. By leveraging sophisticated data intelligence and modeling techniques, this workflow ensures the smooth transfer of information from design to construction and beyond, enhancing project efficiency and accuracy. With an emphasis on object-based data modeling and structured information management, the integrated workflow facilitates informed decision-making and supports ongoing O&M activities.

Object-based data modeling allows for a more precise and detailed representation of the project at each phase, facilitating seamless data sharing between phases. For example, in highway projects, object-based data models can represent various infrastructure assets such as pavement sections, bridges, culverts, signs, and guardrails. Each object can contain detailed information about its location, geometry, material properties, installation date, and maintenance history. Structured information management ensures that data are organized and accessible, which is essential for transitioning from traditional paper or file-based models to more integrated, digital models. Overall, the Integrated Lifecycle Digital Workflow represents a forward-looking strategy to optimize project outcomes and maximize asset lifecycle management.

A detailed description of the Integrated Lifecycle Digital Workflow is provided in the *Guide for Digital As-Builts—Using Integrated Digital Workflows*, a companion document. Two case studies using the Integrated Lifecycle Digital Workflow are described below.

3.2.1 Colorado Department of Transportation

Colorado stands as the pioneering state in the nation to require a SUE survey at the preconstruction stage of a project to address a crucial gap in the construction process. The lack of reliable information about the underground utility locations during the design phase of civil engineering projects, such as highways and pipelines, has been a significant challenge. Colorado has taken a proactive approach by enacting and implementing legislation and regulations that revolutionize the acquisition of underground infrastructure location data for public civil engineering projects throughout the state.

To strengthen the foundation of utility safety measures and foster heightened accountability, CDOT formulated and upholds a set of comprehensive goals pertaining to data standards. These objectives are meticulously designed to govern the accurate and efficient management of utility information throughout the lifecycle of civil engineering projects. The agency goals are outlined as follows:

- Having attribute data about each utility enables more efficient and productive coordination with utility owners.
- Knowing the location and depth of utilities enables designers to change designs to avoid costly utility relocation and delays in project delivery.
- During construction, contractors can pull up mapping systems that accurately display the location and depth of the utilities, so the utilities can be avoided and delays prevented.
- The ability to store data in a single platform can minimize the cost of data collection on future projects.

Process Flow

The integration of a centralized repository, Transparent Earth, facilitates the seamless collection, consolidation, and sharing of 3D multi-utility data within CDOT. CDOT's permitting process mandates utility company participation through the OneCall Center, ensuring comprehensive and updated data within the repository. Existing location requests are strategically leveraged to guarantee ongoing updates to Transparent Earth. This dynamic system harnesses data from diverse sources such as surveys, SUE, CAD, GIS, utility relocations, new installations, and OneCall locates. The cohesive utilization of PointMan and Transparent Earth enhances data integration, providing a comprehensive and real-time understanding of the utility landscape for effective decision-making and infrastructure management.

Data Submitters and Data Users

Data submitters and users encompass entities such as the DOT, SUE teams, utility companies, and designers within the infrastructure management framework. The initiation of data collection follows established protocols, with data submitters undertaking the responsibility of uploading information onto the central PointMan Enterprise repository. This uploaded data encompasses survey data, SUE data, GIS data, and CAD files. The seamless collaboration between PointMan and Transparent Earth is pivotal for data users who leverage this cohesive system to access and use the 3D utility data securely. This encompasses utility relocation, new installations, OneCall Locates, and upcoming projects. The ongoing data collection by data submitters adheres to standard protocols, ensuring a continuous influx of information into the cloud. Concurrently, data users are tasked with responsibly accessing and using the utility data through the secure 3D utility data access interface.

Data

Within the CDOT SUE data lifecycle, adherence to ASCE 38 standards is paramount across planning phase, 0–30 percent design phase, and 30–90 percent design phase. In the planning phase, as-built data from the database is collected and assessed, serving as a foundation for planning and SUE records in proposals. The 0–30 percent design phase mandates Engineering Design SUE Quality Levels B, C, and D (as defined by ASCE 38-02), with updates to existing utility data in the database, emphasizing the importance of Quality Level B for the 10 percent design goal. Progressing to the 30–90 percent design phase, SUE data become instrumental in engineering design, incorporating Quality Level A test hole data for 3D conflict analysis. As the project advances, the 90–100 percent design phase and construction phase necessitate compliance with Construction Management ASCE 75 standards. This phase involves final engineering design, early utility relocations, ongoing updates to the Subsurface Utility Map (SUM), and concurrent construction management and as-built survey activities. The construction phase focuses on construction management and as-built survey, allowing for the real-time updating of as-built data into the SUM. Throughout this lifecycle, utility coordination remains a pivotal aspect, ensuring seamless integration and accuracy across the subsurface utility data spectrum.

CDOT employs a data dictionary architecture that serves as the convergence point between survey and GIS functionalities. The survey systems use coding systems established by surveyors, ensuring a standardized approach. Utility systems, spanning telephone, gas, sewer, and others, have a unique code assigned to each utility system. The unique code can be applied in MicroStation for streamlined integration. The seamless transition from survey to the GIS environment incorporates customized attributes such as material, facility, owner, size, type, depth, note, and feature code. This dynamic integration, facilitated by the cloud, allows for real-time visibility of changes in the field, enhancing adaptability and convenience. Additionally, this system is optimized for use on mobile devices, providing a versatile and accessible platform for field operations. CDOT used the data dictionary schema to collect improved accuracies for geospatial XY and Z depth are collected on a single platform for stakeout and mapping directly/indirectly of surface/subsurface assets that includes utilities, geotechnical, and materials testing.

Tools and Technologies

CDOT employs an innovative suite of tools and technologies to enhance the accuracy and efficiency of its utility management processes. At the forefront is the PointMan mobile application, seamlessly integrated with Trimble R10/R12 devices, ensuring precision in utility relocation and as-built data within the narrow tolerances mandated by the agency—achieving horizontal and vertical accuracy of plus or minus 2 centimeters and meeting ground coordinate corrections between 0.06-feet horizontal and 0.16-feet vertical. The acquisition of multi-utility data is facilitated through GNSS real-time kinematic (RTK) surveys using mobile devices. These data, enriched with attributes, permits, survey pedigree, and custom form information, are consolidated and shared through the central PointMan Enterprise repository. In addition, CDOT uses Prostar PointMan's Software as a Service application for utilities. This is seamlessly integrated with Bentley ORD/MicroStation, Esri GIS, and AWS Cloud Services. The license management system meticulously regulates roles and permissions, ensuring that utility companies have access to their specific data while maintaining security and confidentiality. CDOT has also embraced Trimble RTX services, offering satellite-based solutions for enhanced accuracy. Prostar PointMan, functioning as a real-time mobile application, is instrumental in tandem with survey GNSS/GPS RTK rovers, handheld devices, and smartphones. It facilitates survey corrections for the seamless transition of data between CAD to GIS, GIS export to CAD, and projections, further streamlining CDOT's utility management operations.

CDOT Utility Engineering Project Lifecycle

The CDOT engineering lifecycle commences with planning. During the design phase, CDOT strategically uses ASCE 38-32, the SUE standard, mandated by Colorado Revised Statute 9-102.68 for a majority of projects. As project planning starts, the scope of work is evaluated to decide whether it is a SUE project. As the project advances to the 10 percent design phase, a high-quality set of SUE data is meticulously gathered, serving as the foundational utility data throughout the project's entirety. This robust SUE dataset proves instrumental in conflict resolution, test hole operations, and capturing 3D attributes at Quality Level A between 30 percent and 60 percent of the design process. Progressing to the 90 percent design phase, early utility relocations and redline activities leverage Construction ASCE 75-22, the as-built standard. This comprehensive approach continues into roadway construction, relocation activities during construction, and the subsequent operation and maintenance period, looping back into the planning stages for the next lifecycle project. CDOT consistently employs ASCE 38-22 and ASCE 75-22 throughout the entire lifecycle. Moreover, the integration of utility coordination efforts within this data capture framework is crucial.

Planning and Preliminary Design (10 Percent)

During the planning phase of the engineering lifecycle, CDOT implements a thorough data acquisition strategy. This involves the extraction of data from existing as-builts, where a comprehensive analysis of historical infrastructure documentation is conducted. Employing traditional survey techniques, UAS, or mobile applications, CDOT ensures a diverse and comprehensive approach to data collection. This phase adheres rigorously to the standards outlined by ASCE 38-22, ensuring a consistent and precise data collection process. Essential attributes are meticulously captured, encompassing details such as the type, size, condition, and material of subsurface utilities. The gathered data are meticulously collected and subsequently published to the GIS database, laying a robust foundation for informed decision-making throughout the project's lifecycle. As the project progresses into the 10 percent design phase, CDOT gathers a high-quality set of SUE data. This dataset becomes the foundational utility data throughout the project, proving instrumental in conflict resolution, test hole operations, and the detailed capturing of 3D attributes at Quality Level A, spanning the critical design phases between 30 percent and 60 percent of the project's development.

Design (30, 60, and 90 Percent)

In the design phase, spanning 30 percent, 60 percent, and 90 percent of the engineering lifecycle, CDOT employs a comprehensive approach to ensure precision and efficiency. The process begins with the export of data from the GIS to CADD platforms, facilitating seamless integration for designers' use. Field verification, conducted through test holes, further enhances the accuracy of the collected data. CDOT strategically leverages this dataset for clash detection, identifying potential conflicts that require resolution. The identification of conflicts informs the relocation strategy, ensuring that utilities are relocated before the construction phase commences. This process culminates in the delivery of final design deliverables tailored for construction, thereby laying the groundwork for a streamlined and conflict-free implementation phase. CDOT's proactive approach, incorporating field verification and clash detection, ensures that potential challenges are identified and addressed well in advance, contributing to the overall success and efficiency of the process.

Construction

During the construction phase, CDOT ensures that critical SUE information is readily available to construction inspectors, fostering informed decision-making. This phase is marked by construction observation records, including visual documentation through pictures and videos.

A notable illustration of CDOT's success in utility management is evident in the $1.2 billion I-70 Design-Build project in Denver. This initiative, which commenced in 2015 and is expected to conclude in 2023, employed advanced e-construction and surveying methods with PointMan in 2018. The I-70 Design-Build project used advanced e-construction and advanced surveying methods to collect model-based as-built utilities data to relocate utilities prior to construction and during construction to deliver the project and provide utilities asset information within the ROW for design, construction, and asset management use. Moreover, the I-70 Design-Build project demonstrated substantial cost avoidance, with an estimated return on investment ranging from $800,000 to over $4 million, with Kiewit and Kraemer contractors adopting this method for utilities tracking. The comprehensive utility digital processes, including model-based relocation and as-built data collection, were integral in delivering the project and furnishing utilities asset information within the ROW. Inadequate utility records increase project risk to cost, schedule and public safety, which was reduced as compared to previous projects by capturing and recording standardized utility data at the time of installation and systematically recording the data on existing utilities exposed during construction.

A specific example within the project highlighted the relocation of fiber optics in the transformation from signalized off-ramps to roundabouts, showcasing utility attribute, permit, and survey pedigree data. This model-based approach not only documented 88,000 potholes for utilities using PointMan, but also recorded 850 linear feet of utilities per acre. The resulting benefits encompassed enhanced production efficiencies, reduced delays, proactive damage prevention, mitigated risks, improved inventory tracking, and the establishment of a comprehensive utilities map.

Operations and Maintenance Phase

Throughout the O&M phase, continuous updates of digital as-built records for subsurface utilities are promptly integrated into the PointMan Enterprise dashboard in real-time. This dynamic integration facilitates detailed visualization, QA/QC, and seamless data export into CAD for design, construction, and model record as-builts. Notably, professional certification is not mandatory for utility contractor as-built submissions; instead, reliance on metadata provides essential "pedigree" information, confirming accuracy through equipment type and survey accuracy data akin to traditional survey notes. The ASCE 75-22 guidelines include accuracy requirements, serving as a valuable communication tool for conveying precision information to various stakeholders. CDOT's strategic approach enables construction field and office personnel to harness data from diverse sources within PointMan and PointMan Enterprise. This integration empowers PointMan Enterprise to stream remote online SUE files, encompassing existing and new utilities, CDOT designs, drone imagery, and OneCall excavation notifications directly to the PointMan mobile app at the project site. This comprehensive utility asset visualization, geolocation, mapping, and documentation process enhances overall project management efficiency.

Challenges

CDOT has faced challenges, particularly pushback from utility companies, in enforcing the mandated requirement for permits with accurate geospatial location/depth for utilities using the PointMan system. Initially, utility companies resisted the CDOT specification code. But after some initial friction, they eventually complied with the permit requirements. In the legislative landscape, Colorado encountered pushback regarding utility requirements, with concerns raised by utility companies related to homeland security and proprietary data. However, investigations by agency attorneys revealed that these concerns did not apply to utilities within the CDOT ROW, except for critical infrastructure. While certain areas have critical infrastructure, the majority of utilities fall outside this category. To address this, CDOT implemented a permitting system, requiring utilities within the CDOT ROW to adhere to specific permits and specifications. This ensures that CDOT is informed when critical infrastructure enters or exits the ROW. The agency previously relied on licensed surveyors for certifying as-builts, but due to practical challenges, this process has been revised to maintain consistency in data, storage location, and equipment/process standards for utility data collection and verification. Despite initial resistance, CDOT has encountered pushback from utility location companies, consultants, and contractors due to liability concerns related to depth accuracy by utility locators. However, the permitting process within CDOT's ROW necessitates compliance with this procedure.

Lessons Learned

CDOT's adoption of advanced utility data practices have yielded numerous benefits, emphasizing the importance of incorporating these lessons into future projects. The advantages include streamlining utility relocation timelines, enabling effective clash detection, and significantly reducing project schedule overruns and associated costs. Real-time mapping and data sharing have proven instrumental in avoiding damages, providing a dynamic and accessible resource for preconstruction design considerations. Moreover, the reuse of survey data enhances project efficiency and contributes to the overall success of infrastructure endeavors. In addition, having access to detailed information such as Elevation, Northing, and Easting simplifies utility data stakeout processes and ensures precision and accuracy in on-site implementations.

One crucial realization is that private utility company owners comprehend the contractual dynamics operating between the agency and the utility owner within the ROW. Recognizing this relationship enables the sharing of 3D data among various stakeholders, including design and engineering teams, fostering collaboration, and improving interactions with utility entities. This collaborative strategy results in the creation of more comprehensive records, supporting enhanced design processes through better-recorded information. It is essential to note that this sharing practice primarily serves internal collaboration purposes and is not outward facing to the public. These lessons underscore the importance of transparency, collaboration, and data-sharing practices in the successful implementation of subsurface utility programs.

CDOT's as-constructed program extends its focus beyond pavements and bridges, placing a primary emphasis on model-based utilities within the ROW. This expansion reflects a forward-thinking approach, recognizing the importance of incorporating utilities comprehensively within the project scope. This broader perspective enhances the overall project understanding, providing a more complete representation of the infrastructure landscape.

Moreover, the implementation of DABs should go beyond subsurface utilities, incorporating aboveground utilities into the program. Recognizing the significance of seamlessly managing both subsurface and aboveground assets ensures a holistic approach to infrastructure management. This lesson emphasizes the importance of considering all utility elements for a comprehensive and accurate representation.

CDOT's experience underscores the importance of standardization in the DAB implementation process. The development and adherence to standardized procedures contribute to the efficiency, consistency, and reliability of utility data management. Establishing clear guidelines ensures that the entire project team, including utility companies, follows a uniform and effective approach, minimizing discrepancies and enhancing overall project outcomes.

3.2.2 Iowa Department of Transportation

Iowa DOT’s overarching goal is to advance the use of digital data to establish a unified source of truth so that every user can access and use information for decisions related to each lifecycle phase of a facility or asset. The agency envisions a future state where seamless data handoffs are the norm to incorporate geospatial information and harness the potential of available technologies. To achieve this vision, the agency has strategically employed a fourfold approach: (1) using 3D models to develop project models that can serve as legal documents; (2) expanding data collection to enrich the digital models; (3) leveraging various existing and new technologies, including Masterworks and e-Ticketing, to support specific business functions; and (4) developing and implementing data-management processes to streamline data flow and ensure effective communication among various systems.

Iowa DOT undertook two pilot projects to showcase the implementation of DAB projects to promote a broader understanding among contractors of the advantages of employing 3D models directly at construction sites. The first pilot project, the I-80/I-380 Interchange Reconstruction

Project, used 3D BIM models as the deliverable for constructing the ramp bridges. The second pilot project, the US 30 Roadway Project in Benton County, employed digital models as part of its project delivery.

Iowa DOT's primary objective for the two pilot projects was to develop a comprehensive BIM model that thoroughly examined the risks and opportunities within the bridge group. Both pilot projects departed from the conventional approach of using plans for contractor submittals, opting instead to submit and use models as legal documents. Actively using the BIM model at the construction site allowed Iowa DOT and its contractors to perform real-time updates to capture essential information, including both design modifications and non-model-based data. Iowa DOT retained a consultant with sufficient expertise to make changes to the 3D BIM model to add in the as-built additional asset attributes ascertained during the construction process. Given that changes to the bridge design model require approval from the Engineer of Record, this process provided the necessary policy compliance and removed the burden from the contractor to understand the design tools. Consequently, comprehensive database housing design details and asset-related information were established and consistently maintained post-construction to serve as a valuable resource for future endeavors.

Furthermore, the pilot projects assessed the feasibility and benefits of incorporating many technology-based solutions within the context of digital delivery initiatives and laid the foundation for achieving the objectives outlined in Iowa DOT's SPDD Roadmap.

I-80/I-380 Interchange Reconstruction Project

The I-80/I-380 Interchange Reconstruction Project in Johnson County began in 2017 and was completed in late 2020. This reconstruction project entailed the design and construction of three bridges: Ramp B Bridge, Ramp BH Bridge, and Ramp H Bridge. The project adopted a hybrid approach in collaboration with the local associated general contractors. A 3D BIM model was developed and delivered as a legal document for the Ramp B Bridge, (a three-span steel plate girder bridge). A combination of BIM model information and 2D plans were provided for the Ramp BH Bridge and Ramp H Bridge. The BIM model for these bridges was provided for informational purposes only and was not a part of the model as legal deliverable pilot.

The digital model that was developed serves as a supplementary component to the bridge design contract and aligns with Iowa DOT's initiative to test and extend the capabilities of Bentley's BIM software. The 3D BIM model for the Ramp B Bridge was digitally sealed using a special provision. Throughout the project's duration, the project design team used Bentley Software, including OpenBridge Modeler, ProStructures, and Navigator Connects. OpenBridge Modeler was used to define the primary elements of the bridge model, including the bridge deck, girders, and substructure elements. ProStructures was then employed to incorporate granular details into the model, while Navigator Connect served as the visualization tool.

To ensure accessibility for contractors in the field, the project design team initially attempted to employ a free software tool to view the design model. However, due to the limitations of the free model viewer, the contractor ended up purchasing Bentley View software. Bentley View software promoted contractor engagement and effectively reduced associated risks throughout the project's construction phase. Furthermore, there was active coordination with contractors to maximize the utility of these models during the construction phase to gain insights into the advantages and challenges associated with contractor engagement in BIM use.

One notable benefit of using digital submittals and the BIM model was the ability to continuously update BIM models during construction. These updates encompassed vital information such as pier elevations, disc bearings, and anchor bolts. Moreover, non-model-based data, including shop drawings, requests for information, photos, and material certifications, were integrated into the model. SYNCHRO, a collaborative digital construction solution for real-time project data, modeling, and performance analyses, was actively tested on this project. However, the standardization of the non-proprietary IFC format is still pending, and the conversion process may lead to potential data loss.

Iowa DOT used OpenRoads Designer to create DABs. The 3D models within OpenRoads Designer incorporate elements with underlying intelligent information and feature links to PDF and Excel summaries. Each as-built Excel worksheet includes embedded PDF documents, accessible through Excel cell links. These PDF documents contain links that direct users to various files, such as material certifications, boring logs, submittals, requests for information, construction photos, special provisions, developmental information, soil profiles, profile sheets, and other pertinent as-built details. Nevertheless, securing the appropriate technology for the pilot projects presents a challenge in the context of DABs. Discrepancies have become more pronounced when the model has been exported to different applications. Consequently, the exploration and procurement of diverse technologies might prove challenging, particularly when the design project is under a tight timeframe.

US 30 Roadway Project in Benton City

The US 30 Roadway Project in Benton County began in 2021. This project, a proposed four-lane expansion of 7 miles of concrete paving in Benton County, includes two bridges, boxed culverts, and stream mitigation. Iowa DOT employed a combination of traditional plans and digital modeling, and conducted photo scanning of the as-built construction model for the project.

Although a digital model was provided, the contractor expressed the need for plan and profile sheets. However, contractors generated cross sections using SYNCHRO during construction. Consequently, this model as legal document pilot project only provided the final model, plans, and profile sheets in PDF for contractors.

Key lessons learned from this pilot project include recognizing the importance of initiating early conversations with stakeholders and collaborating closely with software vendors. While it was evident that construction staff recognized the value of digital models in certain aspects, field inspectors encountered challenges in effectively navigating the tools.

Challenges

Iowa DOT experienced several challenges related to data collection and management, use of tools and technologies, and technology adoption. Notable points are as follows:

- Digital tools were generally effective; however, because no single comprehensive suite of software applications was available to support the DAB process, field users experienced several challenges:
    - Certain tools are designed for specific purposes, necessitating the use of multiple tools. For instance, OpenBridge Modeler was used to generate digital models with a low level of design detail granularity. ProStructures was then used to augment these models with additional data, such as rebar details.
    - Field inspectors potentially faced accessibility and integration problems due to software compatibility issues.
    - Handling multiple tools in the field for information retrieval was a challenge.
    - Sharing detailed models with contractors and field inspectors was challenging due to licensing and software capabilities.
- Technology Adoption Challenge: Inconsistent adoption of technology into the GIS platform across different disciplines in the agency, with a 50 to 60 percent adoption rate, contributed to disparities in workflow efficiencies and data-management practices.
- Challenges in Achieving Process Standardization: It was difficult to achieve uniform design details across all districts for effective 3D model introduction, including georeferencing in CAD files.
- Need for Standardized Protocols and Guidelines: The development of standardized digital delivery protocols was time consuming because it represented a significant shift from the current system.
- Personnel-related Challenges: The lack of a dedicated team, resource limitations, and insufficient CAD training among staff hindered digital delivery adoption.
- Missing Georeference Data Despite CAD Standards: Challenges in asset management data persisted because CAD files lacked georeferencing. Despite rigorous standards for CAD files, design files often lacked georeferencing and required manual digitization, which increased the risk of errors.
- Lack of Data Governance Plan: The absence of a formalized data governance plan exacerbated these challenges, hindering seamless integration into the system. The agency plans to check design files for georeferencing and make this a standard process. Iowa DOT has a complete asset data repository for digital integration, but this also poses challenges.
    - 2D and 3D GIS data: Assessing if future GIS databases can handle CAD survey, 3D survey, 2D GIS, and 3D data together without data loss during transfer.
    - Survey data: Handling large unstructured files such as Demographic Transition Model surfaces, LiDAR point clouds was difficult; and merging them with other data formats was complex.
    - Legacy data: Converting LandXML format for alignments at Iowa DOT and DXF file format for 3D line strings to an open or usable format was challenging.

- IFC or open data future: IFC is still under development. Iowa DOT identified a need for information exchange requirements for asset classes, which was addressed by project mapping.

- Training and Development: Significant investments are needed in training and development, especially for non-CAD users.
- Communication and Feedback: Clear channels and robust mechanisms are vital to address challenges effectively.
- Continuous Efforts: Coordinated efforts with a focus on training are key for successful digital adoption and improved collaboration.

To address these issues, Iowa DOT is actively standardizing data collection, particularly in construction, and improving georeferencing in CAD files. The agency has created a new digital delivery subcommittee to guide these improvements. Furthermore, Iowa DOT has been investigating emerging technologies, including vGIS and OnStation, to support its DAB processes. The agency also is reassessing its workflow and data governance policies to establish data repositories and data-management procedures to effectively collect, store, and integrate data. The integration of GIS maps and e-Ticketing information on platforms like OnStation allows users to efficiently locate project-related plans and correlate data from various sources. This enhances collaboration by sharing information through an enterprise GIS portal. Additionally, Iowa DOT is exploring vGIS, an augmented reality platform that enables field users to visualize 3D models on mobile devices, providing a detailed view of project features on a map.

Lessons Learned

Effective engagement with stakeholders, the construction team, and a software vendor is always pivotal for the successful implementation of DABs.

In the context of Iowa DOT's I-80/I-380 Interchange Reconstruction Project, a notable advantage is the ability to repeatedly access the model for visualization purposes. This capability enables the swift retrieval of on-site information directly from the model, bypassing the need to involve designers when the information is not readily available on 2D plans. The dynamic nature of the model, which is updated during the construction phase, further enhances its utility.

Nonetheless, the two pilot projects highlighted the challenges in leveraging existing tools and technologies for DABs (e.g., licensing, software incompatibilities, and limited capabilities) and the emerging applications of newer tools for visualization, mapping, and integration purposes. Collaborating with a software vendor could alleviate the challenges associated with software adoption.

Contractors were generally receptive to embracing new technologies; however, they found it challenging to handle several tools for information access and their lack of proficiency with CAD software was a contributing factor. Consequently, the technology adoption rate has been uneven across Iowa DOT. Contractors require comprehensive training to adapt themselves to this new routine. Integrating the construction data with the GIS data also posed challenges. The issues including fragmented processes; inconsistencies in entering georeferencing data in design files; and poor quality of field data collected by field inspectors emphasized the importance of developing data standards, implementing data governance, and training.

Strategic planning plays a critical role in facilitating the transition from electronic to digital workflows. While strategic plans have guided Iowa DOT's steady and significant progress to date, the agency could benefit from establishing a dedicated digital delivery team and enterprise project lead, adequate staffing resources, and effective change management measures, such as training.

4. IMPLEMENTATION STRATEGIES, CAPABILITY MATURITY, AND CRITICAL SUCCESS FACTORS TO ADVANCE DIGITAL AS-BUILTS

4.1 Implementation Strategies

As noted in Chapter 2, the research team observed State DOTs using two primary implementation workflows to advance DABs.

- Simplified Digital Workflow
- Integrated Lifecycle Digital Workflow

The choice of workflows depends on various factors, including the complexity of the project, the agency's commitment to 3D design, the agency's technological capabilities, and other important foundational elements and drivers. For example, some State DOTs, like Minnesota, are driven by their TAMP and asset management needs, while others, such as Colorado and Iowa, are motivated more by their design processes.

4.2 Change Management Strategies

Key steps to aid State DOTs to transition to, advance, and implement DABs and digital delivery include:

- Work with senior management, functional area practitioners and champions, and information technology staff to set up digital delivery and data governance collaborative steering committees and workgroups and identify benefits/costs, barriers/gaps to overcome, and outcomes/performance goals.
- Identify key priority assets needed for DAB data collection, storage, and use across agency enterprise phases for lifecycle asset inventories.
- Identify priority asset data requirements needed (graphical-geometric-parametric/geospatial data, nongraphical attribute/documentation data, and metadata).
- Identify processes, methods, specifications, standards, schemas, and policies needed and implement changes at the agency.
- Collaborate and communicate with external stakeholders (consultants, contractors, and technology service providers) for process and workflow improvements.
- Identify needed tools, technologies, applications, and platforms to deliver, store, and update model-based DABs and partner with internal information technology staff to set up, procure as needed, and deploy.
- Develop a digital delivery strategic workplan, implementation tactical plans, program delivery plans, data governance plan, and communication/training plan.
- Implement pilot projects for early successes with lessons learned for adopting improvements.

- Establish funding and resources internally or external grants if needed for delivery (e.g., FHWA State Transportation Innovation Council [STIC], Accelerated Innovation Deployment [AID], Smart Grant and Advanced Digital Construction Management Systems [ADCMS]).
- Implement programs and projects regionally and statewide and adopt lessons learned for continuous improvement.

4.3 Capability Maturity/Critical Success Factors

State DOTs approach the transition to DABs and advancing digital delivery initiatives from multiple different starting points, and implementation requires them to evaluate their systems and staffing as they prepare for the transition. Agencies can evaluate their readiness to advance DABs and digital delivery initiatives by completing a capability maturity self-assessment evaluation tool (CMM) described below. The CMM is a companion EDC-6 DAB document, developed to assist agencies with charting a strategic and tactical roadmap to implementation.

The self-assessment evaluates six components using different metrics, and agencies can use the results of the evaluation to place themselves on continuum of crawl, walk, run, or fly. The parenthetical notes next to each factor provide a mapping to one or more of the four key implementation areas: people, process/workflow, tools/technology, and data. This crosswalk helps to illustrate how each component contributes to the overall digital transformation. The components are:

1. Awareness
    - Context awareness around DABs and how they fit within the larger context of BIM (people, process/workflow)
    - Specific awareness (people)
    - Performance awareness and application (people, process/workflow)
2. Systems and Programs that Support Digital As-Builting
    - Research and development (process/workflow, tools/technology, data)
    - Pilot programs (people, process/workflow, tools/technology, data)
    - Institutional knowledge of management systems (people, process/workflow)
    - Ease of funding access (people, process/workflow, tools/technology, data)
    - Legal and regulatory challenges (process/workflow, tools/technology, data)
    - Software systems, applications, and tools (tools/technology)
    - Hardware devices and technology (tools/technology)
3. Culture and Organization that Supports Innovations Such as DABs
    - Leadership support, collaboration, and teamwork (people, process/workflow)
    - Support from internal partners (people, process/workflow)
    - Organizational barriers (people, process/workflow)
    - Risk-reward response (people, process/workflow)
4. Innovation and Supportive Staff

- Staff capacity (people)
- Knowledge acquisition and sustainability (people, process/workflow)

5. External Collaboration
    - Interaction with construction sector stakeholders (people, process/workflow)
    - Communication beyond the transportation community (people, process/workflow)
6. Software Systems, Hardware Systems, Data Modeling, and Exchange
    - Information requirements (process/workflow, data)
    - Data standards (data)
    - Data modeling and quality (process/workflow, data)
    - Data interoperability, integration (process/workflow, tools/technology, data)
    - Data use (process/workflow, data)

5. GLOSSARY

Asset Information Model (AIM) —A model that contains information to support the management and operation of the asset.

Common data environment (CDE)—A CDE is a centralized environment that allows for the collection, storage, collaborative editing, review, approval, sharing, and dissemination of digital data models. In typical practice, a CDE is designed and built to share information during the design and construction phases of a project, but ideally the contents of the CDE should not be limited to assets or objects created in a BIM or CAD environment. The models and documentation stored in the CDE can include both geometric and nongeometric information about assets from all of the asset lifecycle phases.

Data management—Data management encompasses defining data, creating data architecture, modeling data, collecting or gathering data, processing data, storing and securing data, ensuring the quality of data, defining reference data, documenting metadata, ensuring data integration and interoperability, performing document and content management, designing and implementing data-warehousing solutions, and maintaining business intelligence.

Data/information models—Data/information models are used to represent the structure of and relationships among data elements in a way that describes the real-world. Data elements refer to the geometric or nongeometric attributes or properties of highway infrastructure assets. The dimensionality of a data/ information model determines the type of asset data captured in the model. Two- or three-dimensional models contain data elements representing an asset's design and geometry in two or three dimensions, four-dimensional models contain data elements describing construction and maintenance scheduling for an asset, five-dimensional models contain data elements providing detailed quantity and cost information about an asset and its components, six-dimensional models contain data elements associated with the lifecycle of an asset and its components, and so on.

Data transformation—Data transformation is a data- management activity involving changing a data model using a certain object-type library (OTL) and a certain set of terms and definitions into a different data model using a different OTL and a different set of terms and definitions.

Digital Twin—a digital representation of a physical object, process or service.

Digitalization—Digitalization involves creating a digital version of an analog or physical thing, such as a paper document, microfilm image, photograph, or sound. Digitalization's purpose is to create systems of record or engagement. Digitalized business operations, business functions, business models and processes, and business activities have been enabled, improved, transformed by leveraging digital technologies and broadly used and contextualized digitized data, and turned into actionable knowledge, with a specific benefit in mind. Automation is a large part of creating digitalized processes.

Digitization—Digitization involves managing data and information, such as text, pictures, graphics, and tables, in a digital format for easy processing by a computer.

Extract, transform, load/extract, load, transform (ETL/ELT)—ETL is a data-management activity involving extracting data from a system, transforming the data from the format used by the source-system object model to the format used by the target-system object model, and loading the data into the target system. Sometimes the data are transformed after they have been loaded into the target system. In such cases, the term ELT is used to describe the data-processing operation.

Federated-information models—A federated- information model describes an information model consisting of connected but distinct individual information models. Federation refers to a scenario in which a group of systems and networks operates in a standard, collective, and connected environment.

Federation involves establishing a central unit for integrating various disconnected entities (i.e., software systems, databases, or applications) within an enterprise. The central unit ensures the internal autonomy of the constituent systems is maintained and that these systems do not have to be integrated directly with each other to exchange information. For example, a federated-database system is a type of metadatabase-management system that transparently maps multiple autonomous- database systems into a single federated database. The constituent databases are interconnected via a computer network, may be geographically decentralized, and utilize the central authority to exchange data rather than interface with each other.

Object—An object is a data entity used to represent the physical and functional elements of a real-world highway infrastructure element in the digital world. An object is described by its attributes or properties, which can include both geometric data, such as the object's dimensions in space, and nongeometric data describing the object's characteristics, such as the object's name, type, owners, and condition.

Object-type library (OTL)—An OTL lists standard object-type names (e.g., bridge, road, tunnel) and their attributes or properties.

Project Information Model (PIM) —A model that contains information to support the design and construction of the asset.

Project delivery—Project delivery refers collectively to the design and construction phases of the asset lifecycle. At the end of project delivery, the built, reconstructed, or rehabilitated asset or highway facility is handed over to the O&M units of the overseeing highway agency so the asset can be managed throughout its lifecycle.

6. ADDITIONAL REFERENCES

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