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16. Abstract

Since 2012, MDOT has been leading national efforts to modernize design development with 3D modeling. Early focus on roadway projects yielded streamlined plan production and digital data for construction. As MDOT pivots to 3D model-centric design, national and international movements gain traction to extend the value of 3D models to bridges. Researchers conducted a thorough review of the state of the practice and engaged with industry partners to help create a plan that will help MDOT implement 3D models for bridges. The plan includes recommendations for producing, managing and documenting the production of bridge models, and a framework to organize the information in the models, define the level of development and visual quality of model elements, manage geospatial distance distortions, and clarify desired outputs from the models. The project also tested a 3D bridge modeling software on real projects and provided training materials to advance the market-ready 3D modeling applications for bridge designers.

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Executive Summary

MDOT's policies for road design, survey, and construction that leverage benefits of 3D modeling have served as an example to other states, notably during the Federal Highway Administration's (FHWA's) deployment of 3D modeling under Every Day Counts (EDC). Locally and nationally, bridges were identified as the next discipline to benefit from 3D model-based design. MDOT initiated this *Development of 3D and 4D Bridge Models and Plans* research in 2016 to evaluate the state of the practice, industry trends, emerging opportunities, and to create a plan to implement the technology.

This research facilitated engagement with FHWA, the American Association of State Highway and Transportation Officials (AASHTO), MDOT staff and industry partners, taking into account national trends and local priorities in developing a framework for creating and using 3D and 4D bridge models. Software for creating 3D bridge models was tested using MDOT project datasets. Training materials were developed to advance the market-ready 3D modeling applications for bridge designers. This final report summarizes information from the Phase I and Phase II reports and provides an implementation plan of short-term and long-term action items to advance the practice.

The overall outcomes from this research are a framework and a training program to guide MDOT in the implementation of 3D models for bridges. Specific efforts from this research include:

- A literature review and summary of the national state of the practice to create an understanding of the context and national efforts for 3D bridge modeling.
- An outreach effort to the local and national bridge design community to request valuable input to prioritize the most favorable uses for MDOT.
- An approach that can immediately be used to produce, manage and document the production of bridge models.
- A thorough review of the 3D geometric bridge modeling software that MDOT has under license.
- Training material and standard bridge templates for the CADD workspace.
- Initial training sessions and guidance for practitioners to use in future training sessions.
- Recommendations for implementing the research products.

The findings of this research have both local and national impact. Locally, MDOT has a plan to leverage their 3D modeling software for bridge design in a way that optimizes the benefits of investing in the technology for a range of MDOT project types. Early benefits include visualizations, particularly for staged construction, structural analysis, and plan production efficiencies. Nationally, AASHTO has raised over $1.3 million for the pooled fund study Building Information Modeling (BIM for Bridges and Structures, TPF-5(372) being led by the Iowa Department of Transportation to help advance standardization for 3D modeling for bridges, which is the foundation for implementing BIM practices. (National Cooperative Highway Research Program, 2017). The purpose of the pooled fund study is to help advance the implementation of BIM for Bridges and Structures in the United States by funding the development of open data standards using Information Foundation Classes (IFC), and guidelines for bridge owners and other project stakeholders to easily exchange bridge information throughout the lifecycle of the structure. Through this research, the pooled fund and future MDOT research and implementation, MDOT aspires to be a leader and direct influencer to future AASHTO national standards.

1. Introduction

The AASHTO Committee on Bridges and Structures passed a resolution in 2005 acknowledging the importance of "*Comprehensive Integrated Bridge Project Delivery through Automation*." (Chen & Shirolé, 2006) Yet, many challenges remain, including lack of software maturity, undefined standards for communicating the levels of detail and accuracy in models for potential uses, and the uncertainty of their overall value to owner agencies and their stakeholders. Also, 3D workflows and modeling tools for bridges vary based on many factors, such as the low adoption rate by construction industry. Roadway contracting community has been demanding 3D models for over a decade for specific purposes while it has not been the case for bridges. Thus, the uncertainty of contractor use of bridge models, makes the framework for defining when and how to model bridges more complex than for highways.

1.1 Background

MDOT began a transition to digital delivery in 2012 by adding 3D roadway data to the Reference Information Documents (RID) provided at bid. MDOT and their partners have been benefiting from the predictable, repeatable, and reliable delivery of standardized roadway data from design to construction. Advancing digital delivery by extending 3D models to bridges was the next logical step for MDOT.

The value of extending 3D models to bridges could be realized in many ways; the benefits vary depending on timing in the project development process, type of project, intended uses of the 3D model, the detail in the model, and the accuracy of the model. There is more variety in 3D workflows for bridges than there is for roadways. The tools used to model bridges vary by structure type and whether the bridge is new, being replaced, or being rehabilitated or modified. The framework for defining when and how to model bridges is expected to be more complex than that developed for roadways.

Bridges vary greatly in structure type, which significantly affects the parametric rules that govern layout. Although the layout rules are relatively simple for most structure types, the software development efforts and market are fragmented. The absence of a standard data format for bridges is significant, making it difficult to use different software in series to increase detail of the design without data degradation. Guidance for bridge modeling is timely and necessary; the industry is advancing towards adopting Industry Foundation Classes (IFC) as the data standard for bridges, under a hybrid stewardship model. (Mlynarski & Hu, 2016).

However, the results of those efforts will not be available for quite some time; the pooled fund project *Building Information Modeling (BIM) for Bridges and Structures* initiated in 2017 has a five-year timespan. (National Cooperative Highway Research Program, 2017) Interim guidance would help MDOT further the goals for advancing digital delivery and implementing 3D models for bridges.

There are many ways that geometric 3D models can enhance bridge project delivery, which can be illustrated through sample models. A framework can provide the resources to scale the use of these geometric 3D models to individual project needs. The intention of the framework developed through this research is to be adaptable as efforts to advance data standards for bridges mature.

1.1.1 Objectives

The overall objectives of the research were to provide recommendations to advance use of 3D and 4D models for bridges as a standard agency practice, including a framework that can be used to develop the models such that they add value to MDOT's bridge project delivery process and recommendations for implementing 3D bridge modeling short and long term.

1.1.2 Scope of Work

Specific tasks to accomplish the overall objectives included:

- Conduct a literature search using traditional methods (e.g. published literature and previous studies) and a focused collection of non-traditional sources (e.g. industry and bridge owner interviews, and user-group engagements).
- Identify and interview peers from several agencies that are exploring and using 3D and 4D bridge models.
- Interview MDOT staff in survey, bridge design, and roadway design to identify past experiences with 3D bridge models, pain points with current workflows, and opportunities for using 3D bridge models.
- Create a list of 20 potential uses of 3D and 4D bridge models and collect feedback from MDOT's design community as to the priority and perceived value of each.
- Prioritize specific applications of 3D bridge models and evaluate how they apply to MDOT's policies and procedures for bridge design.
- Create a framework for describing, creating, and managing 3D and 4D bridge models.
- Identify sample bridge projects and prioritize uses to evaluate through creating sample bridge models.
- Create sample bridge models using various 3D bridge modeling software tools (e.g. OpenBridge Modeler, LEAP Bridge Enterprise, and ProStructures).
- Provide a preliminary bridge design template library to aid designers with sizing and placement of components using MDOT computer aided design and drafting (CADD) workspace.
- Document a workflow to better quantify and identify limits of earth disturbance for projects requiring earthwork and more accurately identify extents of items such as retaining walls and return walls as substructures.
- Identify advanced uses of bridge models and make recommendations for future research.

2. Project Approach

The researchers executed the work in the four phases, shown in Figure 1, which also identifies the outcomes from each phase.

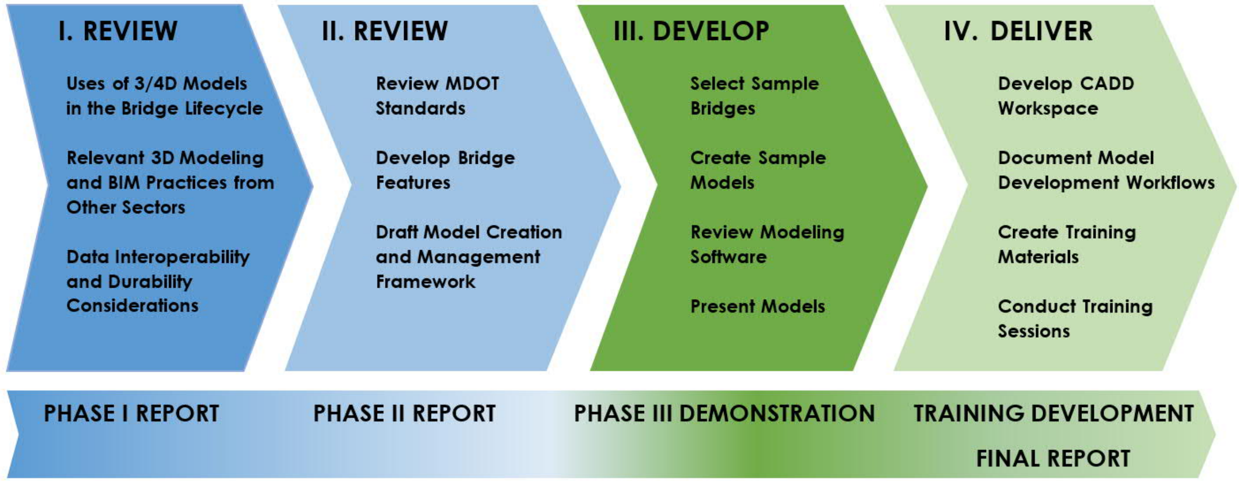


Figure 1: Research phases.

2.1 Phase I

The first phase of this research explored emerging practices and research efforts nationally to set the context for developing a framework in the next phase. Representatives from peer agencies were interviewed to coordinate with any ongoing efforts. Some agencies were piloting 3D, 4D and 5D models of bridges, and Iowa DOT had developed an implementation plan that created a structured approach to evaluating and piloting 3D modeling. (Jeffers, 2015) Selected representatives from MDOT were interviewed to identify opportunities to insert 3D and 4D models into MDOT's current processes for bridge development. Finally, the requirements and priorities were established for the framework to be developed in Phase II. The full Phase I report is included in Appendix 3.

2.2 Phase II

In Phase II, the research team first filtered the many uses of 3D models identified in Phase I down to twenty feasible and potentially favorable uses. Next, the team conducted outreach to MDOT's design community to assess the priority, perceived value, and other input on their perspectives of these twenty applications. The results were analyzed to identify the highest priority and highest value uses. These uses were then assessed according to the screening criteria identified in Phase I. Tables were added to summarize the results and identify opportunities for secondary model uses based on the high-value, high-priority primary purposes. During Phase II, researchers considered the key elements that should be considered and tested for developing the framework to help MDOT's bridge designers to clearly identify and articulate the model requirements, how to manage horizontal distance distortions implicit to state plane coordinates in a state that contains three state plane zones, and project selection criteria for 3D model uses. The elements of this framework would then be tested in the last two phases of the research, and discussed in this final report. Finally, a set of selection criteria were identified for the sample models in Phase III. A full detailed report was delivered, and it is included herein as Appendix 4.

2.3 Phase III

The main objective of Phase III was to develop four sample models using real project datasets identified in Phase II. The four data sets that were recommended for the sample models in Phase II are summarized in Table 1. The prioritization exercise conducted in Phase II helped to narrow down the top priority 3D model uses to examine through sample models.

Table 1. Proposed project datasets for sample models and their characteristics.

Project	Scope of Work	Type of Superstructure	Type of Substructure	Sample Model Objectives
M-28 over Jackson Creek	Full replacement with full closure and traffic detour	60-ft single span 45” PCI beams	Cantilever abutments with pile supported footing	Determine level of effort to repurpose the abutment models and plans.
I-94 over Jackson and Lansing Railroad	Full replacement with partial-width construction	724-ft 6-span Michigan 1800 PC beams	Cantilever abutments with pile supported footings and cap and column piers on micropiles or H-piles	Create a multi-span bridge example in OBM
M-57 over Shiawassee River	Full replacement with full closure and traffic detour	142.5-ft single span Michigan 1800 PC beams	Cantilever abutment with micropiles	Evaluate ground distance distortion. Create a set of models, plans, and 3D PDFs for different design stages. Create visualizations.
I-75 over Coolidge Highway	Two full replacements with staging TBD	Steel and concrete options assessed in study, single span PCI beams preferred	Cantilever abutment with pile supported footing	Assess data exchange between LEAP Bridge, OBM and ProStructures. Evaluate the use of 3D PDF for plan review.

Specific activities to meet the objectives of Phase III were to:

- Create a set of sample models that can be incorporated into training materials to be developed in Phase IV.
- Test the framework including:
    - Approaches to managing geospatial distance distortions.
    - Model progression specifications and/or model inventories.
    - LOD designations.
    - Outputs in 3D PDF, i-Model, and IFC format.

- Model at least one pre-stressed concrete bridge and one steel bridge.
- Develop OpenBridge Modeler (OBM) templates that can be incorporated into the MDOT_02 workspace.
- Investigate staged model deliverables for different design phases.

Once the model samples were created, the research team hosted a virtual demonstration to show both the process and tools used during the development, and the sample bridge models. The products delivered at the end of Phase III were the OBM workspace, the four sample models, and a recording of the Phase III demonstration.

After developing the sample models, the researchers recommended to focus the short-term implementation of 3D and 4D Bridges at MDOT on:

- Visualization and public outreach.
- Parametric model-based design to assist with plan production.
- Structural analysis and design.

2.4 Phase IV

The work in Phase IV focused on developing training materials and the final report, which includes a plan for how MDOT can implement the outcomes of the research.

Three training sessions were planned and delivered as part of Phase IV:

- Introductory webinar to set expectations and requirements for the next sessions.
- Practical training for bridge designers using OBM.
- Training for project managers on expectations and applications to consider.

The technical training for bridge designers was created to provide guidance for directly using the software to create the models and the plans. The project manager training was designed to provide guidance for developing model requirements and managing projects in which bridge modeling will be used.

3. Literature Review

The research began with a thorough literature review of relevant uses of 3D and 4D bridge models and plans. The literature review was delivered in the Phase I Report, which is included in Appendix 3.

The literature review identified three main areas that informed the development of the framework in the second phase of the research. These three areas were:

1. Uses of 3D and 4D models in the bridge lifecycle.
2. Relevant 3D modeling practices from other sectors.
3. Data interoperability and durability considerations.

3.1 Uses of 3D and 4D Models in the Bridge Lifecycle

Chen and Shirolé were primary authors of several studies exploring data exchange through the bridge lifecycle, (Chen & Shirolé, 2006) (Shirole, et al., 2008) (Chen, 2010) especially the integration of analytical and geometric modeling. (Chen, et al., 2006) (Chen & Shirole, 2013) Figure 2 illustrates the various applications of 3D models throughout the bridge lifecycle proposed by Shirole et al. (2008). Around the same time, there was effort to promote the benefits and returns on investment that BIM use was bringing to the buildings sector. (McGraw-Hill Construction, 2009) (Bernstein, et al., 2012) (McGraw-Hill Construction, 2014)

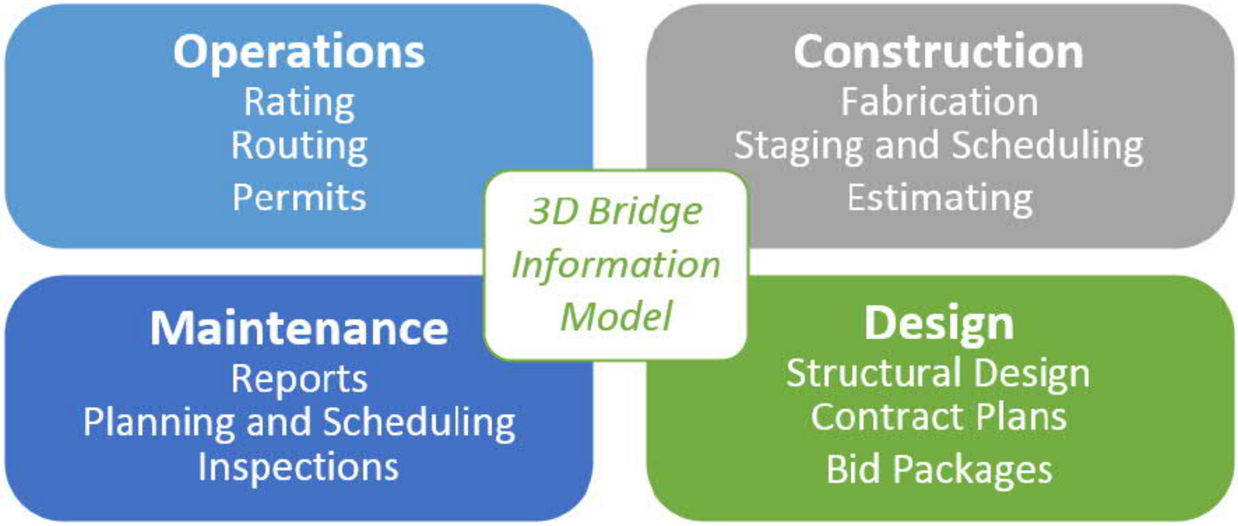


Figure 2: Lifecycle uses of 3D bridge models (Shirole, et al., 2008).

As BIM use for geometric design, plans production and construction planning (i.e. clash detection and 4D scheduling) became institutionalized in the building sector, and with the benefits of the IFC data standard; additional uses of those 3D models emerged for whole lifecycle cost analysis (particularly energy use), safety and other code checking, and for facility management. Nevertheless, the primary use of 3D bridge models being explored was structural analysis; there is a long history of lifecycle use of bridge geometric data in the AASHTOWare Bridge analysis products for bridge design (BrD) and bridge rating (BrR). (American Association of State Highway and Transportation Officials, n.d.)

Examples of favorable uses of 3D models of bridges were identified from planning through operations and management, notably with MDOT's use of the 3D B^{RIDG}E App for inspection data collection. (Michigan Tech Research Institute, 2016) However, the various uses required different levels of geometric accuracy, model disaggregation, and visual effects or photorealism. Figure 3 illustrates four discrete uses from planning to construction, which require distinctly different levels of geometric accuracy and model disaggregation. This makes it difficult to serve multiple uses with a single model, unless the model meets the highest common denominator for each use.

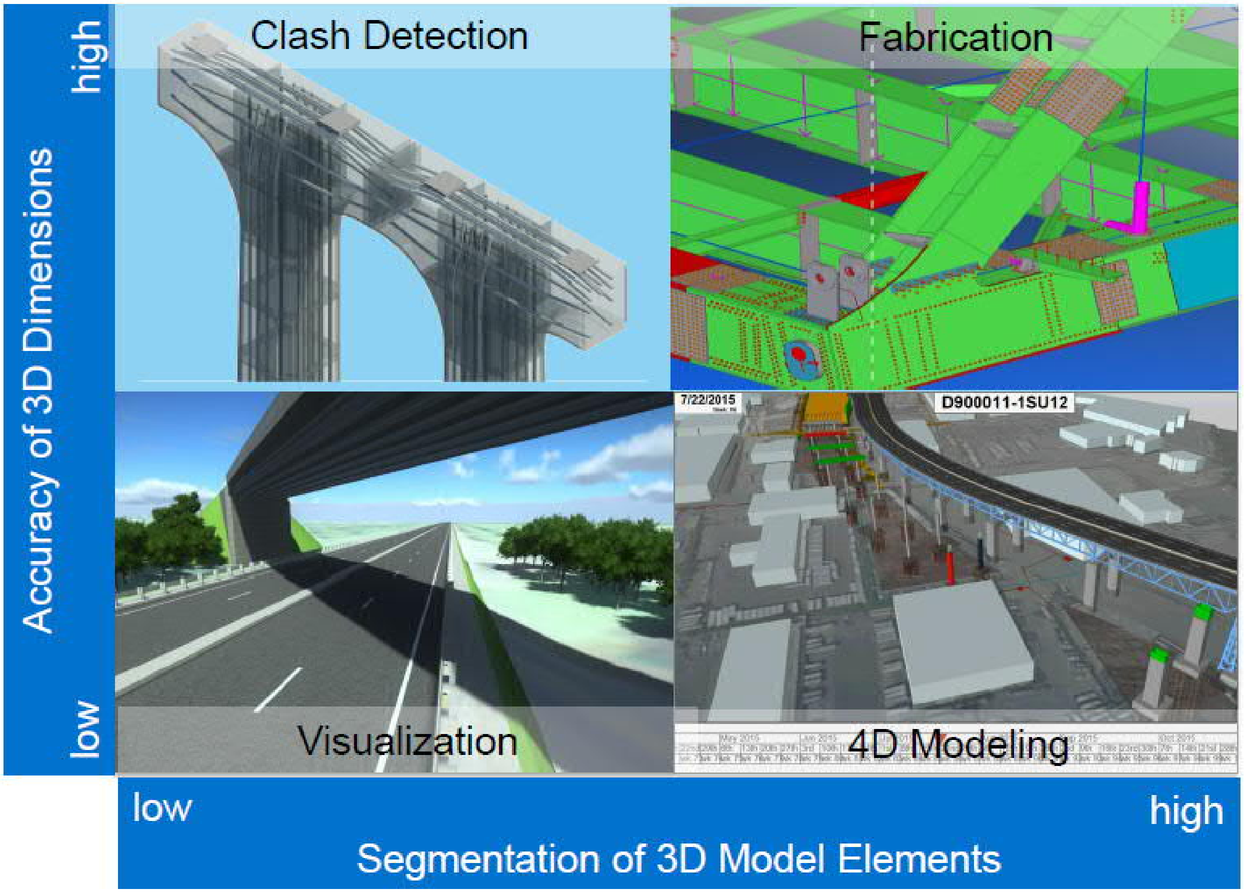


Figure 3: Applications require different levels of accuracy and model segregation.

3.2 Relevant 3D Modeling and BIM Practices from Other Sectors

Other sectors were explored to identify additional potential uses of 3D and 4D bridge models, as well as to identify transferable practices and standards for model management and collaboration. Bridges and buildings have some common functional elements, such as foundations, columns, bearings, beams, and slabs. In many ways, bridges have more in common with buildings than they do with roads. The exception is the horizontal geometric layout methods that bridges inherit from the roadways they convey.

The most favorable mature or maturing uses that are transferable to bridges were:

- Widespread use of visualization for design review and construction planning.
- Computer-based clash detection, especially for structural detailing.
- Enhanced automation for detailing and reinforcement schedule production.
- Structured, open format asset inventory data. (Scarponcini & Nisbet, 2013)
- Collaboration with other disciplines, especially optimization of data models, such as terrain surfaces, alignments and profiles.

Project Execution Planning (Computer Integrated Construction Research Program, 2011) was identified as a transferable practice for defining the deliverables and managing interdisciplinary collaboration. A Project Execution Plan (PxP) is developed during project initiation to identify the goals and uses for 3D models and BIM. The team then plans data exchanges and documents the model requirements to support these uses in a model progression specification. The model progression specification is effectively an inventory of model content, which relies upon a classification for model elements and a reference standard for Level of Development (LOD), which is a measure of the maturity of the information in the model. In other words, LOD defines the reliability of the data behind the model used to communicate its intent. There are foundational LOD designations that are generic, as well as element-specific designations, which are more detailed. (BIMForum, 2017). LOD is a broad term that is still evolving in the industry, but it typically defines the level of detail and information behind each element, the geometric accuracy, and visual quality.

3.3 Data Interoperability and Durability Considerations

Lack of data interoperability was identified early as a barrier to reaching the potential of BIM and 3D modeling for bridge development. (Chen, et al., 2006) This work noted a shift from a drawings-focused (i.e. 2D) delivery of construction documents to an information-centric approach that supports downstream uses of the information. Further, Chen et al. (2006) acknowledged a need to change workflows as well as to adopt data standards. Initial efforts to explore data standards considered an XML-based exchange specification, which aligned with a concurrent project, TransXML. The TransXML research examined data exchange needs for four areas, including highway bridges. (Ziering, et al., 2007) While Chen et al (2006) had identified IFC and suggested perhaps an IFC-Bridge, the IFC standard at the time was recently published (International Organization for Standardization, 2005) and not yet well adopted.

While the potential of TransXML was recognized and a stewardship model was proposed (Turnbull, 2014), ultimately, interest in data standardization for bridges looked elsewhere. More recent work identified international efforts to adapt IFC to infrastructure in general and bridges specifically, and laid out a roadmap for implementing BIM for bridges. (Chen & Shirole, 2013) FHWA sponsored work to advance two aspects of this roadmap: a modeler/viewer tool called OpenBrIM (Bartholomew, et al., 2015) and the creation of an IFC Model View Definition (MVD) for bridges. (Grant, et al., 2015) FHWA is currently supporting additional work to test that MVD on a sample project (Severns & Maier, 2018) and the AASHTO BIM for Bridges and Structures, TPF-5(372) pooled fund to facilitate wide use of IFC as an exchange standard for bridges. (National Cooperative Highway Research Program, 2017)

4. Outcomes

The overall outcome from this research was tangible input to aid MDOT to implement 3D models for bridges, as well as training products that enable MDOT's designers to begin using the tools already at MDOT's disposal to create and use 3D bridge models. The research resulted in practical applications and recommendations that can be immediately used for advancing the use of 3D models for bridges within MDOT's bridge community.

4.1 Review of the State of the Practice

A review of the state of the practice resulted in understanding the context and national efforts for 3D bridge modeling. Researchers worked with MDOT to line up the efforts of this study to help advance national practice.

4.2 Industry Collaboration

Outreach to the bridge community, which raised the level of understating of how 3D models can improve bridge development, as well as produced valuable feedback. This collaboration with industry resulted in prioritization of the most favorable uses for 3D models for bridges to MDOT's program and has set the stage for future engagement.

4.3 Tools for Managing and Documenting Bridge Models

An approach that can immediately be used to produce, manage and document bridge models, including a framework to organize the information in the models, define the level of development and visual quality of model elements, manage geospatial distance distortions, and clarify desired outputs from the models.

4.4 Initial Training Sessions

Three training sessions to address the needs for different audiences. One introductory training session, one virtual training session specifically designed for project managers, and one in-person interactive training session for bridge designers.

4.5 Training Material and Technical Resources

Guidance for practitioners, including workflows for market-ready modeling tasks, video tutorials, sample models, standard bridge templates for the CADD workspace, and a list of currently-available external resources that will allow first adopters to start producing 3D bridge models.

4.7 Implementation Plan and Final Report

A plan to implement research products, including short and long-term goals and a timeline to accomplish them, as well as recommendations for future considerations to continue the advancement of bridge modeling in a final research report.

5. Bridge Model Framework Discussion

A model framework can be used to clearly define the 3D model requirements and data limitations for each intended use. After the input from stakeholders, study of the state of the practice, and development of sample models the following framework concepts were documented:

- Model Requirements
- Model Element Organization
- Level of Development (LOD)
- Visual Quality
- Managing Distance Distortions
- OBM File Formats and Metadata
- Derivative Products

5.1 Documenting Model Requirements

A Model Inventory is like the “read me” file for the model, and should include:

- A list of all elements included in the model.
- The LOD and LOV associated with each model element.
- The authoritative source of information for each element.
- The name of the responsible party or discipline for developing each element.
- Comments or notes that may be helpful for the project manager.
- Project combined scale factor, or CSF for each bridge element as applicable.

A Model Inventory documents the final model state at a predefined exchange point such as delivery with the contract plans for construction. However, if the model will be used during the project delivery to coordinate with multiple design team members and/or disciplines, then it is important to carefully coordinate the staged development of a model using a model progression specification (MPS). A MPS is like a Model Inventory, but it is a blueprint for the development of the model, documenting the agreed LOD by element at each defined milestone. This allows teams to plan for the quality of information that they need to deliver and will receive at different stages of the project. The LOV is also documented in the Model Inventory or MPS based on the purpose of the model.

The purpose of an MPS is to clearly communicate information about the model to stakeholders to manage expectations and coordinate information exchanges. Model authors need to know what level to develop elements to, and those receiving the models must understand the quality and reliability of information they will receive, and when. This allows multidisciplinary teams to plan when to invest their own efforts based on the quality of the information available. The MPS should be developed in an early, multidisciplinary planning meeting, and it is part of an overall Project Execution Plan (PxP), which defines:

- The purpose and need for the model, which will drive much of the decision-making about the LOD, and data exchanges.
- The roles and responsibilities of team members, including key project delivery milestones dates.
- The reference LOD specification, which will inform the appropriate authorized uses for the model content.
- The LOV guidelines appropriate to support any visualization and simulation uses.

A PxP is a project management tool that is used on a project-by-project basis. Templates could be created for common bridge model uses to give a starting point and make specific project customization easier. For example, a template could be created for a bridge model primarily used for visualization of staged construction in which the Model Inventory and/or MPS is partially completed for LOD/LOV and responsible parties based on the common needs for this model use.

An MPS with multiple milestones should be developed for complex or large bridge projects where information maturity may vary from typical projects (e.g. alternative delivery), as well as for projects that support visualization or simulations uses. However, if the intended use is plan-production or parametric modeling for detailing, the LOD should support design review milestones. Lastly, a Model Inventory should be required for final design models.

Table 2 shows these milestones, how they relate to the MPS, and the guiding policy documents. A sample MPS can be found in Appendix 3.

Table 2: Bridge development milestones and policy references.

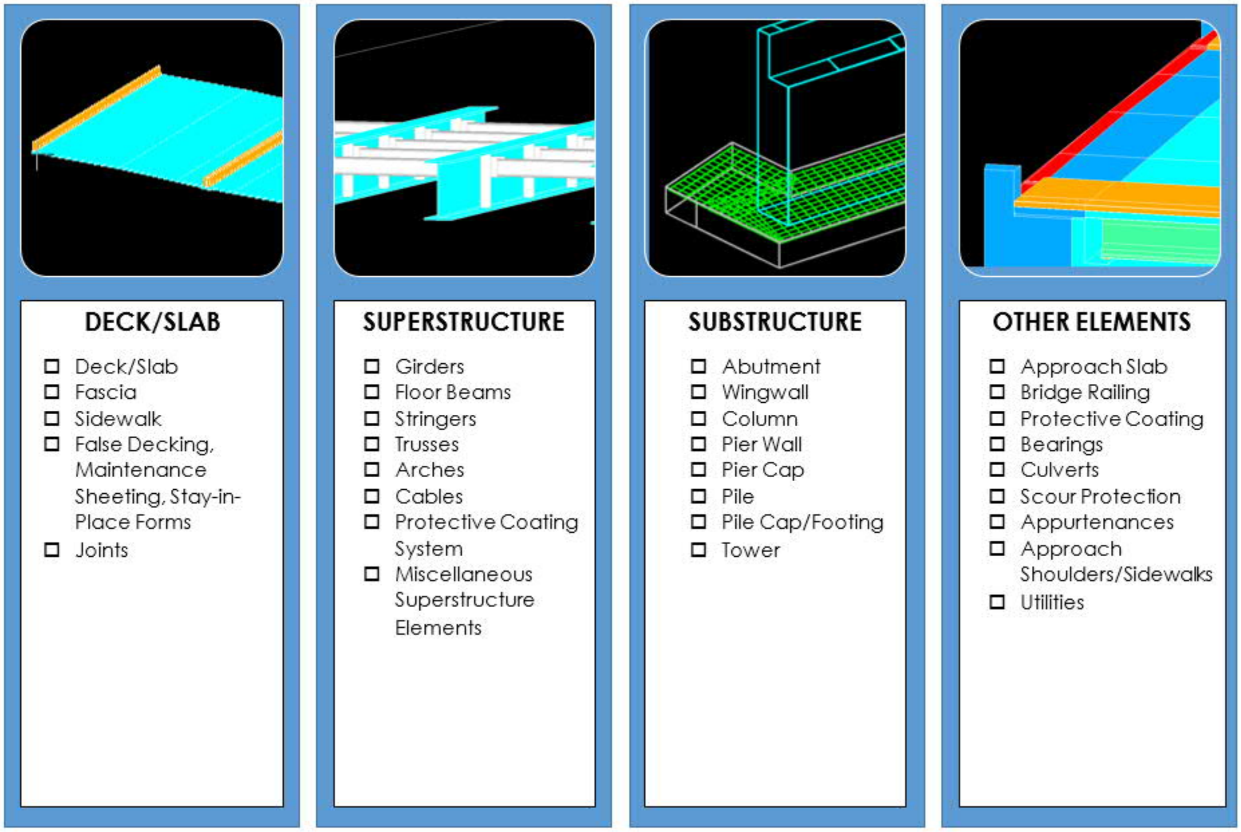
Milestone	Considerations for MPS	Policy Reference
Scoping	Articulate the needs for the project	Bridge Design Manual and Project Scoping Manual
Scope Verification	Select the right level of survey and SUE data needed to fit the future project needs	Bridge Design Manual
Study	Defines elements for the Model Inventory or MPS	Bridge Design Manual
Preliminary Plans	Define LOD for reviewers	Bridge Design Manual
Final Design	Define LOD for reviewers	Bridge Design Manual

5.2 Model Element Organization

The foundation of the Model Inventory or MPS is the list of elements included in the model. The organization of bridge elements should follow a logical classification system. There is not yet a standard classification system for bridges; the classification system used should support design responsibility delineations, construction bid item and specification classifications, and the bridge management and inspection data model(s). While the immediate goal is to support design functions, the element organization should be consistent with the major and sub-categories of the *Michigan Structure Inspection*

Manual. This level of planning will position MDOT well for future use of 3D models in inspection activities. Figure 4 lists MDOT's bridge element organization.

In almost all cases, proposed elements need to be included; and in many cases, existing elements also are needed. These may need to be displayed on plans, used to compute quantities, or they may be important to fully communicate staging or demolition sequences. Often, existing elements are not needed at the same LOD as the proposed. It may not always be worth modeling an existing structure. For example, if the model will only be used for plans production, it may be easier to use traditional means to represent the existing structure.



DECK/SLAB

- ☐ Deck/Slab
- ☐ Fascia
- ☐ Sidewalk
- ☐ False Decking, Maintenance Sheeting, Stay-in-Place Forms
- ☐ Joints

SUPERSTRUCTURE

- ☐ Girders
- ☐ Floor Beams
- ☐ Stringers
- ☐ Trusses
- ☐ Arches
- ☐ Cables
- ☐ Protective Coating System
- ☐ Miscellaneous Superstructure Elements

SUBSTRUCTURE

- ☐ Abutment
- ☐ Wingwall
- ☐ Column
- ☐ Pier Wall
- ☐ Pier Cap
- ☐ Pile
- ☐ Pile Cap/Footing
- ☐ Tower

OTHER ELEMENTS

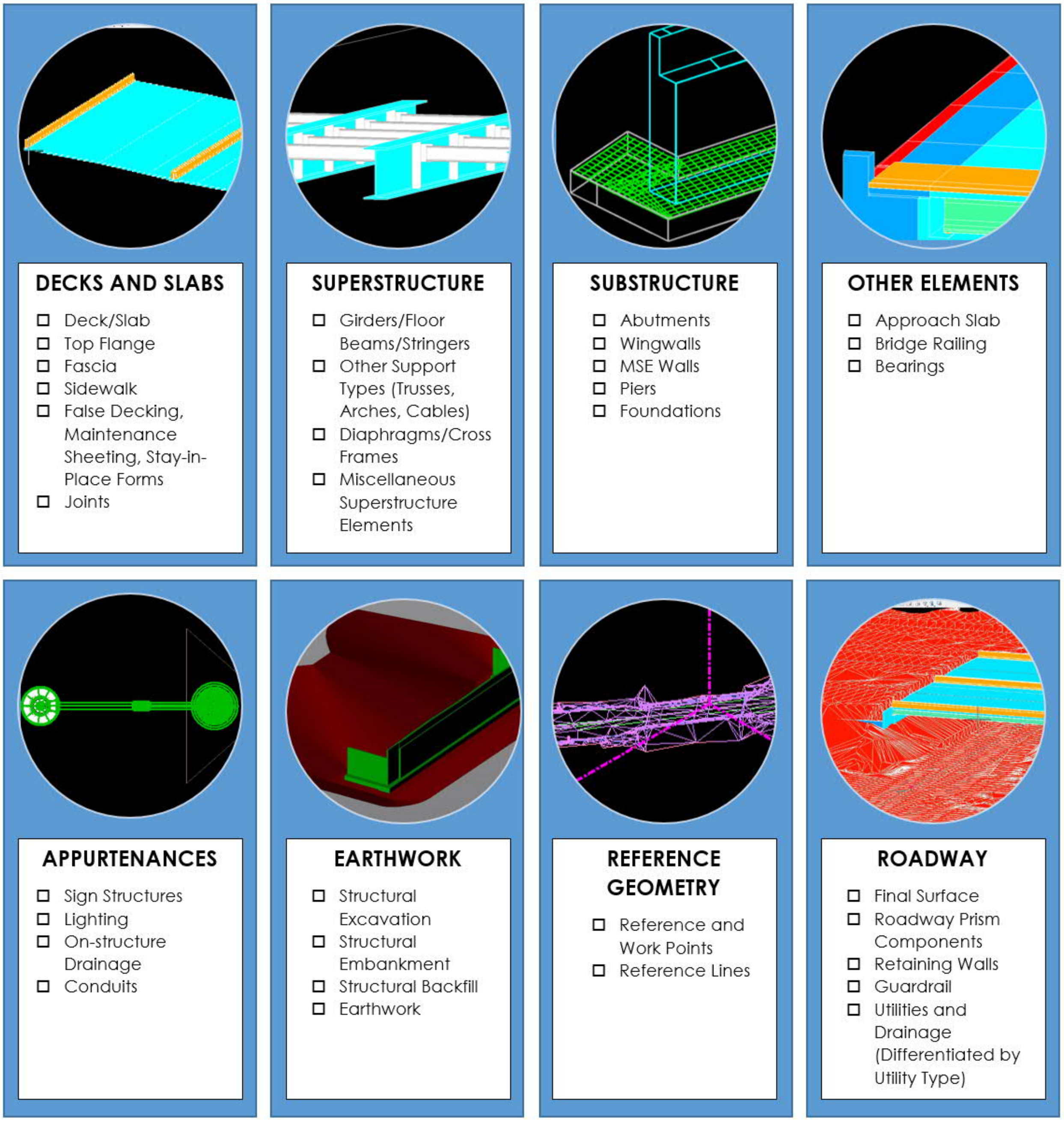
- ☐ Approach Slab
- ☐ Bridge Railing
- ☐ Protective Coating
- ☐ Bearings
- ☐ Culverts
- ☐ Scour Protection
- ☐ Appurtenances
- ☐ Approach Shoulders/Sidewalks
- ☐ Utilities

Figure 4. Bridge element organization (Michigan Department of Transportation, 2015).

The model element and sub-element organization for the specific bridge features should follow the same organization as Figure 5, but may be consolidated to show only Elements or even Categories such as representing all Existing Features with LOD if they are only needed for visual purposes as part of a construction staging model used for public outreach. Figure 6 shows only the non-bridge features, and reflects the need to differentiate SUE designations for existing subsurface utilities and the different model content type for depicting existing roadway features compared to proposed roadway features. That is, proposed roadway features would comprise 3D corridor components, whereas existing roadway features would be depicted as the top of roadway terrain. Context elements would be included when the model is used to examine or visualize impacts outside of the project limits (such as traffic impacts), especially when the model is used to produce images or videos for engaging with the non-technical stakeholders.

There are hierarchies of model organization. A bridge model may be split into separate files for specific uses or phases of construction (e.g., proposed.dgn, stage_1.dgn, etc.). Also, larger projects with multiple bridges can be added in the same dgn file; however, only one individual can be working in a single file at a time, so it may be beneficial to have separate files for each bridge. Elements may be placed as parametric components driven by bridge component template libraries, which function like smart 3D cells. Element Templates store pre-defined graphical properties (such as level, color, line style, line weight, fill, and transparency). Element Templates can also be used to assign materials for rendering and visualization. These templates are organized into Feature Definitions which correspond to the OBM bridge element categories (e.g., Deck, Abutments, etc.) and are selected as the elements are created in the model. MDOT uses the MDOT_02 workspace, which establishes standard cells, levels, level filters, colors, line styles, line weights, etc. The MDOT_02 workspace includes a level library for bridge structures. The workspace has also been extended for use in OBM which now includes Element Templates, Feature Definitions, and parametric component templates for 3D bridge models. Levels in MDOT's existing MDOT_02 workspace were used in lieu of creating separate levels for the 3D model components which reduced the amount of modifications to the current workspace.

Responsibilities for modeling and data entry can then be assigned to individuals who are part of the discipline advancing the design of the relevant elements. Each model element is assigned a designated LOD that is minimally sufficient to support the intended uses. By defining the LOD by model element, the bridge engineer does not need to progress the design of all model elements simultaneously. Authorized use of the 3D model information can then be assigned by model element.



DECKS AND SLABS

- ☐ Deck/Slab
- ☐ Top Flange
- ☐ Fascia
- ☐ Sidewalk
- ☐ False Decking, Maintenance Sheeting, Stay-in-Place Forms
- ☐ Joints

SUPERSTRUCTURE

- ☐ Girders/Floor Beams/Stringers
- ☐ Other Support Types (Trusses, Arches, Cables)
- ☐ Diaphragms/Cross Frames
- ☐ Miscellaneous Superstructure Elements

SUBSTRUCTURE

- ☐ Abutments
- ☐ Wingwalls
- ☐ MSE Walls
- ☐ Piers
- ☐ Foundations

OTHER ELEMENTS

- ☐ Approach Slab
- ☐ Bridge Railing
- ☐ Bearings

APPURTENANCES

- ☐ Sign Structures
- ☐ Lighting
- ☐ On-structure Drainage
- ☐ Conduits

EARTHWORK

- ☐ Structural Excavation
- ☐ Structural Embankment
- ☐ Structural Backfill
- ☐ Earthwork

REFERENCE GEOMETRY

- ☐ Reference and Work Points
- ☐ Reference Lines

ROADWAY

- ☐ Final Surface
- ☐ Roadway Prism Components
- ☐ Retaining Walls
- ☐ Guardrail
- ☐ Utilities and Drainage (Differentiated by Utility Type)

Figure 5. Model element organization: proposed features.

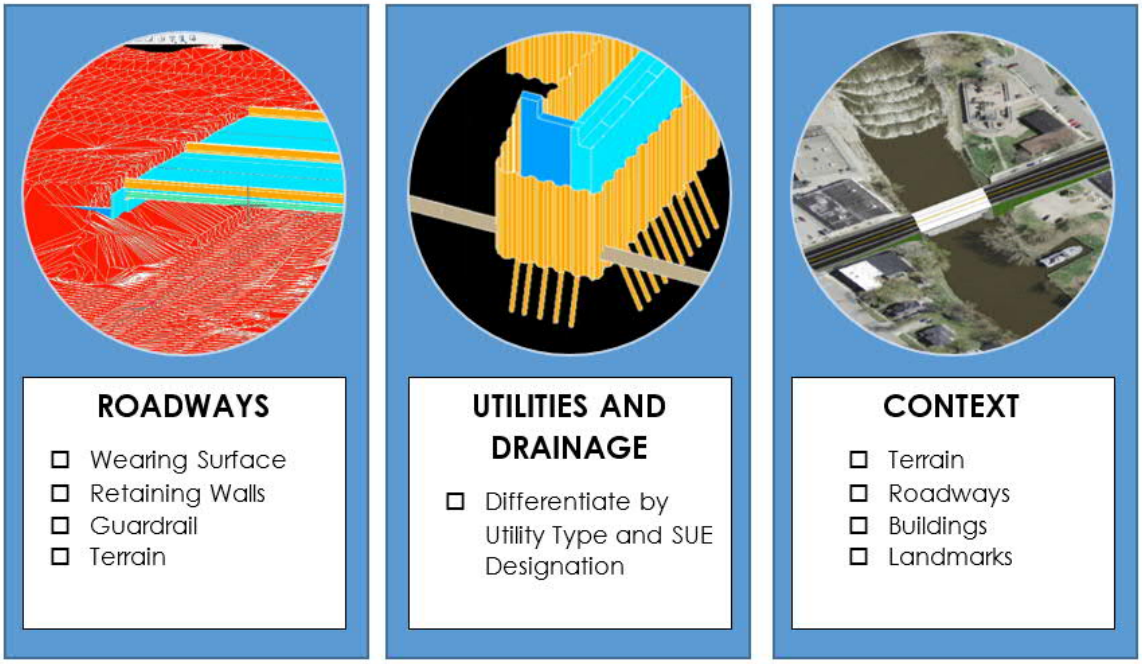


Figure 6. Model element organization: existing features.

When the model will be used for staging, simulation, or visualization, it may be necessary to include temporary works as shown in Figure 7 interim conditions, and construction equipment (e.g. cranes).

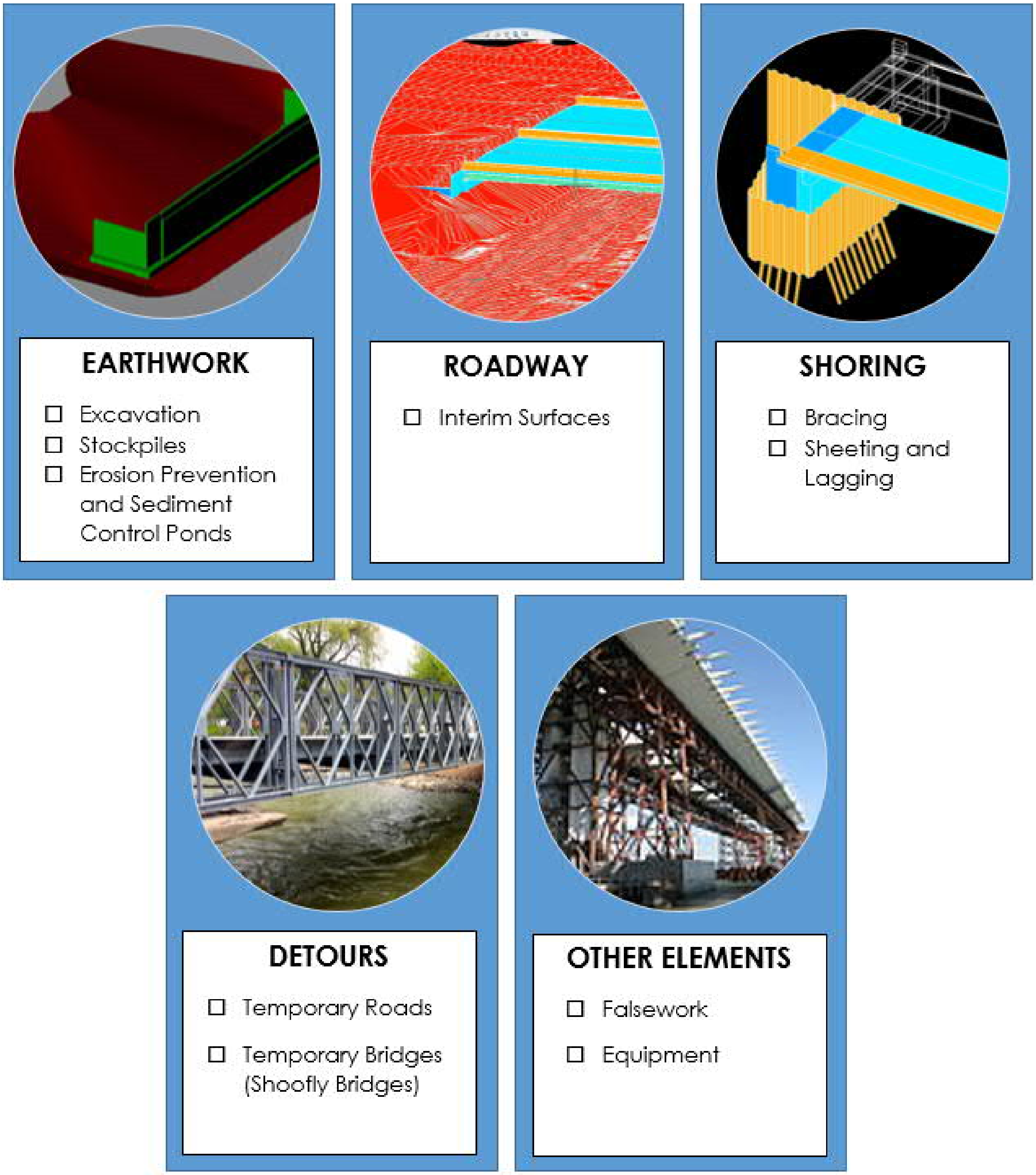


Figure 7. Model element organization: temporary works.

5.3 Level of Development (LOD)

LOD indicates how reliable the model geometry and information are at the different phases of project development. (American Institute of Architects, n.d.) It is expressly not a measure of the modeled object's detail, but rather how closely it reflects design intent and constructability. However, as Figure 8 illustrates, increasing development often requires increasing detail.

Figure 8: Three levels of development for a prestressed beam.

The level of design intent maturity for each milestone is already defined in the Bridge Design Manual, which defines the requirements for each milestone (Study, Plan Review Meeting, Plan Completion, Turn-in) (Michigan Department of Transportation, 2009) with additional information included for final plan completion through the Guidelines for Bridge Plan Preparation. (Michigan Department of Transportation, 2016) These requirements for the level of development of the various design elements at each milestone are relatively well understood. The LOD designations for bridges are most important at the construction hand-over when the model passes from the original creator to others who need to be able to use it reliably; however, LOD definitions at other milestones may be needed for purposes such as facilitating design reviews. LOD designated by element at each milestone is more valuable than if specified for an entire model because the design matures asynchronously for different systems and elements.

While there are no industry standards for LOD definitions specific for bridge elements, the American Institute of Architects (AIA) established guidelines may be adapted as shown in Table 3. Alternatively, a more generic LOD schedule for bridge-related features may be more desirable, such as the BIMForum fundamental designations. (BIMForum, 2017)

MDOT is currently setting and defining a LOD framework for their roadway modeling features. Future LOD development should include coordination with the Digital Delivery Work Group (DDWG) partnership between MDOT, consultants, and contractors to develop LOD standard encompassing all transportation disciplines.

Table 3: AIA definitions of LOD as applicable to bridges. (American Institute of Architects, n.d.)

LOD	Model Element Requirements	Authorized Uses
LOD 100	Overall massing indicative of height, volume, location, and orientation. May be modeled in three dimensions or represented by other data.	Limited analysis Aggregate cost estimating High-level staging
LOD 200	Elements are modeled as generalized systems or assemblies with approximate quantities, size, shape, location, and orientation. Attributes may be attached to model elements.	Preliminary analysis High-level cost estimating High-level scheduling
LOD 300	Elements are modeled as specific assemblies and are accurate in quantity, size, shape, location, and orientation. Attributes may be attached to model elements.	Construction documents Detailed analysis Project controls
LOD 400	As per LOD 300, plus complete fabrication, assembly, and detailing information	Model-based fabrication Actual cost tracking Look-aheads Virtual mock-ups
LOD 500	Elements are as-constructed assemblies accurate in quantity, size, shape, location, and orientation. Attributes may be attached to model elements.	Maintenance and planning of future construction

Table 4: A possible generic LOD schedule for bridge-related features.

LOD	Description
LOD-V	Graphics are sufficiently developed to support a corridor study, and high planning level cost estimates. This type of model may be sufficiently developed for **visualization** for public outreach. The geometry looks correct, but bridge elements are depicted as single objects showing only exterior features (e.g. entire deck as a single object).
LOD-A	Graphics and design intent are sufficiently developed to support **structural analysis**. The model is geometrically accurate for major systems, but there may be simplifications where the detail does not affect the analysis. Model communicates sufficient engineering intent to estimate costs for the superstructure and substructure units. Lacks the detail to create plans or details
LOD-P	Graphics and design intent are sufficiently developed to support **final design plans**, including **constructability reviews, macro clash-detection,** and **most plans production**. The model is geometrically accurate to the measurement precision with sufficient detail to create plans and take-off quantities, and geometry is based on robust analysis. Graphics and design intent are sufficiently developed to support **final design plans**, including all necessary details to **produce a complete set of bridge details** when tools support a full plan production.
LOD-F	Graphics and design intent are sufficiently developed for **contractor use**. The graphics are sufficiently developed for **fabrication**. This would essentially be guidance to contractors on what to deliver for shop model review and to keep for post-construction applications.

5.4 Visual Quality

Creating visualizations can be very open-ended. As the software matures, there will be opportunities to create standard libraries and element templates that have the visual textures pre-applied. As for today, creating visualization outputs still requires setting lighting, placing cameras in the view, and rendering images. Most technical uses of 3D models do not require this level of sophisticated visualization (Federal Highway Administration, 2016). Coloring a surface green, as opposed to applying a “grass” material texture, makes a difference to the file size, render time, and visual quality.

Incorrect assumptions about the intended level of visual quality can quickly increase costs for models and their video and image outputs. However, software such as ConceptStation can produce relatively representative images (Figure 9) with context such as aerial imagery, approximate terrain, etc. with minimal effort. When visualization uses are indicated, it is helpful to provide guidance as to what the needs are to suit the target audience. Table 5 describes different grades of visual quality and associated target audiences.

Figure 9. Visualization output created with Bentley ConceptStation software.

Table 5: Grades of visual quality and applicable uses.

Visual Quality	Visualization Elements	Target Audience
Photorealistic	3D elements are *textured* with *materials* *Perspective* view style Defined *camera* locations Defined *lighting* (locations, colors, intensities) *Rendering* required to produce images and videos	General public
Representative	3D elements are *colored* in solid colors *Perspective* or *orthometric* view style Defined *camera* locations, *lighting,* and *rendering* optional (can use *shaded* view styles and screen grabs to create images)	General public Non-technical stakeholders Technical stakeholders
Illustrative	3D elements may be any color No cameras, lighting, or rendering needed Can use *shaded* or *wireframe* view styles Can create images with screen grabs	Technical stakeholders Project team

Figure 10 contrasts a wireframe model and a rendered model of the same scene. The rendered model appears to use a mix of material textures and representative colors (e.g., light gray for asphalt in preference to an asphalt material).

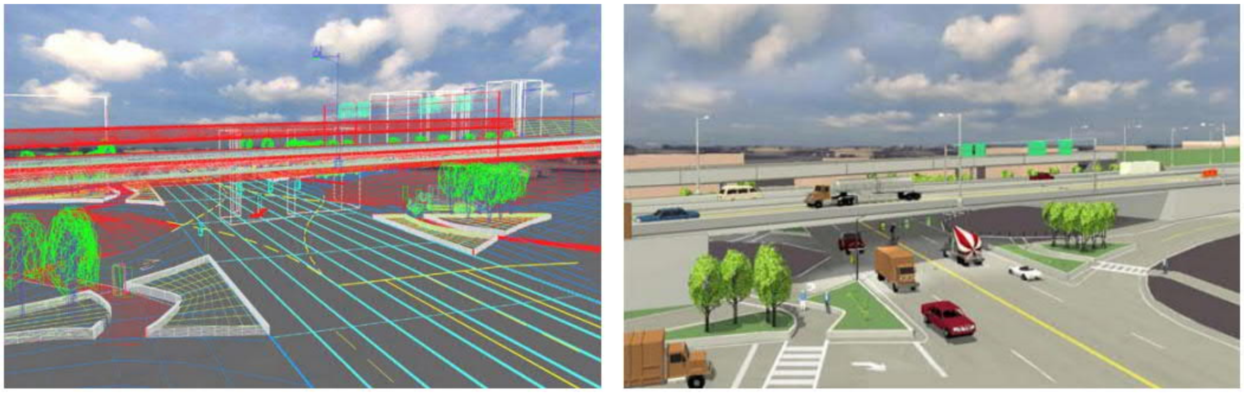


Figure 10: A wireframe model (left) and a rendered model (right) (American Association of State Highway and Transportation Officials, 2003).

5.5 Managing Distance Distortions

MDOT uses the Michigan Coordinate System 1983 (MCS 83), commonly known as the state plane coordinate system. This system uses a Lambert Conformal Conic projection with three zones (north, central, and south) (State of Michigan, 1988). This means that design coordinates in International Feet are distorted relative to the true distances on the ground. The amount of distance distortion varies depending on the distance from the project location to the standard parallels that define the MCS 83 zones.

The horizontal distance distortions are computed by a licensed surveyor and expressed as a Combined Factor. The Combined Factor describes the ratio of grid distances measured in MCS 83 coordinates to true ground distances. In reality, the Combined

Factor varies at every point in the state, but for a small project, usually a single Combined Factor will be reported. For widely dispersed projects, sometimes a Combined Factor is computed for every bridge location.

Many areas in Michigan have significant distortion. The midpoint of each of the three State Plane zones has similar levels of distortion; the worst-case distortion depends on elevation as well as location. For example, a Combined Factor of 0.99987029 is close to the maximum distortion in the southern zone. Here, a distance measured as 500 feet using coordinates on the MCS 83 grid is 500 feet and 3/4 of an inch on the ground. Construction surveyors manage this distortion to stake out the bridge.

Traditionally, survey and coordinate data is provided in MCS 83 grid, but bridge designers draft in ground units in a custom coordinate system that has no distortion. In construction, once the reference points and lines are set using the MCS 83 grid coordinates, all the work is relative to those points in the ground-based distances. This workflow is effective. Using 3D models disrupts this practice; the intent is for a single model to serve both purposes. The distance distortion in a 3D model created on MCS 83 grid coordinates may be so significant that the model is not accurate within normal measurement precision.

In order for the 3D bridge models to line up with the 3D roadway models and other design information (such as utilities), the bridge models need to be created in the same MCS 83 grid coordinates. This ensures that they can be used for visualization, simulation, design coordination, and constructability review. However, depending on the longest dimension in the bridge, and the Combined Factor, this means that the bridge model may not be dimensionally accurate to the normal 1/8-inch measurement precision reflected in standard plans for bridge elements when the MCS 83 grid distances are scaled to ground distances. This creates a problem that must be managed.

Figure 11 is a nomograph to help bridge designers determine whether distance distortion will be significant for their project, based on the CSF. To be accurate with a 1/8 inch measurement, the maximum acceptable distance distortion is 1/16 inch. For places with Combined Factor close to the maximum distortion, ¾ of an inch over 500 feet works out to 1/16 of an inch over 30 feet. That most likely is not an issue for dimensioning the substructure units, but it would be a problem for beam lengths.

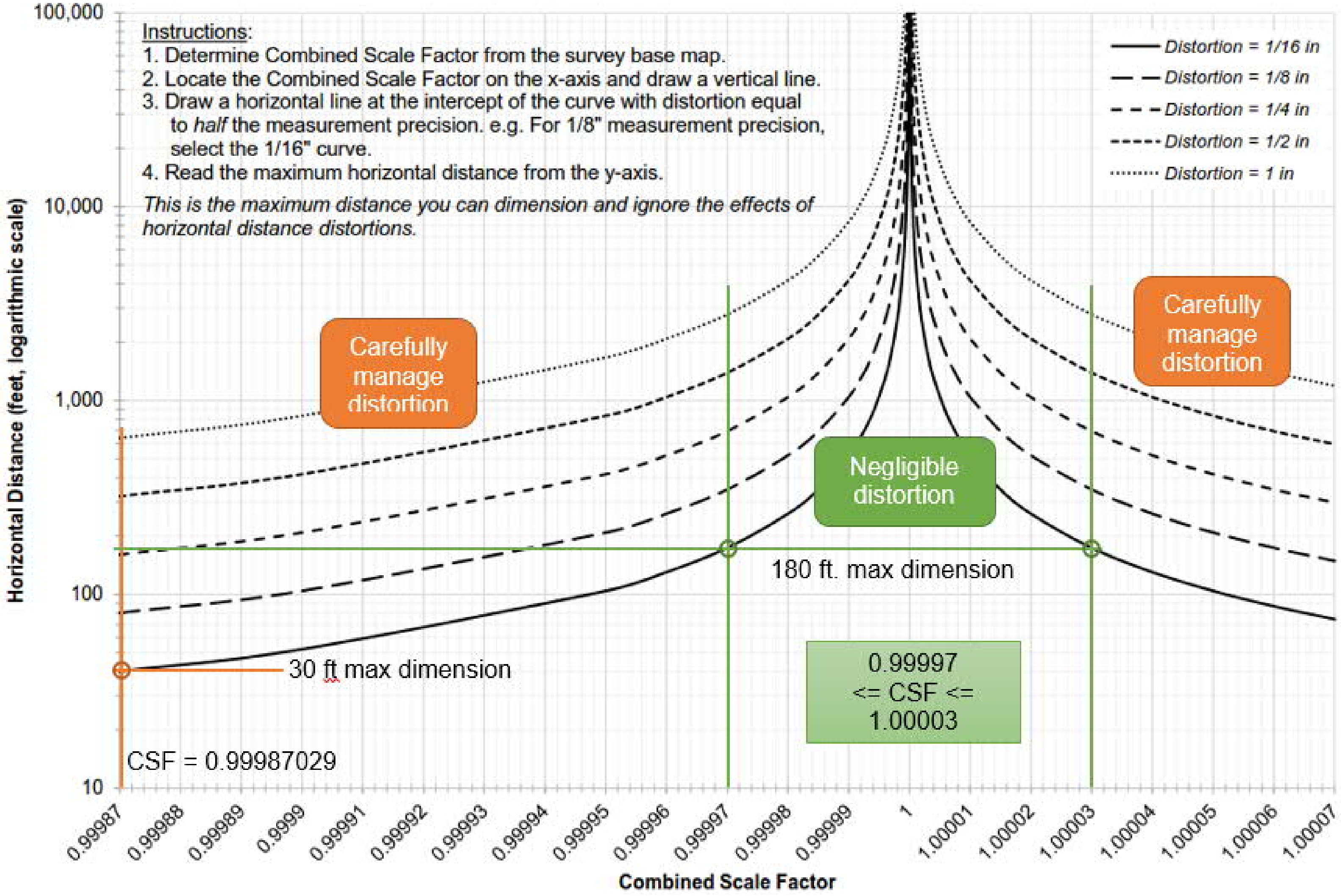


Figure 11. Nomograph to determine maximum undistorted distance.

Bridge models also need to be dimensionally accurate so that they can be used for fabrication. When dealing with a large Combined Factor, it takes advanced and sophisticated CADD management to have a single dimensionally accurate 3D bridge model (measured in ground distances) that lines up with the roadway and other models on MCS 83 grid coordinates. OBM uses the horizontal geometry to lay out the bridge. This workflow enables roadway geometry changes to propagate dynamically through the bridge geometry. In other words, OBM models the bridge in MCS 83 grid coordinates. This model could be projected into ground coordinates for dimensioning, but the workflow to do so relies on creating a custom coordinate system and using the geospatial references function in MicroStation. It also introduces the risk that custom coordinates that appear on the surface to get MCS 83 coordinates may inadvertently be sent to construction.

Another approach that avoids this risk and does not rely on advanced MicroStation skills would be to have two models; a grid scale model for location plans, design coordination, and visualization, and a ground scale model for structure plan dimensioning and detailing. This largely mimics the current workflow. However, the dynamic change propagation between OBM and ProStructures is disrupted. The MPS or Model Inventory would need to clearly identify the authoritative source for the information to be used in construction. More research and collaboration with the Michigan Infrastructure and Transportation Association (MITA) is needed to clarify requirements needed in the field and the best way to manage digital data. It is recommended to engage construction partners in a focus-group to identify how to use and manage the digital data and address ground scale models.

Figure 12 shows how data is exchanged and managed from the MCS 83 grid coordinates for survey base map, roadway, and other design information through local, ground coordinates for structure plans that are dimensionally accurate. The third row shows how the data is used in construction. Data that is used in geospatial (MCS 83) grid coordinates is shown in the light blue boxes. Data that is used in local ground coordinates is shown in the dark blue boxes.

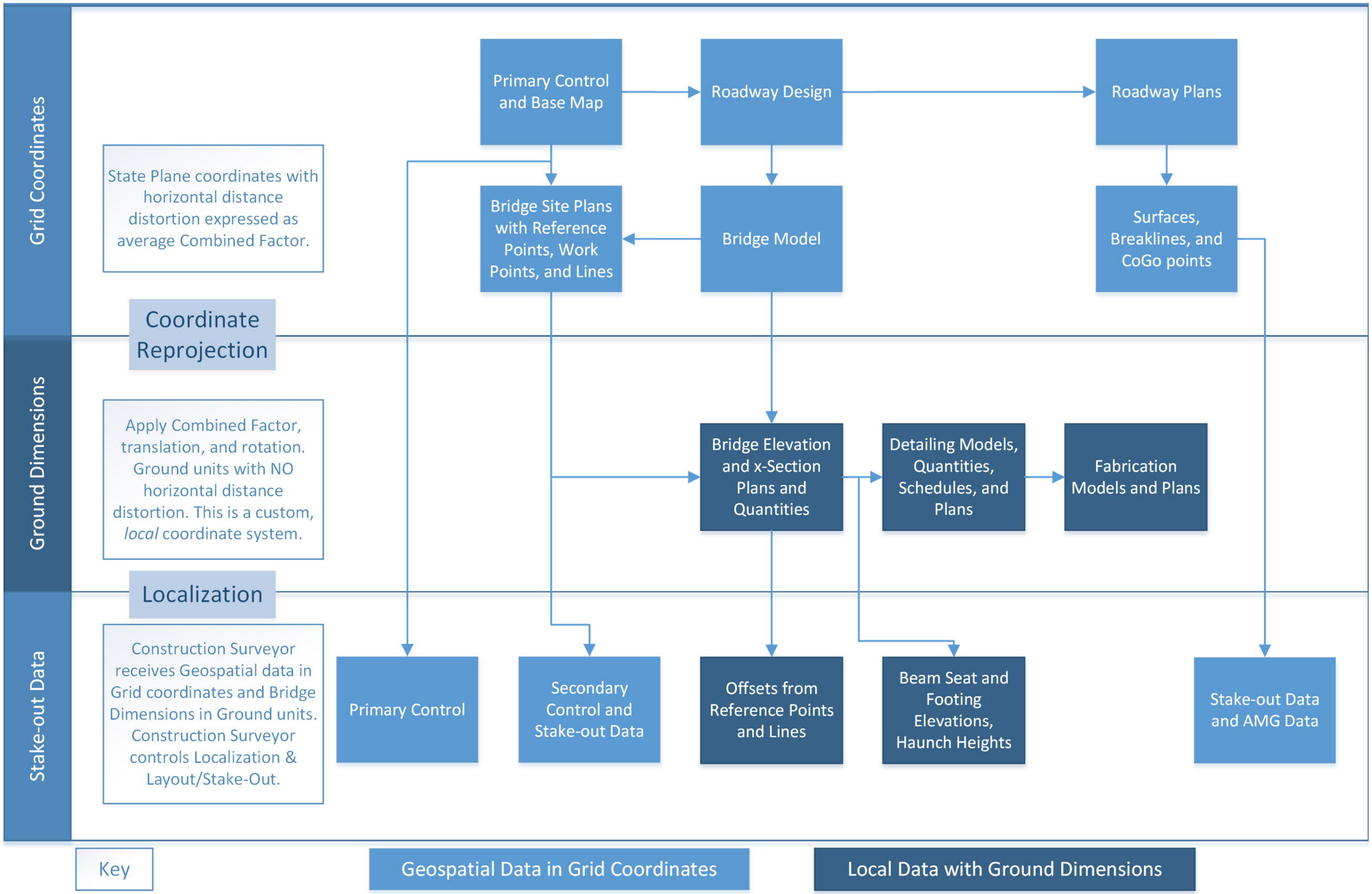


Figure 12: Data flow to construction managing local and MCS 83 coordinates.

5.6 OBM File Formats and Metadata

MDOT currently has an Enterprise License Agreement (ELA) that allows access to the Bentley OBM software, which creates data in proprietary file formats that are only interoperable within other Bentley products. Table 6 provides a summary of file formats that OBM uses for 3D model development. While the researchers created a preliminary template library for OBM, it will not cover every situation encountered in typical bridge designs. There will always be project specific elements that will need modification even if the libraries are further developed. Thus, designers may need to create additional templates to supplement the library. Additionally, MDOT may need to add feature definitions and additional cell and material libraries. Nevertheless, investing in setting up these libraries will result in benefits from standardizing the enterprise CADD workspace.

Table 6: Configuration variables for OBM.

File Type	MDOT Delivered Format
CAD Graphics (2D & 3D)	.DGN (PowerGeopak design file)
Survey Control Coordinates	.TXT (ASCII)
Alignments (Horizontal & Vertical)	.XML (LandXML)
OBM File	.DGN
LEAP Bridge Concrete and Steel Analysis Files	.LBC, .LBS, .XML
ProStructure File	.DGN
Reports	.PDF
Photographs	.JPEG
Video	.MP4

The models created as part of the bridge design process are important deliverables. Additionally, it is important to preserve the key metadata to ensure the model can be used reliably. The necessary metadata is listed in Table 7, along with the purpose for the metadata.

Table 7: Important 3D model metadata

Purpose of Metadata
MPS or Model Inventory
Defines authoritative source of information for each element Identifies responsible party for each element Identifies the authorized uses for which the model can be applied reliably
Geospatial Metadata
Provides information to construction surveyor for accurate layout Provides CSF to determine reliable measurement precision
LOD Standard or Reference
Defines the LODs used in the MPS or Model Inventory

5.7 Derivative Products

Many derivative products can be created as outputs from the models. The number and type of derivative products will affect the cost. The level of effort to prepare these outputs depends on the required visual quality and how the outputs will be used. Some derivative products, especially those related to visualization and simulation, can be expensive to produce. Consequently, it's important to clearly identify how they will be used, how many are needed, and the requirements for visual quality. Table 8 and Table 9 list derivative products from 3D models for visualization and project development respectively. Some are standard design deliverables (contract plans, schedules, estimated quantities), while others are value-added products. It is important to note that as the software matures to add more functionality, a complete parametric model will become easier to develop, and thus be more cost effective to produce derivative products.

Table 8. Derivative visualization products from 3D models.

Description	Guidance
Images	
PowerGEOPAK has powerful visualization tools. As described above, images can be created in a variety of ways, some with little effort, others requiring expertise with the visualization tools.	Images can be included in plan sheets to convey the design intent or staging, used in presentations at public meetings, added to permit applications, etc.
Fly-through Videos	
PowerGEOPAK has powerful visualization tools. Creating fly-through videos requires expertise with the visualization tools. Visual quality needs will affect the cost to produce.	Fly-through videos can be useful for design review and stakeholder engagement.
Simulations	
PowerGEOPAK has simulation (4D modeling) tools. Creating a simulation requires a critical path method schedule with uniquely named tasks and organizing the 3D model into item sets that correlate with the schedule tasks.	The simulation is a PowerGEOPAK file that can be updated by editing either the schedule or the model. The simulation can be played within the PowerGEOPAK file.
Simulation Videos	
The simulation videos are created from a simulation. An image is produced for each time step (e.g., one per week) and composited together in post-production.	Simulation videos represent one scenario and cannot be edited. They are more easily shared and played for the public or other stakeholders.

Table 9: Derivative project development products from 3D models.

Description	Guidance
Contract Plans	
Created from parametric models that are geometrically accurate within the measurement precision. Uses core CADD tools and production workflows.	Current policy (Bridge Design Manual, Guidelines for Bridge Plan Preparation) addresses the guidance for creating and using contract plans.
Rebar Schedules	
Created from parametric models that are geometrically accurate within the measurement precision. Uses core ProStructures tools and production workflows.[1]	Current policy (Bridge Design Manual, Sample Bridge Plans) addresses requirements for schedules.
Estimated Quantities	
Created from parametric models that are geometrically accurate within the measurement precision. Uses core PowerGEOPAK, OBM, and ProStructures tools and production workflows.	Current policy (Bridge Design Manual, Standard Specifications and Special Provisions) addresses the guidance for estimating quantities.
Reports	
Created from parametric models with preset templates including deck elevations, beam seat elevations, model input forms, and quantity/cost estimates. Uses core OBM tools and production workflows.	Current policy (Bridge Design Manual, Standard Specifications and Special Provisions) addresses the guidance for required report content for the individual items.
Analysis Model	
Created from parametric models include necessary geometry and material properties with loading and other required analysis parameters added in the analysis software. Uses core OBM and LEAP Bridge Concrete and Steel tools and production workflows.	Current policy (Bridge Design Manual, Standard Specifications and Special Provisions) addresses the guidance for analysis.
3D PDFs	
Created directly in the CADD software. 3D PDFs preserve saved views and level view functionality. The 3D models can also be navigated and sectioned within the PDF. Normal PDF mark-up functions are also preserved.	3D PDFs could be a useful addition to plan review processes, as they do not require special software and thus are more accessible than 3D models in proprietary formats.

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[1] Current suggested workflow is inefficient, but integration with other software tools and improvements in OBM should improve this process.

6. Conclusions

6.1 Conclusions from the Study

The research identified the most market-ready, beneficial uses of 3D bridge models, which were:

- Visualizations, particularly for staged construction, and
- Leveraging data exchanges for structural analysis, and parametric design for producing standard reports.

The researchers found that the level of effort with the current version of OBM (version 08.11.12.57) to use a 3D model-based for a full plans production workflow did not justify the benefits for most typical bridge projects at this time. Nevertheless, there are some efficiencies that can be gained with existing functionality for certain tasks, and as the software matures, which is occurring rapidly, the level of effort should be reevaluated as the benefits are large once the process of plans production can be automated further with a 3D model-based workflow.

Further, the results of this study have both local and national impact. Locally, MDOT has a plan to leverage their 3D modeling software for bridge design in a way that optimizes the benefits of their currently-available technology. Nationally, AASHTO has raised over $1.2m for a pooled fund study that will advance BIM for bridges and structures. The framework created in the second phase of this research will inform these national efforts.

6.2 Recommendations for Further Research

6.2.1 Creating the Business Case for Implementation of 3D Bridge Models

AASHTO and FHWA efforts to make national standards, and engage with the software community to adopt an open format data exchange are in line with the outcomes of this research. MDOT began an investment to implement 3D bridge models with this research, and would benefit from continued investment to develop staff, and implement the framework developed through this project. The researchers recommend MDOT should use the outcomes of this study to develop the business case for continued support to implement 3D bridge modeling, and continue to evolve digital project development practices as the software and standards mature. It is important to recognize that any technology deployment efforts will affect current productivity as staff learns new software, tools, and methods necessary to adopt model-centric project development as shown on Figure 13. However, as the tools mature, and the staff gets comfortable with the software and new methods; productivity will ultimately increase. (Gartner, n.d.)

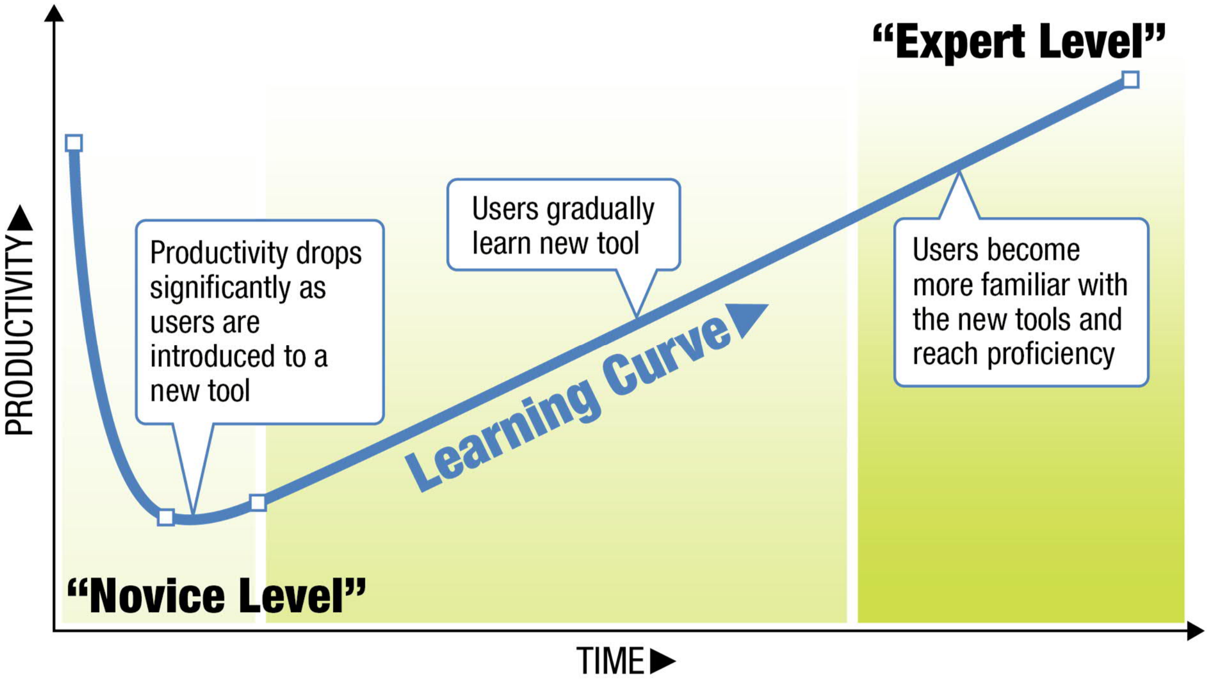

Figure 13. *Illustration of user learning curve. (Shah, et al., 2016)*

6.2.2 AASHTO Pooled Fund Coordination

The purpose of the upcoming pooled fund study is to help establish standards, guidelines, or manuals for bridge project stakeholders that will facilitate a non-proprietary BIM data exchange specific for bridges. MDOT's investment for the study of 3D modeling for bridges should be leveraged in any future efforts related to this topic. Thus, it is highly recommended that MDOT becomes an active participant of the AASHTO T-19 committee and the pooled fund study to ensure MDOT's outcomes from this research and any future standards are aligned with the national efforts.

6.2.3 Collaborative Review

The engineering support staff is currently working on a plan to leverage 3D engineered models to conduct collaborative real-time reviews for producing better designs and minimizing the risk of change orders. The bridge staff should discuss how the implementation of 3D bridge models align with those efforts.

6.3 Research Implementation Plan

This section summarizes the recommendations for implementing the outcomes of this research.

6.3.1 Updates to MDOT Standards

To be effective, the framework developed in Phase II of the research needs to be incorporated into the relevant sections of MDOT's policy that guides how bridge information is created and used. The screening process led to a focus on policy for bridge design, where the models would typically be created. However, as the industry progresses toward data standards for bridges, it will be important to keep in mind the future data needs for construction, inspection, operation, and asset management and update the standard for creating models as these evolve.

MDOT already has a plan in place for using 3D models to collect bridge inspection data. It is important to keep that recognized use of bridge 3D models in mind and to coordinate with MDOT's bridge management section when developing MDOT's protocols for creating 3D models in bridge design.

6.3.1.1 Bridge Design Manual

There is a current research project that is considering best practices for modernizing MDOT's Bridge Design Manual, guides, and policy documentation. While the policy to guide the development and quality control of 3D bridge models would reside in the Development Guide Wiki, full value capture requires using 3D models and their derivative products in the standard processes and decision-making milestones of project development, which are guided by the Bridge Design Manual.

The Bridge Design Manual should be updated to include any pertinent information for understanding the 3D model derivative products (such as 3D PDFs, images, videos, and simulations) that are used in decision-making. The framework presented in Section 5 should be incorporated into the Bridge Design Manual, and at a minimum, it should include the following:

- LOD definitions to guide the production of the models,
- LOV guidelines to inform staff about visual aids needed,
- Identification of derivative products that support decision-making, and
- A decision-tool for project managers to identify which 3D model uses are appropriate to their project characteristics

6.3.1.2 Guidelines for Bridge Plan Development

The Guidelines for Bridge Plan Development provide direction on the information to be included on each sheet. MDOT's Digital Delivery initiative is evaluating how MDOT provides information for construction and is a larger initiative than the implementation of 3D bridge models. However, implementing 3D model-based plan production (when it is mature) creates an opportunity to restructure how some of the information is delivered, either for efficiencies in plan production or in how the information is consumed by contractors and inspectors.

MDOT should collaborate with MITA to discuss what digital data could be eliminated from the plans if it was provided through another electronic media. The industry engagement will be long-term commitment to understand how contractors consume 3D bridge models and related digital design data, and may result in setting interim and long-term goals. For example, MDOT is already working on implementing rebar schedules as stand-alone spreadsheets instead of as plan graphics because the data is more accessible in that format. This could reduce the level of effort to create plans and improve the accuracy of the contract documents by avoiding manual steps in the process.

Implementing model-based plans production necessitates an evaluation of the processes of creating the plans from the models. The authoritative information source needs to be identified for each sheet. Sheets that conflate local dimensions and MCS 83 grid-based information should be reconsidered because of the challenges of aligning the two coordinate systems. Over time, MDOT may realize efficiencies from building a library of parametric detailing models for standard elements (such as beams) and systems (such as abutments). These models could include pre-defined plan sheets and schedules that update automatically with changes to the geometric parameters.

6.3.1.3 Development Resources Wiki

This resource details the requirements for design submittal requirements. It is currently most mature in how it addresses road design. This guidance should be updated per the recommendations in Table 10.

Table 10. Recommendations for updates to the development resource wiki.

Resource	Location to be Updated	Recommendations
Selection Criteria	Development Resources Design Submittal Requirements Chapter 2 - Data Requirements	Add the “Project Selection Criteria for Bridge Modeling” information included in the *3D Bridge Modeling for Project Managers* training material.
LOD and LOV	Development Resources Design Submittal Requirements Chapter 2 - Data Requirements	Add the “Model Development Specifications” information included in the *3D Bridge Modeling for Project Managers* training material.
Standards for MPS or Model Inventory	Development Resources Design Submittal Requirements Chapter 4 – Developing Electronic Data	Add the “Model Development Specifications” information included in the *3D Bridge Modeling for Project Managers* training material.
Standard Naming Conventions	Development Resources Design Submittal Requirements Chapter 3 – Standard Naming Conventions	Add the “Data Management” information included in the *3D Bridge Modeling for Project Managers* training material.
Guidance for acceptable file formats for models and derivative products	Development Resources Design Submittal Requirements Chapter 2 – Data Requirements	Add the “Software Requirements and Deliverables” information included in the *3D Bridge Modeling for Project Managers* training material.

6.3.1.4 Support Services Help Webpage

This resource details the requirements for design submittal requirements. It is currently most mature in how it addresses road design. This guidance should be updated per the recommendations in Table 11.

.

Table 11. Recommendations for updating the support services help webpage.

Resource	Location	Recommendations
Guidance for creating models and derivative products	Modeling – Bridge Training Workflows	Add the delivered training material as applicable (e.g. training or workflows)
Quality control and review checklists	Modeling – Bridge	Create a new subcategory called "Checklists". Add the delivered checklists here.

6.3.1.5 Bridge Design Workspace and Technical Support

The MDOT_02 workspace provides the automation tools and resources that MDOT's designers and technicians use to develop 3D models and plans. It is recommended to build upon the preliminary workspace developed to create the four sample models. The following items were delivered as part of the preliminary workspace:

- Sample models (e.g., OBM files with models, saved views, and sheets).
- Libraries of standard parametric components and templates based on MDOT standards (e.g., decks, barriers, piers, and abutments) for OpenBridge Modeler.
- Library of materials used in bridge model components based on MDOT standards.
- Libraries of Feature Definitions and Element Templates to incorporate standard level symbology, and standard views with level presets.
- Seed files for OpenBridge Modeler.

MDOT should continue to develop the workspace to include additional templates created by structural designers. While it is a good CADD management practice to restrict what users can add to the workspace, it is highly recommended to establish a protocol for allowing power users to submit recommendations for additions. Empowering advanced users will accelerate the organic growth of bridge modeling within MDOT.

6.3.2 Staff Development

It is critical to establish a plan for developing current and new staff to use the tools necessary for understanding the processes for designing bridges in 3D, producing derivative products, and producing plans. New high school and college graduates have been exposed to 3D modeling in school and college. Their expectations for how they will work do not align to current 2D workflows. MDOT should find a balance between empowering these young designers and technicians to use their aptitudes and skillsets with the software MDOT already has under license, and the need to provide consistent, repeatable and reliable bridge information to contractors and inspectors.

Training is most effective when it is provided on-demand to ensure the user will practice the skills learned immediately. Peer-to-peer training can also be effective providing the mentor is excited and willing to help the mentee. There is a tremendous opportunity for mentoring and intergenerational knowledge transfer as young staff with an aptitude for

3D modeling help project managers and senior staff who have not been hands-on with CADD for many years.

For the initial deployment, it is recommended to train a group of designers who will be working together on a project, so they can build their skills set together in an environment that is collaborative and empowering. Nevertheless, statewide adoption for developing MDOT staff will require focused training to develop specific skills for different applications. Table 12 summarizes the training necessary to build specific skill sets based on MDOT priorities for 3D bridge modeling.

Table 12. Training recommendations for developing specific skills sets.

Tasks	Necessary Skills	Recommended Training
Managing 3D Bridge Modeling Projects	Basic understanding of 3D models, Model Inventory, LOD, LOV, and contract requirements	PM Handout
Using Roadway Data	Working knowledge of common roadway data and files	MDOT Using OpenBridge Modeler MDOT OpenRoads Beginner Learning Path
Creating 3D Bridge Model for Analysis	Comprehension of basic OBM tools and understanding of LEAP Bridge Concrete and Steel analysis software	Bentley Bridge Analysis YouTube Channel (LEAP Bridge Concrete and Steel content)
Staged Construction and Temporary Works	Working knowledge of PowerGEOPAK drawing and solids modeling tools and OBM tools	MDOT Workflow – Using Bridge Models in Staged Construction
Creating Plan Sheets from 3D Bridge Model	Ability to use PowerGEOPAK solids modeling, annotation, and drawing tools as well as OBM view tools	MDOT Workflow – Model Output (Generating plan views)
Creating Basic Visualization Models	Comprehension of basic OBM tools and PowerGEOPAK view settings	MDOT Using OpenBridge Modeler
Creating Advanced Visualization Models	Basic use of OBM, ConceptStation, and LumenRT	Bentley LEARNserver – Using OBM and Lumen RT

6.3.3 Recommendations for Software Evaluations

A critical success factor for statewide implementation of 3D bridge modeling is having the right tools at the right time. MDOT identified plan production, visualization and structural analysis as the top three priorities for short-term implementation. However, as the software and national standards evolve, MDOT may want to evaluate additional programs to effectively and efficiently advance 3D bridge models for other applications. As national standards and data exchanges using IFC become available, and interoperability is no longer an issue; it may be possible for owner agencies to purchase multiple software packages that provide the best solution for a particular task. Researchers recommend to keep options open as software packages become less proprietary and information can be exchanged from one vendor solution to another.

6.3.4 Initial Testing and Pilot Projects

The group of selected power users should perform the initial testing of the workspace and the framework. These power users should work closely with the project team and engineering support to provide continuous input, document lessons learned, and make recommendations for selecting other projects. After the initial testing period, MDOT should analyze the lessons learned, and select several pilot projects to track benefits, incorporate lessons learned, and engage with the consulting community. The initial piloting phase should be implemented immediately upon the initial training is received. Six months is an acceptable piloting period before evaluating the new process. Recommendations for initial testing is illustrated in Figure 14.

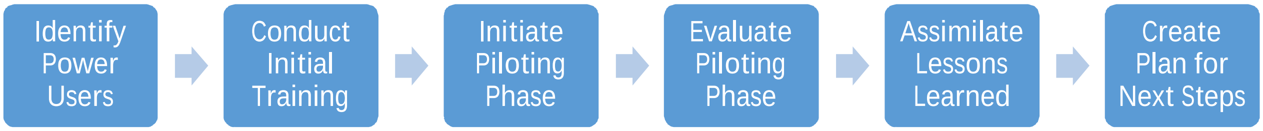

Figure 14. Recommendations for initial testing.

Appendices

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Appendix 1. List of Acronyms, Abbreviations and Symbols

Appendix 1. List of Acronyms, Abbreviations and Symbol

This section introduces some of the key acronyms used in this report.

3D: Three-dimensional. Has properties that are defined for three axes, nominally x, y, and z, in a Cartesian coordinate system.

4D model: Four-dimensional model. A 3D simulation of change over time. For example, a 3D model that has been connected to a construction schedule to produce a simulation of the construction process, or a 3D simulation of deterioration.

AASHTO: American Association of State Highway and Transportation Officials. A standards-setting body for specifications, test protocols, and guidelines. Voting members are representatives of U.S. State highway and transportation agencies.

AIA: American Institute of Architects. A professional organization that produces a collection of Digital Practice Documents, some of which relate to standard practices for use of Building Information Modeling.

BIM: Building Information Modeling. A process involving the generation and management of digital representations of physical and functional characteristics of places.

CADD: Computer-Aided Design and Drafting. A category of computer software that is used to develop roadway designs. CADD software typically uses an object-oriented approach to apply mathematical rules that automate the process of drafting roadway designs. 3D digital design data is a common output of the application of CADD software.

FHWA: Federal Highway Administration. An agency within the U.S. Department of Transportation with a mission to provide national leadership and innovation to improve mobility on the nation’s highways.

IFC: Industry Foundation Class. A platform-neutral, open data model and file format specification that is intended to describe building and construction industry data. It is an international standard for BIM (International Organization for Standardization, 2013).

LOD: Level of Development. A qualitative designation that communicates the degree of engineering intent behind a 3D model that defines the authorized uses. Normally the LOD will increase through the design development process.

LOV: Level of Visualization. A qualitative designation that communicates the degree of visual enhancement given to the 3D model elements, to suit the needs of different target audiences. Generally, non-technical audiences need color-realistic geometry or even photo-realistic materials to be able to understand bridge models.

MPS: Model Progression Specification. A specification that defines how the LOD for individual model elements increases over the project milestones. The MPS will assign a specific, minimum LOD to each model element for each milestone. The LOD typically increases from milestone to milestone.

XML: Extensible Markup Language. A text-based, human-readable and machine-readable structured data schema.

Appendix 2. Training Materials

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A2.1 Training Approach for Developing Materials

The researchers created training material to address two different audiences: the structural designers and the project managers.

The training material for structural designers was specifically created to provide technical guidance for directly using the software for producing bridge models to support visualization, structural analysis, basic plan production and reporting. This training material was used during the initial interactive “over-the-shoulder” session for a select group of power users who had been previously identified by bridge design leadership. The intent for this training approach was to empower these power users with the knowledge base necessary to test and pilot bridge modeling, and eventually to become the in-house experts to implement bridge modeling in an organic way within the organization.

On the other hand, the training material for project managers was developed to provide guidance for developing contract language and managing projects in which bridge modeling will be used. This training material was used during a virtual presentation to introduce them to bridge modeling and contract management best practices.

A2.2 Training Courses

A2.2.1 Training Course #1: Virtual Kickoff Training

A kick-off webinar was held on February 20, 2018 to set expectations and provide information to meet pre-requisites for the interactive training session.

Intended audience: Project Managers and Structural Designers.

A2.2.2 Training Course #2: MDOT 3D Bridge Modeling for Project Managers

This course was delivered on March 19, 2018. The materials for this course include a handout that follows MDOT’s training template and provides a general overview of 3D modeling for bridges, and contract that is specific to MDOT.

Intended audience: Project Managers.

A2.2.3 Training Course #3: MDOT 3D Bridge Modeling for Structural Designers

This course was delivered on March 28, 2018. The materials for this course include a handout that follows MDOT’s training template and provides technical guidance for developing 3D bridge models using Bentley’s OBM using MDOT specific CADD workspace.

Intended audience: Structural Designers.

A2.3 List of Workflows

A2.3.1 Using and Modifying Templates

This workflow was developed to help designers understand the steps for placing and modifying elements using parametric templates delivered in the MDOT workspace for Bentley's OpenBridge Modeler (OBM) version 08.11.12.57 and PowerGEOPAK SS4. The tools used in this document provide a starting point to create specific bridge elements to make modeling more efficient.

Skill Sets Required to Follow this Workflow:

1. Working knowledge of PowerGEOPAK drawing tools
2. Working knowledge of standard OBM tools

Training for Developing Required Skill Sets:

1. MicroStation Basics-2D Drafting and Detailing (MDOT) (Bentley LEARN)
2. Using OpenBridge Modeler (MDOT)
3. Creating Deck Templates in OpenBridge Modeler (Bentley Bridge Analysis YouTube Channel) (8:19)

Companion Video Tutorials to Workflow:

1. Using and Modifying Templates (14:49)

A2.3.2 Placing and Modifying Wingwalls

This workflow was developed to help designers understand the steps for placing and modifying wingwall elements, or return walls, for Bentley's OpenBridge Modeler (OBM) version 08.11.12.57 and PowerGEOPAK SS4. This document provides guidance in creating these elements since it is a new functionality in this version of OBM and documentation included in the software is limited.

Skill Sets Required to Follow this Workflow:

1. Working knowledge of standard OBM tools

Training for Developing Required Skill Sets:

1. Using OpenBridge Modeler (MDOT)

Companion Video Tutorials to Workflow:

1. Placing Wingwalls in OpenBridge Modeler (Bentley Bridge Analysis YouTube Channel) (4:39)

A2.3.3 Model Outputs

This workflow was developed to help designers understand the steps for creating specific outputs directly from the model using Bentley's OBM version 08.11.12.57 and PowerGEOPAK SS4. The tools used in this document provide instructions for generating reports, creating 3D pdfs, and generating 2D drawing views directly from the model so they can be placed on traditional 2D drawing sheets. The training material includes a handout that follows the MDOT training template and a short video.

Skill Sets Required to Follow this Workflow:

1. Working knowledge of PowerGEOPAK drawing composition tools
2. Working knowledge of standard OBM tools
3. Working knowledge of Adobe Acrobat Reader 3D tools

Training for Developing Required Skill Sets:

1. MicroStation Basics-2D Drafting and Detailing (MDOT) (Bentley LEARN)
2. Using OpenBridge Modeler (MDOT)

Companion Video Tutorials to Workflow:

1. Model Outputs (10:48)

A2.3.4 Supplementing Bridge Model Development

This workflow was developed to help designers understand the steps for adding higher Level of Development (LOD) to 3D bridge models beyond the current capabilities of Bentley OpenBridge Modeler (OBM) version 08.11.12.57. The tools used in this document provide some alternative solutions to add approach and sleeper slabs, retaining walls, and diaphragms, which are not included in the basic OBM element tools. Also, this workflow will walk the user through the steps for modifying elements previously placed with OBM tools, such as abutments for return/end walls.

Skill Sets Required to Follow this Workflow:

1. Working knowledge of PowerGEOPAK drawing tools
2. Working knowledge of standard OBM tools
3. Working knowledge of PowerGEOPAK 3D solids modeling tools

Training for Developing Required Skill Sets:

1. MicroStation Basics-2D Drafting and Detailing (MDOT) (Bentley LEARN)
2. MicroStation Everything 3D: 02-AccuDraw and B-Splines (Bentley LEARN)
3. Using OpenBridge Modeler (MDOT)

Companion Short Video Tutorials to Workflow:

1. Supplementing OpenBridge Modeler (OBM) Element Development (8:18)

A2.3.5 Using Bridge Models in Staged Construction

This workflow was developed to help designers understand the steps for creating construction joints consistent with staged construction for Bentley's OpenBridge Modeler (OBM) version 08.11.12.57 and PowerGEOPAK SS4. These instructions provide guidance in how to efficiently create and use the models in these situations since the functionality is not provided in this version of OBM and requires additional tools.

Skill Sets Required to Follow this Workflow:

1. Working knowledge of PowerGEOPAK drawing tools

2. Working knowledge of standard OBM tools
3. Working knowledge of PowerGEOPAK 3D solids modeling tools

Training for Developing Required Skill Sets:

1. MicroStation Basics-2D Drafting and Detailing (MDOT) (Bentley LEARN)
2. MicroStation Everything 3D: 02-AccuDraw and B-Splines (Bentley Learn)
3. Using OpenBridge Modeler (MDOT)

Companion Video Tutorials to Workflow:

1. Using Bridge Models in Staged Construction (4:29)

A2.4 List of Videos

A2.4.1 Recorded Meetings

Several training sessions and meetings were recorded and provided as a deliverable of this research. The most valuable recordings were summarized and are provided in Table 1.

Table 1. Training Recordings.

Name of the Video	Date Recorded	Topic	Length (Hr:Min:Sec)
Phase III Demonstration	Oct. 3, 2018	Demonstration of research sample model bridges	(01:33:16)
Initial Virtual Kick-Off Training	Feb. 20, 2018	Training Session #1: Webinar training to set expectations and provide information for meeting pre-requisites for Instructor-led Power User Training.	(00:58:17)
PM Webinar Training	Mar. 19, 2018	Training Session #3: Webinar training to provide overview of 3D bridge models, determine how to determine projects suitable for 3D bridge design, and create plans for using 3D models on a project.	(00:47:11)

A2.5 Additional Training Resources

A2.5.1 Bentley Bridge Analysis YouTube Channel

Bentley has a dedicated YouTube channel for topics related to bridge analysis, in specific for LEAP and OBM. Bentley uploads short videos on a frequent basis. The researchers selected the top videos that could be beneficial for MDOT staff to watch and are listed in Table 2.

.

Table 2. Recommended training videos from the Bentley Bridge Analysis YouTube Channel.

Name of the Video and Link to YouTube	Date Published	Description	Length (Min:Sec)
OBM Overview	Jun 24, 2016	Provides a general overview of the OBM product	01:53
How to Build a 3D Bridge Model in 5 minutes with Bentley's OBM	Jul 12, 2017	Provides a quick overview of the OBM software [No voice instructions]	06:05
Initial Setup for an OBM Bridge	Aug 9, 2017	Walks the user through the steps of setting up geometry and terrain files (from roadway design) for an OBM project	03:58
OBM Starting with Geometry	Aug 9, 2017	Provides instructions on how to import alignments and profiles from a roadway project GPK file or referencing civil geometry from a DGN provided by the roadway designer	02:25
OBM Terrain Models and Elevation Constraints	Aug 9, 2017	Describes how terrain models work with the placing of piers as your substructure elements using elevation constraints	03:16
Placing Pierlines in OBM	Aug 9, 2017	Explains the details of applying span lengths and skew angles to place pierlines	05:13
Placing Wingwalls in OBM	Aug 9, 2017	Walks the user through the process for placing wingwalls	04:39
OBM Camber	Aug 9, 2017	Walks the user through the process of exporting camber information from LEAP Bridge Concrete to OBM for generating reports	02:51
OBM Variable Deck Width	Jul 13, 2017	Walks the user through the steps for setting up a variable deck width	04:21
Variable Cap in OBM	Sep 5, 2017	Describes the process for adding a variable cap	07:56
OBM – Attaching a Roadway Superelevation to a Bridge Deck	Oct 27, 2017	Walks the user through the steps for attaching superelevation to your bridge model	05:48
OBM to LEAP Bridge Concrete and Back	Oct 2, 2017	Walks the user through the steps for exchanging data between OBM and LEAP Bridge Concrete	08:12
OBM Placing Bearings from Catalog Services	Sep 15, 2015	Walks the user through placing bearings using a catalog service.	02:09
Variable Cap in OBM	Sep 5, 2017	Walks the user through the steps to create a variable cap in the substructure definition of a multi-column pier template	07:57
Steel Bridge in OBM	Aug 30, 2017	Walks the user through designing a steel girder bridge with OBM, including placement of a rolled steel beam layout, cross frames and concrete substructure	11:45

A2.5.3 Virginia Department of Transportation OBM Training Material

The Virginia Department of Transportation (VDOT) shared the training developed for their recent implementation of OBM and has general and step-by-step instructions on the topics listed below that can be used for additional instructional material as needed. This training material will be available to MDOT internal staff.

- General overview of Bentley OBM.
- OBM tools overview.
- Importing roadway geometry and surfaces.
- Adding bridge basic information and setting pier locations.
- Modeling superstructure elements.
- Modeling substructure elements.
- Running various reports.

Appendix 3. Sample MPS

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Appendix 3. Sample MPS

Category	Element	Sub-Element	Preliminary Plans			Final Design			RID			Construction			As-Built		
			LOD	Resp. Party	Notes	LOD	Resp. Party	Notes	LOD	Resp. Party	Notes	LOD	Resp. Party	Notes	LOD	Resp. Party	Notes
Proposed	Decks/Slabs	Deck/Slab															
		Fascia															
		Sidewalk															
		Pedestrian Approach															
		False Decking, Maintenance Sheeting and Stay-in-Place Forms															
		Joints															
	Superstructure	Girders/Floor Beams/Stringers															
		Trusses/Arches/Cables															
		Diaphragms/Cross frames															
		Miscellaneous Superstructure Elements															
	Substructure	Abutment															
		Wingwall															
		MSE Walls															
		Column															
		Pier Wall															
		Pier Cap															
		Pile															
		Pile Cap/Footing															
		Tower															
	Other Elements	Approach Slab															
		Bridge Railing															
		Protective Coating															
		Bearings															
		Culverts															
		Scour Protection															
	Appurtenances	Sign Structures															
		Lighting															
		On-structure drainage															
		Conduits															
	Earthwork	Structural Excavation															
		Structural embankment															
		Structural Backfill															
		Earthwork															
	Reference Geometry	Reference and Work Points															
		Reference Lines															
		Earthwork															
	Roadway	Final Surface															
		Roadway Prism Components															
		Retaining Walls															
		Guardrail															
		Utilities and Drainage (Separated by Utility Type)															

Category	Element	Sub-Element	Preliminary Plans			Final Design			RID			Construction			As-Built		
			LOD	Resp. Party	Notes	LOD	Resp. Party	Notes	LOD	Resp. Party	Notes	LOD	Resp. Party	Notes	LOD	Resp. Party	Notes
Temporary Works	Earthwork	Excavation															
		Stockpiles															
		Erosion Prevention & Sediment Control															
	Falsework																
	Equipment																
	Detours																
Existing	Decks/Slabs																
	Approach Slab																
	Bridge Railing																
	Superstructure	Girders/Floor Beams/Stringers															
		Other Support Types (Trusses, Arches, Cables)															
		Diaphragms/Cross frames															
		Miscellaneous Superstructure Elements															
	Bearings																
	Substructure	Abutments and Wingwalls															
		Piers															
		Foundations															
	Appurtenances	Sign structures															
		Lighting															
		On-structure drainage															
		Conduits															
	Roadways	Wearing Surface															
		Retaining Walls															
		Guardrail															
		Terrain															
	Utilities and Drainage	Differentiate by Utility Type and SUE Designation															
	Context	Terrain															
		Roadways															
		Buildings															
		Landmarks															

Appendix 4. Phase I Report

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1. Introduction

This research project is conducted by WSP | Parsons Brinckerhoff on behalf of the Michigan Department of Transportation (MDOT). This report documents the literature search, survey of ongoing efforts by other State Departments of Transportation (DOTs), a survey of MDOT practices, and other information collected in the first phase of the research to establish the context for the research activities. In subsequent phases, shown in Figure 1, the research team will refine a framework that guides the 3D and 4D bridge modeling process (Phase II), develops sample bridge models (Phase IIIPhase III), and deliver a workspace and documentation that will support implementation of 3D and 4D bridge modeling policies and practices at MDOT (Phase IV).

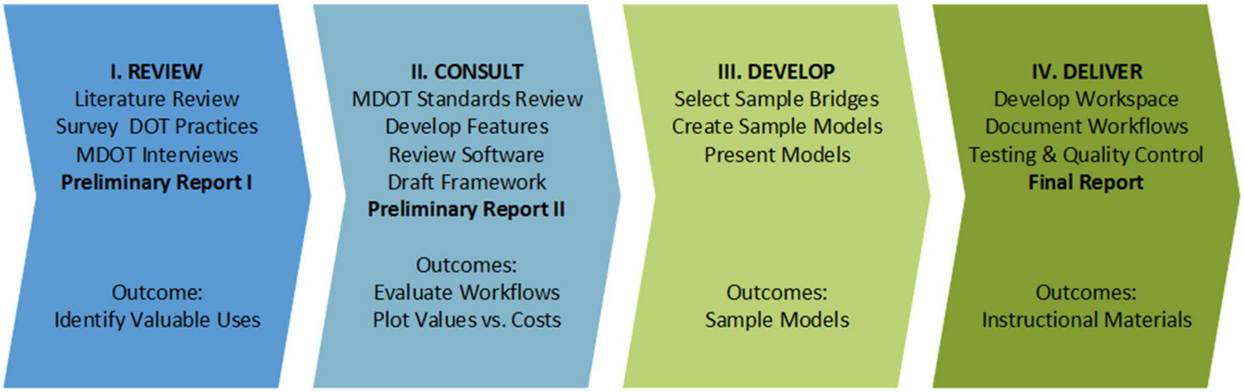


Figure 1. Research phases.

1.1 Background

Over the years, MDOT has developed new policies for designing and constructing road projects that have helped set the national standards for 3D modeling and e-Construction (Federal Highway Administration, 2015c). MDOT and contractor partners are benefiting from the predictability, repeatability and reliability of standardized roadway data delivered from design to construction that is accessible in the field from mobile devices. Bridges stand out as the next logical step for MDOT to push into 3D.

The value of extending 3D models to bridges could be realized in many ways, which vary based on lifecycle phase, type of project, intended uses of the 3D model, the detail in the model, and the accuracy of the model. There is more variety in 3D workflows for bridges than there is for roadways. The tools used to model bridges vary by structural type, and whether the bridge is new, being replaced, or being rehabilitated or modified. The framework for defining when and how to model bridges is expected to be more complex than that developed for roadways.

Bridges vary greatly in structural type, which has significant impacts on the parametric rules that govern layout. Though the layout rules are relatively simple for the majority of structural types, the software development efforts and market are fragmented. The absence of a standard data format for bridges is significant, making it difficult to use different software in series to increase detail of the design without data degradation.

MDOTs objectives for investigating and implementing 3D and 4D models for bridges are:

- Aid designers to size and place components
- Confirm fit-up of precast elements
- Identify conflicts
- Demonstrate staging for part-width, multi-stage, and accelerated bridge construction
- Better quantify and identify limits of earth disturbance for all projects requiring earthwork and more accurately identify extents of items such as retaining walls and return walls at substructures.
- Communicate information in the plans to coordinate and demonstrate project activities
- Provide standardized models that can integrate with operational needs including inspection, rating, and routing.

Bridge design and construction represents a significant capital investment annually for MDOT. However, only a small portion of MDOT's bridges are actively affected by design or construction projects. MDOT manages more than 4,750 bridges with an annual program budget of approximately $185 million. Between 150 and 200 bridges are rehabilitated, improved, or replaced annually.

1.2 Objective

The first phase of this research explored emerging practices and research efforts nationally to set the context for developing a framework in the next phase. This included identifying potential valuable uses for 3D and 4D models for bridges, regardless of their current state of adoption amongst DOTs and their consultant and contractor partners. The objective was to explore uses that had some precedent, as well as potentially overlooked uses. Opportunities for synergies between different practice areas were also explored, for instance, using roadway base files in the bridge plans production process, or using roadway corridor models to extract cross-sections for hydraulic modeling. In the next phase of the research these uses will be filtered to extract the most favorable or practical for further development.

The next stage is to create the framework of a decision tree for bridge designers to identify modeling priorities based on each structure's unique features. Some have simple designs, but challenging locations with high traffic volumes, limited space for staging, and environmental impacts from noise, vibration, and emissions. Others have accessible sites, but challenging design features. The data needs and uses in construction vary as well. For example, 4D models for staging and public involvement need low detail and accuracy, fabrication of steel I-girders does not require a model at all, but rather tables of deck geometry and key elevations, while concrete structures could use highly accurate and detailed models to plan formwork or to prefabricate bridge elements and systems.

Implementation is challenging, but the benefits should not only introduce efficiencies in design, construction, and maintenance, but also support MDOT's institutional knowledge management. MDOT can attract and retain the best skilled staff by embracing tools that empower engineers and technicians to spend most of their time on high-value functions, rather than repetitive tasks. If the framework and methods are intuitive and developed to align with the core job functions of bridge design, construction, and operations, then obtaining users' buy-in is easier. Software proficiency is not a difficult skill to develop compared to professional skills of analysis and design, but proper training resources and clear documentation that articulates the goals and vision of MDOT is necessary for a successful adoption of the technology.

1.3 Scope

In Phase I, the WSP | Parsons Brinckerhoff team conducted a literature review to obtain current practices in the bridge design community. Secondly, the team conducted interviews with MDOT personnel to be able to characterize the nature and extent of bridge modeling internal to the department. Based on the findings from these activities we formulated the requirements for successful definition of a future framework for developing MDOT 3D/4D bridge models and plans, the objective of Phase II of this project. Finally, we captured the knowledge gathered and recommendations into this Phase I Report.

1.4 Methodology

The team reached out to the DOT community, the American Association of State Highway and Transportation Officials (AASHTO) Subcommittee on Bridges and Structures (SCOBS), and the Federal Highway Administration (FHWA) to collect information about on-going work, current and emerging practices.

In order to survey DOT practices, we identified a handful of peer states that have implemented or are implementing 3D modeling for bridges and structures. These were New York, Utah, Iowa, Wisconsin, and California. We identified these agencies either through our engagement with FHWA on 3D modeling technology deployment for Every Day Counts (EDC) rounds two (EDC-2) and three (EDC-3) or through the literature search. We conducted interviews to ascertain the current and envisioned application of 3D models for bridge projects, as well as the perceived challenges and benefits.

There were three other efforts which supported the outreach to those peer DOT agencies in the states mentioned. The first was the National Cooperative Highway Research Program (NCHRP) 20-07–Task 377 workshop in May 2016, the second was an FHWA web-based peer exchange in June 2016, and the third was the AASHTO SCOBS meeting in June 2016.

The research team conducted interviews with MDOT staff across different offices that create and/or consume 3D models in bridge projects. Offices and particular individuals were targeted for the interviews. We developed a standardized interview structure to ensure consistent presentation and results. The content of the interview questions was designed to address four main topic areas; current practices at MDOT, vision, priorities and challenges. Finally, formal meeting minutes captured the responses shared by interviewees.

1.5 Organization of Report

This report is organized in three primary sections; literature review, current practices, and final recommendations to MDOT in support of developing the proposed framework to develop 3D/4D bridge models and plans. The literature review section summarizes the available literature on the use of 3D and 4D bridge models and plans, as well as lessons learned from the use of 3D and 4D models and plans in related industries. The current practices section presents an overview of the state of the practice for using 3D and 4D models and plans within MDOT and peer agencies. Finally, the recommendations section lays forth the constraints and evaluation criteria to be used in Phase II to develop the framework for 3D and 4D bridge models and plans, based on the MDOT interviews and peer agency engagement.

1.6 Acronyms and Definitions

This section introduces some of the acronyms used in this report.

3D: Three-dimensional. Has properties that are defined for three axes, nominally x, y, and z, in a Cartesian coordinate system.

4D model: Four-dimensional model. A 3D simulation of change over time. For example, a 3D model that has been connected to a construction schedule to produce a simulation of the construction process, or a 3D simulation of deterioration.

AASHTO: American Association of State Highway and Transportation Officials. A standards-setting body for specifications, test protocols, and guidelines. Voting members are representatives of US State highway and transportation agencies.

ABC: Accelerated Bridge Construction. An approach to bridge construction that uses innovative planning, design, materials, and construction methods to reduce the construction period. ABC strategies include Slide-in Bridge Construction (SIBC), Self-Propelled Mobile Transporters (SPMTs), Prefabricated Bridge Elements and Systems PBES), and Ultra-High Performance Concrete (UHPC) connections.

AIA: American Institute of Architects. A professional organization that produces a collection of Digital Practice Documents, some of which relate to standard practices for use of Building Information Modeling.

AMG: Automated Machine Guidance. The use of real-time positioning equipment with 3D digital data to guide or control the blade on construction equipment, resulting in real-time construction layout without the need for physical markers such as stakes or hubs.

BIM: Building Information Modeling. A process involving the generation and management of digital representations of physical and functional characteristics of places.

BMS: Bridge Management System. An information system for managing bridges, usually including asset inventory and condition data at the element level, as well as predictive algorithms for bridge conditions used to optimize the type and timing of preservation and replacement activities across the system.

BrIM: Bridge Information Model. Derived from BIM, Bridge Information Models are 3D representations of the physical and functional characteristics of bridges.

CADD: Computer-Aided Design and Drafting. A category of computer software that is used to develop roadway designs. CADD software typically uses an object-oriented approach to apply mathematical rules that automate the process of drafting roadway designs. 3D digital design data is a common output of the application of CADD software.

CAM: Computer-aided Manufacturing. The use of software to control machine tools and related ones in the manufacturing of workpieces.

CFD: Computation Fluid Dynamics. A branch of fluid mechanics that uses numerical analysis and algorithms to solve and analyze problems that involve fluid flows. CFD is one of the technologies that will be deployed by the Federal Highway Administration (FHWA) during Every Day Counts Round 4. (Federal Highway Administration, 2016c)

CNC: Computer Numerical Control. The automation of machine tools that are operated by precisely programmed commands encoded on a storage medium as opposed to controlled manually by hand wheels or levers, or mechanically automated by cams alone.

FEM: Finite Element Method. A method of structural analysis that uses accurate representation of complex geometry in 3D.

FHWA: Federal Highway Administration. An agency within the US Department of Transportation with a mission to provide national leadership and innovation to improve mobility on the nation’s highways.

HEC-RAS: Hydrologic Engineering Center’s River Analysis System. HEC-RAS is a one-dimensional (1D) hydraulic modeling approach that is used for determining the open area for hydraulic crossings. While a 1D modeling calculation using the Manning’s equation, HEC-RAS uses cross-sections that can be derived from 3D surface models.

IFC: Industry Foundation Class. A platform-neutral, open data model and file format specification that is intended to describe building and construction industry data. It is an international standard for BIM. (International Organization for Standardization, 2013)

ISO: International Organization for Standardization. A non-governmental international organization that researches and develops standards.

Lidar: (Portmanteau of "light" and "radar"). Remote sensing technology that measures distance and other information by recording information about laser reflections. Typically, lidar machines consist of rapidly pulsing lasers that are capable of taking millions of measurements in a short time. Information that can be gathered by such devices includes x,y,z coordinates of objects that the laser strikes and intensity of the returned beam. Commonly, a camera captures simultaneous images to extract RGB color of the remote object as well and assign it to the point.

LOD: Level of Development. A qualitative designation that communicates the degree of engineering intent behind a 3D model that defines the authorized uses. Normally the LOD will increase through the design development process.

LRFD: Load and Resistance Factor Design. The specifications for new bridge design (since October 1, 2007) and new culvert, retaining wall, and other standard structures (since October 1, 2010).

MPS: Model Progression Specification. A specification that defines how the LOD for individual model elements increases over the project milestones. The MPS will assign a specific, minimum LOD to each model element for each milestone. The LOD typically increases from milestone to milestone.

NEPA: National Environmental Policy Act. The Federal law with resulting regulations under 23 CFR § 771 to conduct environmental impact statements, environmental analyses, or apply categorical exclusions for highway and bridge projects using Federal funds.

STIP: Statewide Transportation Improvement Program. A four-year look-ahead of transportation capital projects developed in partnership with Metropolitan Planning Organizations (MPOs) and including projects consistent with the statewide transportation plan, as required by Federal law.

XML: Extensible Markup Language. A text-based, human-readable and machine-readable structured data schema.

2. Literature Review

This section summarizes the relevant literature on the use of 3D and 4D bridge models and plans, as well as lessons that can be learned from the use of 3D and 4D models and plans in related industries. In some cases, there are practical examples of 3D and 4D models being used, whereas in other cases these potential uses have been identified, but not yet developed. The section on data schemas summarizes a very dynamic area and emerging trends towards industry standardization. MDOT's framework needs to be informed by potential industry standardization.

2.1 Uses of 3D and 4D Models in the Bridge Lifecycle

3D and 4D models are not seeing the same adoption for use in bridge delivery or lifecycle management as in other categories of infrastructure construction, like roadways. Nonetheless there are multiple uses for bridge projects especially where roadway elements are concerned. Potential uses of Bridge Information Models (BrIMs) have been identified for design, construction, operations and maintenance phases of the bridge asset lifecycle. These uses, shown in Figure 2, assume a consumable, single source of bridge information that resides in a combination of the BMS and in bridge-specific 3D BrIMs. (Shirole, et al., 2008)

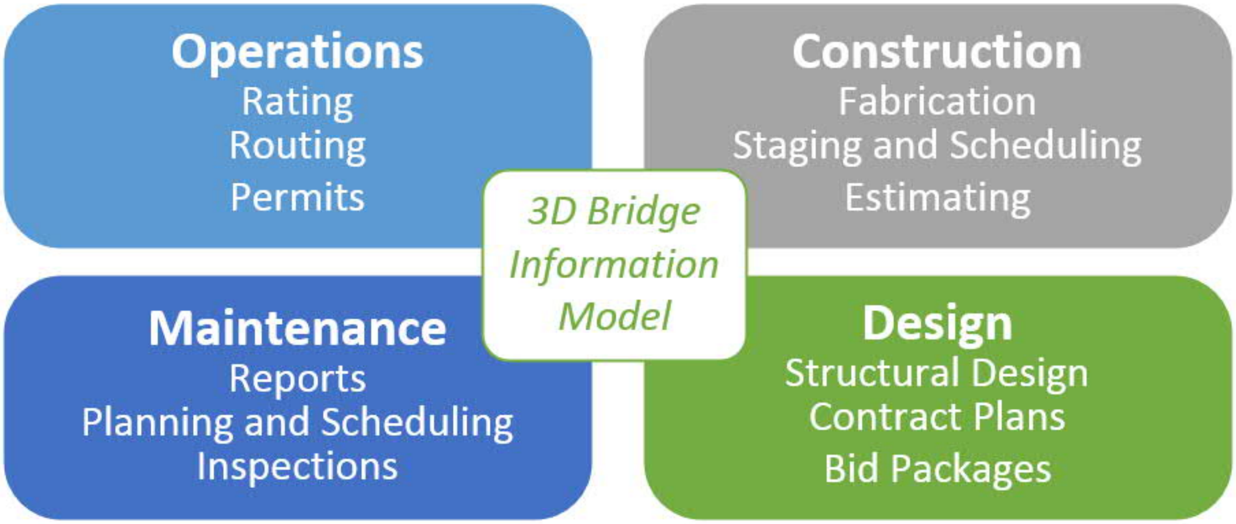


Figure 2: Uses of 3D bridge information in the asset lifecycle (Shirole, et al., 2008).

This literature search explored these emerging uses as well as identified other potential uses of 3D data of all types, including the bridge elements themselves and the related features such as terrain models, roadway models, survey data, utility data, etc.

2.1.1 Planning

Projects that require Environmental Impact Statements or Environmental Assessments under NEPA frequently use 3D models for the purposes of performing visual impact analyses, lighting analyses and public engagement. These models often incorporate representative geometry, but usually do not need engineering detail to accomplish their intent. Newer software applications, such as Bentley OpenRoads ConceptStation, use cloud computing to accelerate 3D modeling with integration of structural and roadway design criteria. The image in Figure 3 took about an hour to generate. With time savings from cloud computing, these tools may be accessible to a wider range of projects and may enable engineers to evaluate more options in greater detail.

Figure 3: New software enables rapid modeling for visual analysis.

2.1.2 Design

Bridge design converges many disciplines that influence the bridge design, placing it on the critical path of project development. Bridge designers are challenged by a need to make assumptions to progress design, and then adapt quickly if the assumptions were wrong. Bridge designers need to balance risks of both construction and lifecycle cost due to overly conservative assumptions, and schedule and design costs when the design needs to be revisited.

MDOT’s Bridge Design Manual defines twenty different bridge data sources that feed the design process. (MDOT, 2009) As shown in Figure 4, these can be sorted into three different categories. While all three categories affect the design, it is the middle column titled “Geometric Constraints” that is the largest source of 3D data that can be consumed by bridge designers. The third column titled “Design Review” is the largest potential consumer of 3D and 4D bridge models of the bridge elements themselves.

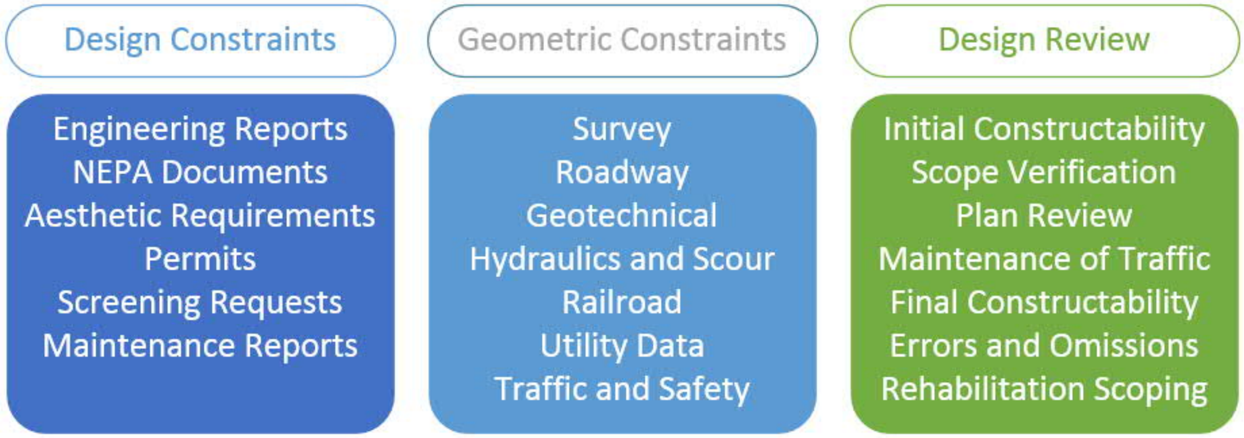


Figure 4: MDOT Bridge Design Data Sources (MDOT, 2009).

The application of 3D and 4D bridge models during design can reap benefits during design, construction, and across the bridge lifecycle if they result in lower maintenance costs. Some of these applications increase plan production and quantity computing efficiency, especially for earthwork or concrete volumes. There are opportunities for using 3D models for analysis also, especially for hydraulic and structural analysis. These are more common, selective uses of 3D models that are not often considered as examples of using 3D models for bridges because the 3D analysis models are not usually geometrically accurate models of the bridge elements. Use of geometrically accurate and detailed models of bridge elements was less commonly encountered.

BrIM uses a single source of bridge information that is exchanged for various applications in the bridge lifecycle. Figure 5 shows the various data exchanges that would be automated and/or complete (without data loss) in a BrIM workflow. The figure is based on two different data exchange maps for steel and concrete superstructures, (Chen, 2010) and has been extended to include the substructure and other analyses that influence the structure design. The benefits identified for BrIM were:

- Avoiding manual data entry, which is error-prone
- Avoiding inconsistencies in duplicated data
- Reuseing design data in construction or beyond
- Avoiding physical pre-assembly through virtual fit-up
- Prefabrication, which accelerates construction

These benefits were summarized as providing better, faster, and more economical outcomes. (Chen, 2010) This research demonstrated that integrated bridge data was possible, but it required expert knowledge of software functionality that limited scalability.

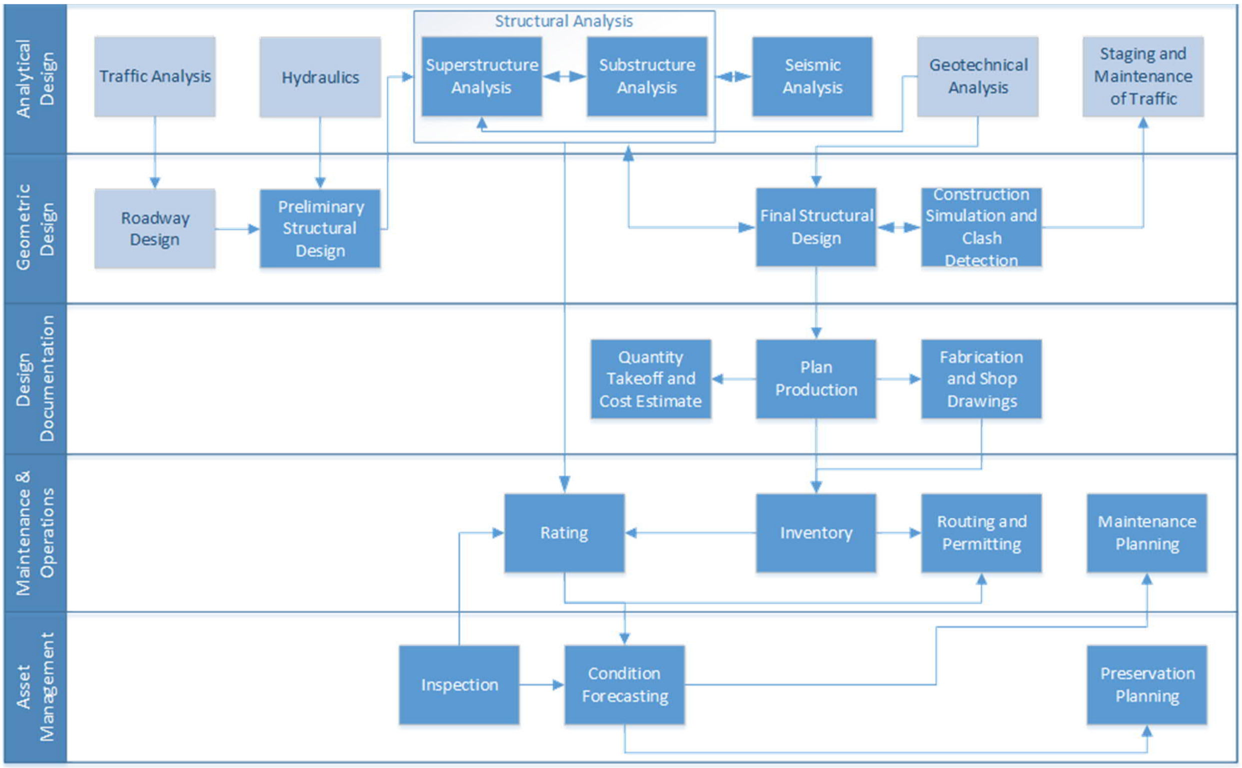


Figure 5: Data Exchanges in a BrIM Workflow.

2.1.2.1 Hydraulic Analysis

HEC-RAS is standard software used to analyze backwater effects, determine open areas, set low chord and freeboard, and to identify scour requirements. HEC-RAS is a one-dimensional model applying the Manning’s equation, but model development depends on cross-sections and the slope which are most efficiently generated through CADD automation to extract the cross-sections and profiles from 3D surfaces. (Hogan, 2013)

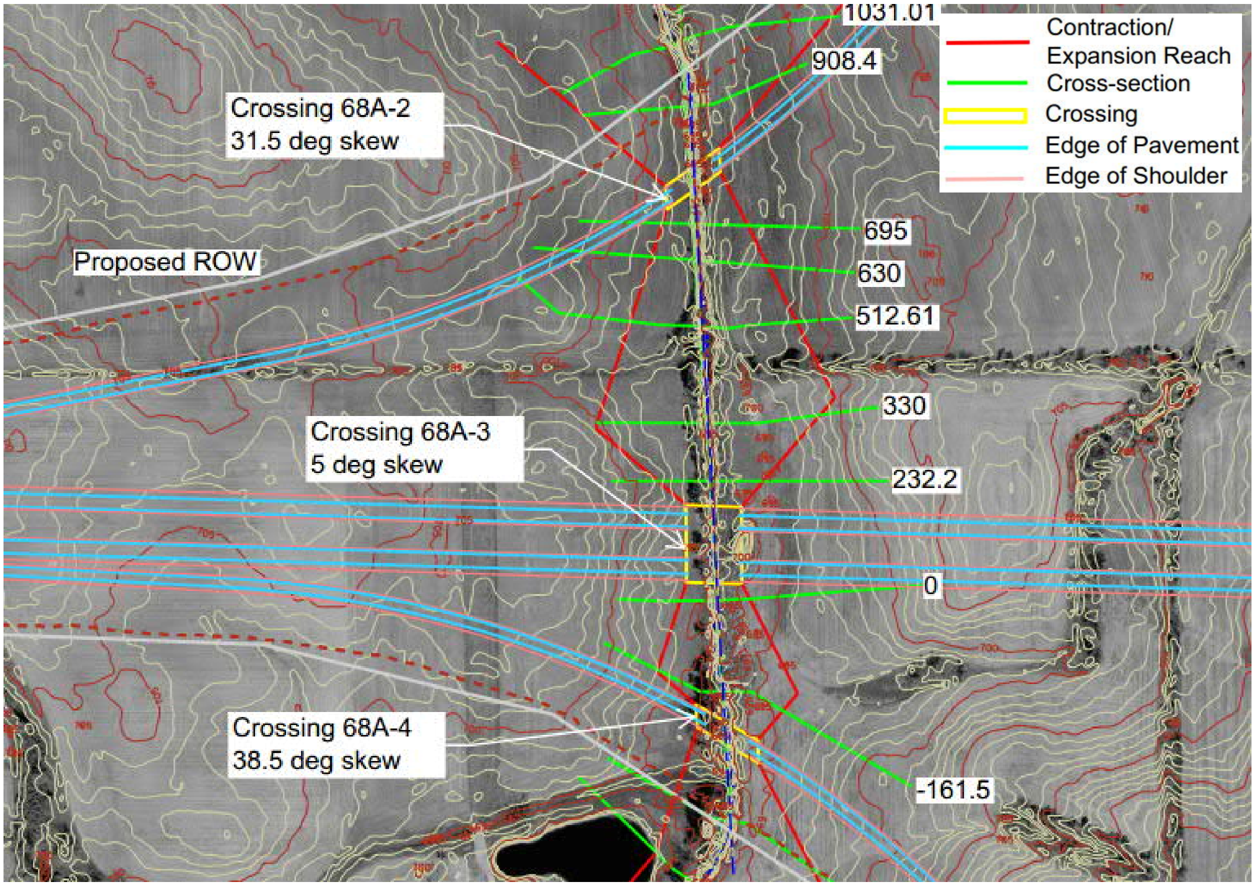


Figure 6: HEC-RAS model development using 3D CADD to automate data entry.

Hydraulic analysis makes extensive use of 3D CADD files, from identifying and extracting physical attributes for HEC-RAS cross-sections, shown in **Error! Reference source not found.**, to determining properties of the bridges or culverts such as length, skew, and width. Identifying culvert lengths and inverts through a roadway embankment is one area where 3D CADD models of the roadway are very helpful, especially for large box culverts.

The FHWA will deploy the use of more advanced hydraulic modeling technology during the fourth round of their Every Day Counts (EDC) initiative. The initiative recognizes that HEC-RAS applies conservative assumptions and newer technologies such as Computational Fluid Dynamics (CFD) leverage more prevalent 3D data to make more accurate analyses. (Federal Highway Administration, 2016c)

2.1.2.2 Structural Analysis

Naturally, the structural analysis lies at the heart of bridge design and would be expected to hold great opportunity for 3D model use. It is a fragmented landscape, from a data type perspective, since the tools and analysis methods vary by structure type (Maier, 2012). Nonetheless many of the tools are established. The structural analysis of both superstructure and substructure design must adhere to AASHTO Load and Resistance Factor Design (LRFD) standards (Federal Highway Administration, 2015b).

Structural analysis rarely requires precise 3D geometry. For most typical structural types, analytical models can ignore horizontal and vertical curvature and use point and line models for 1D linear, 2D planar, or 3D frame analysis. Detailed and geometrically accurate 3D models are usually only used for 3D Finite Element Models (FEM) of complex structures, like the severely skewed, curved bridge deck in Figure 7.

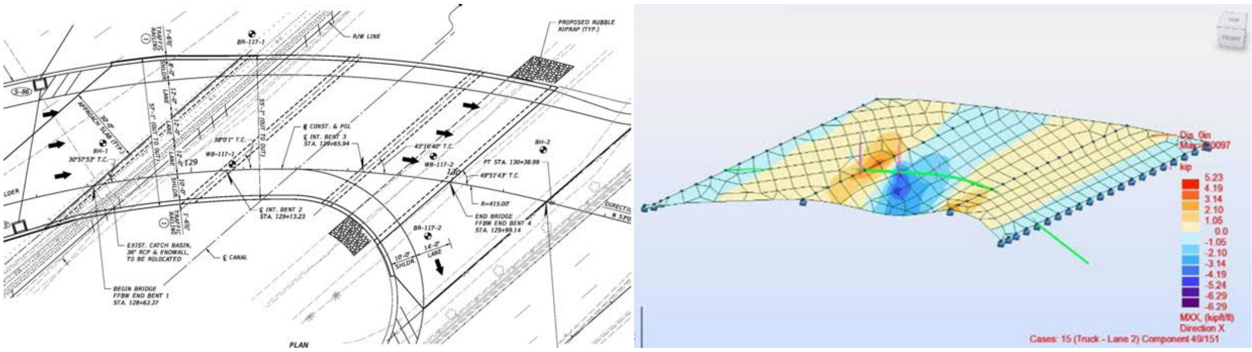


Figure 7: A FEM of a severely skewed and curved bridge deck (Brenner, 2015).

In Figure 8 an analysis model has been used as an underlay to guide a 3D solid model. The differences in detail and accuracy are especially apparent at the pylons and piers. The pink solids are 3D components from the roadway corridor model. These have not been refined to route the shared use path around the pylon.

Figure 8: Analysis model used as an underlay for a 3D bridge model.

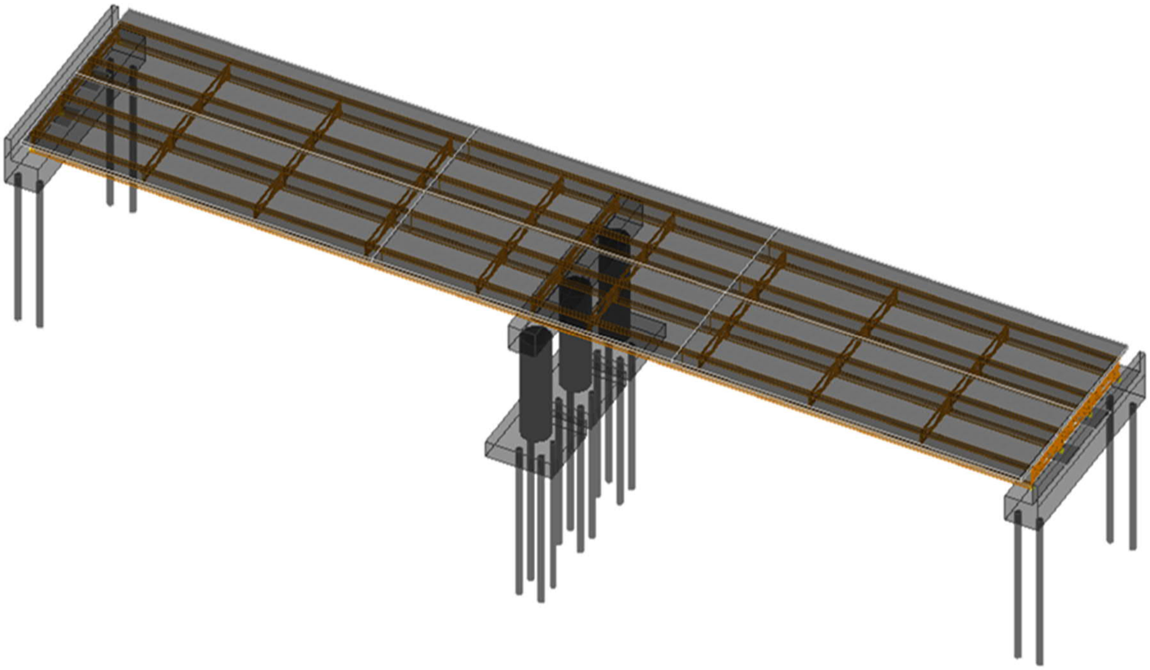


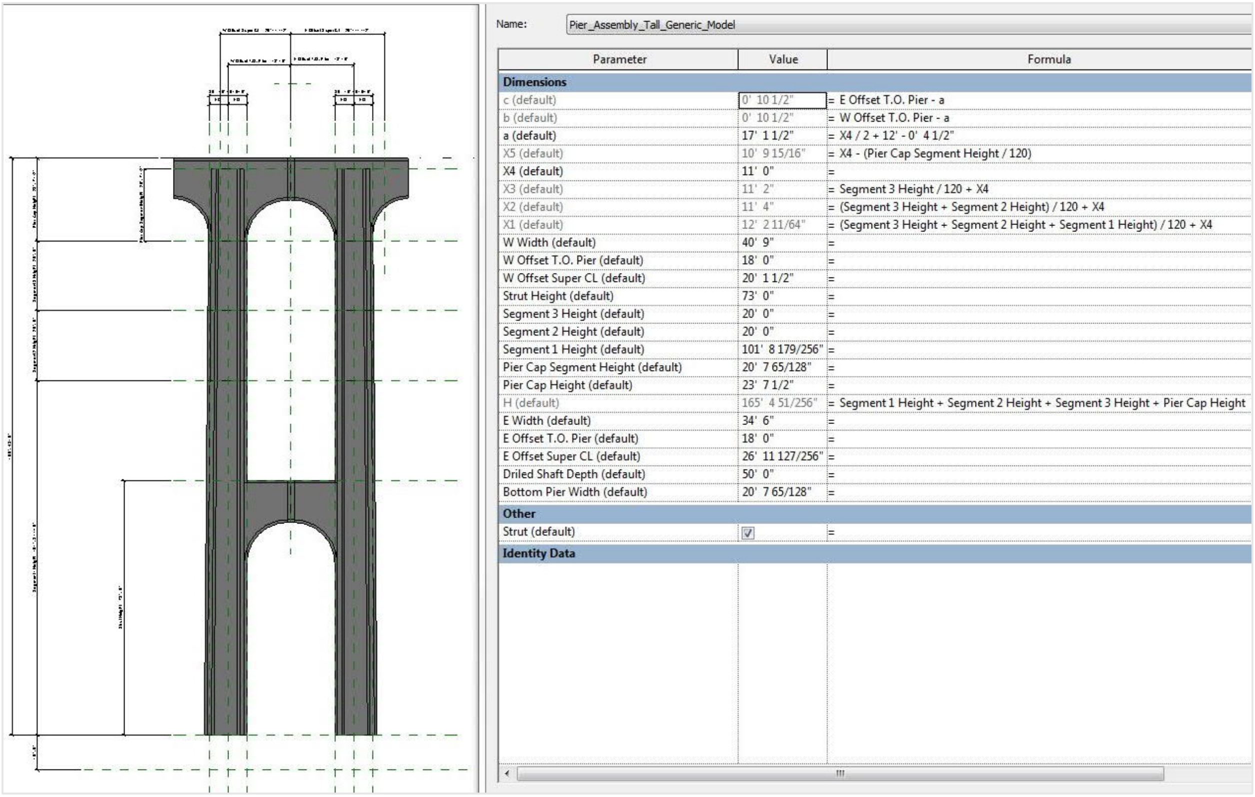
Figure 9: Structural analysis model from LEAP Bridge Steel.

The Bentley LEAP bridge products create low-detail 3D models as part of the process for developing the analytical models. The software has a geometric wizard that can import roadway geometry and the terrain and create a spatially located 3D model as part of the process, though this software is not often used as such in practice. The resulting models, such as the steel bridge shown in Figure 9, include the main structural elements, such as the deck, barriers, beams cross-frames, bearings, abutments, piers, and foundations, but lack detail in the connections and are relatively aggregate.

2.1.2.3 Geometric Design

Bridge design of today is seeing some isolated instances of using parametric modeling, especially to define the elements constrained by roadway geometrics. In a parametric model, geometric and dimensional constraints are established so that the model updates itself as different elements are revised. This is done using the mathematical formulation of interdependencies (Ji, et al., 2011). With more typical 2D drafting, the drafter must select and move elements in all of the related views to manually propagate a change, which is more time intensive with greater likelihood of error.

A parametric input will typically tie elements to the roadway horizontal and vertical alignment. This automates change propagation in response to horizontal geometry changes. Parametric models are especially applicable to substructure elements such as foundations and piers. substructure elements are less constrained by roadway geometrics, other than abutment and pier heights. Substructure dimensions often flex in predictable ways that are easily defined in parametric models. Even the details of architectural finishes can obey mathematical formulae that can be managed with parametric models, such as those in the piers shown in Figure 10. On the right hand side of Figure 10 is the table of variable parameters and parameters governed by mathematical formulae that determine the geometry of tall piers with a strut.



Name: Pier_Assembly_Tall_Generic_Model

Parameter	Value	Formula
Dimensions		
c (default)	0' 10 1/2"	= E Offset T.O. Pier - a
b (default)	0' 10 1/2"	= W Offset T.O. Pier - a
a (default)	17' 1 1/2"	= X4 / 2 + 12' - 0' 4 1/2"
X5 (default)	10' 9 15/16"	= X4 - (Pier Cap Segment Height / 120)
X4 (default)	11' 0"	=
X3 (default)	11' 2"	= Segment 3 Height / 120 + X4
X2 (default)	11' 4"	= (Segment 3 Height + Segment 2 Height) / 120 + X4
X1 (default)	12' 2 11/64"	= (Segment 3 Height + Segment 2 Height + Segment 1 Height) / 120 + X4
W Width (default)	40' 9"	=
W Offset T.O. Pier (default)	18' 0"	=
W Offset Super CL (default)	20' 1 1/2"	=
Strut Height (default)	73' 0"	=
Segment 3 Height (default)	20' 0"	=
Segment 2 Height (default)	20' 0"	=
Segment 1 Height (default)	101' 8 179/256"	=
Pier Cap Segment Height (default)	20' 7 65/128"	=
Pier Cap Height (default)	23' 7 1/2"	=
H (default)	165' 4 51/256"	= Segment 1 Height + Segment 2 Height + Segment 3 Height + Pier Cap Height
E Width (default)	34' 6"	=
E Offset T.O. Pier (default)	18' 0"	=
E Offset Super CL (default)	26' 11 127/256"	=
Driled Shaft Depth (default)	50' 0"	=
Bottom Pier Width (default)	20' 7 65/128"	=
Other		
Strut (default)	☑	=
Identity Data		

Figure 10: Parametric model of a pier and the table of parameters in Revit Structures.

Perhaps the most valuable impact of parametric modeling comes from its ability to speed along plans production or to reduce the amount of design documentation using plans. When the sheets sets are derived directly by the 3D model, all changes to line work and annotations (such as labels and dimensions) quickly propagate through that set (Soka, 2015). Quantity take-off for bridge concrete volumes can be taken directly from 3D bridge solid models. Bridge earthwork take-off can be performed using surface-to-surface comparisons (Soka, 2015).

Traditional parametric modeling software is focused on the vertical construction market. Thus, it does not integrate well with civil design applications and cannot interpret roadway geometric layout rules, and can struggle with complex roadway geometry such as parabolic vertical curvature, horizontal spirals, and superelevation transitions. These tools have been more applicable to substructure designs, which are less sensitive to roadway geometry.

A new software tool developed by Bentley Systems, OpenBridge Modeler, has been developed to consume Bentley's OpenRoads format roadway geometric data and can propagate roadway geometric changes through both substructure and superstructure designs. OpenBridge Modeler is also able to export bridge models to Bentley's structural analysis products. The current version of OpenBridge Modeler creates 3D mesh objects.

Bentley's OpenRoads software can section these mesh objects to create cross-section and profile plans that will update dynamically. (Bentley Systems, 2016)

2.1.2.4 Reinforcement Detailing and Schedules

One area where parametric models can be beneficial is in reinforcement detailing and creating bar schedules. Reinforcement layout follows relatively simple mathematical rules, which are standardized, making it ideal for parametric modeling. As the exterior dimensions change, the software applies the layout rules to update the placement of reinforcement. Laying out the bars initially is faster, but the real value comes in change propagation and automating the bar schedules and quantities. It is especially beneficial where the concrete has complicated dimensions, such as the wall pier in Figure 11.

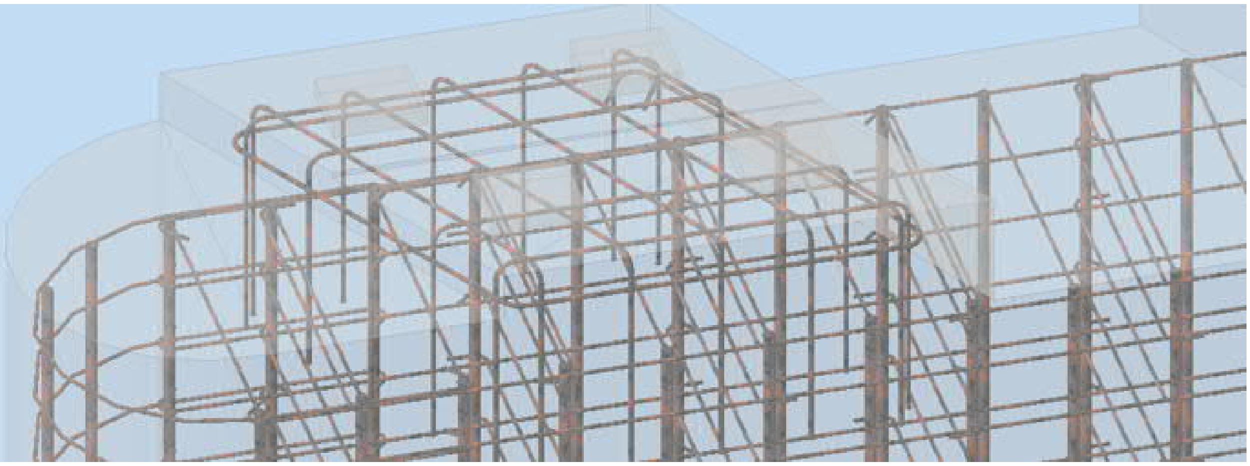


Figure 11: Reinforcement in a parametric model (Brenner, 2015).

2.1.2.5 Constructability Analysis

One bright spot where 3D and 4D models are enjoying success in bridge delivery is for constructability review, particularly in the area of staging analysis. ABC can benefit from 3D models for clash detection, constructability review, public information meetings, and communicating with contractors at the pre-bid meeting (Nelson, 2015). Staging planning is one application of clash detection. Clash detection can also be used for example, in concrete elements that have both reinforcement and post-tensioning.

In most instances, staging analyses require low detail models of the exterior faces of the bridge elements. Staging analyses can also require 3D models of equipment, interim conditions (such as excavation surfaces), and temporary works. Figure 12 shows a staging plan for a lift in a constrained area where there is shoring. Here, the staging of the interim conditions is important to plan the crane mobilization and the lift. Staged excavation planning is challenging from a modeling perspective because it requires understanding the contractor's equipment, means and methods.

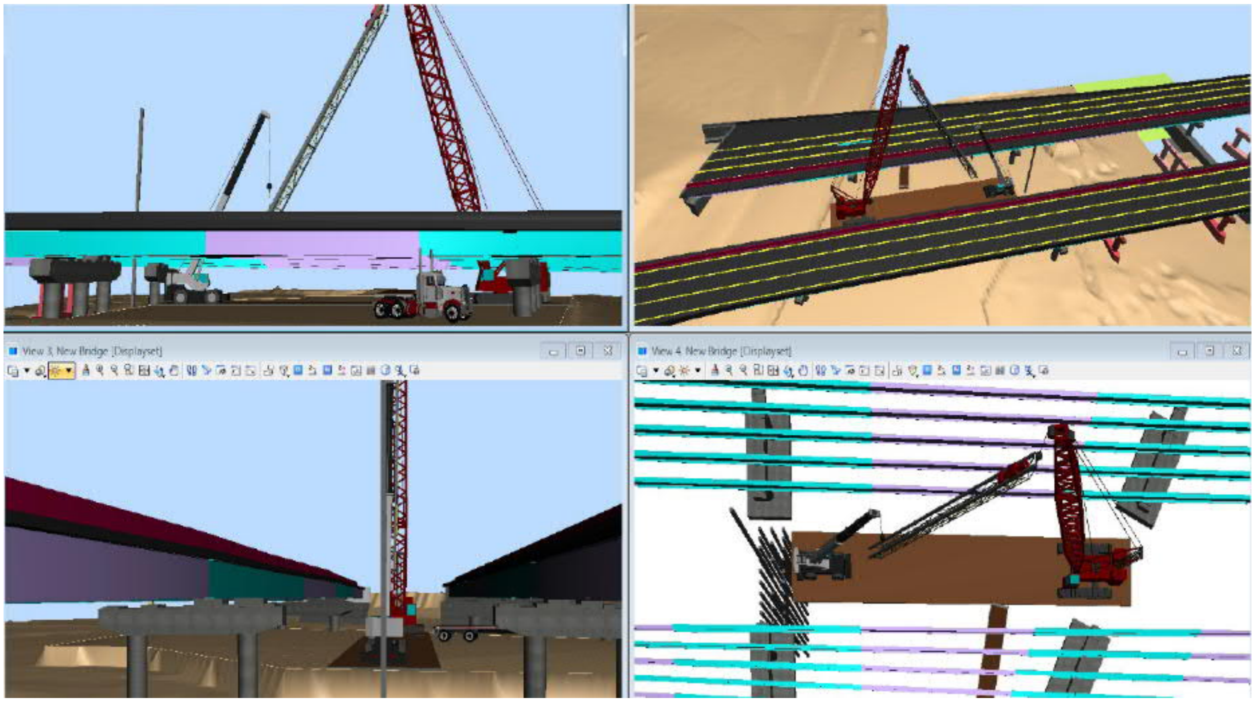


Figure 12: Staging analysis requires terrain and equipment models.

The planning of crane lifts using 3D bridge models can happen with low detail models and may not need detailed site information, such as in Figure 13. Lift planning determines which crane is necessary based on the elements to be lifted and the site constraints. When lift planning can determine with certainty that a smaller crane can do the work, there can be significant savings. Lift planning can be used for both erection and demolition. (Ramkrishnan, 2014)

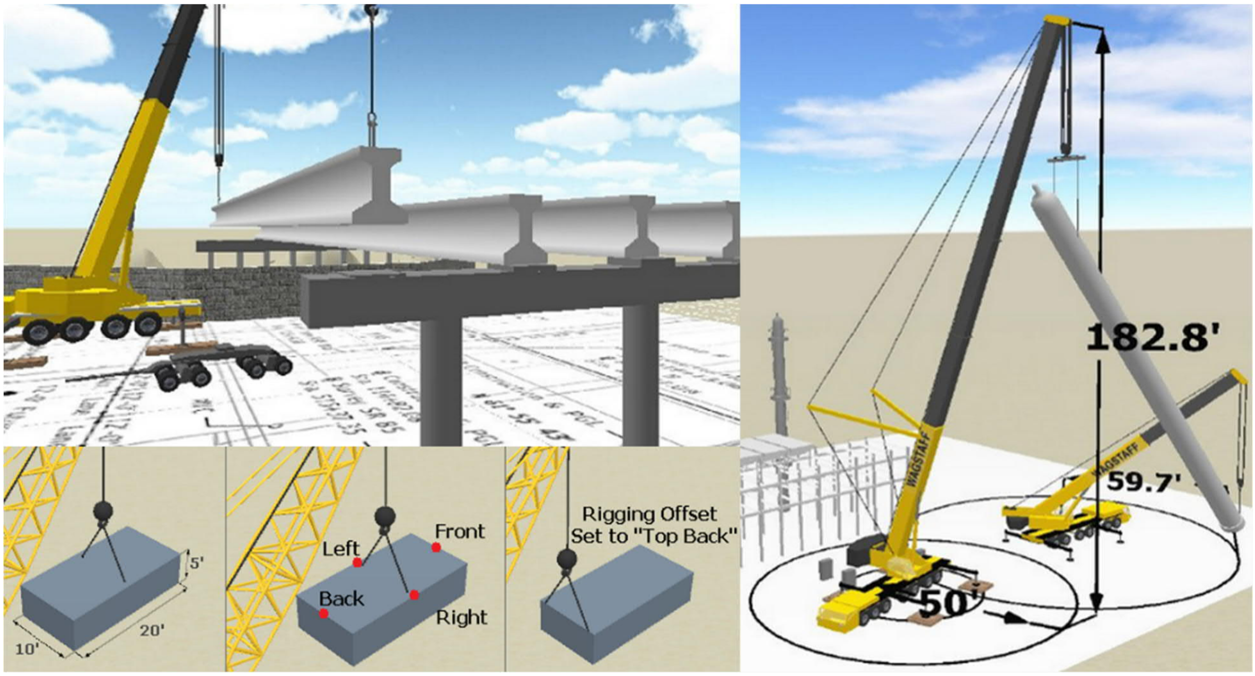


Figure 13: Lift planning with 3D models (Ramkrishnan, 2014).

2.1.3 Scheduling and Simulation

Construction schedules can be more reliably developed and more meaningfully interpreted when they are connected to 3D models to create construction simulations, called 4D models. The New York State DOT (NYSDOT) has used 4D models for several bridge projects in the New York City area with favorable results. Most notably, NYSDOT placed rigorous 4D and 5D modeling requirements on the contractor for the Kosciuszko Bridge project, both during the bid and during construction. NYSDOT felt that the 4D models made the bid schedules easier to understand, and the project is currently ahead of schedule. (Federal Highway Administration, 2016b)

Other agencies, such as the Central Federal Lands Highway Division, Iowa DOT, Caltrans, and Connecticut DOT have used 4D models for a range of projects from small, rural bridge replacements to very large, multi-year, multi-contract projects. These agencies have used construction simulations in public engagement, to communicate maintenance of traffic through dynamic work zones, or illustrate ABC techniques such as slide-in bridge construction.

2.1.4 Fabrication

While an identified use of 3D bridge models, wider adoption is constrained by a lack of standard 3D data format for bridges. Computer Numeric Control (CNC) machines emerged years before standards for 3D models in the transportation industry. Many fabricators use bespoke software and have not developed translators because of both a lack of available 3D data from bridge designers and a lack of data standardization in the bridge industry. (Medlock, 2015)

The desire to use 3D models to drive CNC machines for steel fabrication is constrained by a lack of seamless transfer of data between engineer and steel fabricator. For steel I-girders, which make up the majority of steel bridge fabrication, fabricators need only a 3D data point file, rather than a model. (Medlock, 2015) 3D models are more applicable for complicated details and connections, such as those in Figure 14, and to expedite shop drawing reviews, and can potentially replace the shop drawings themselves with shop models for review. Shop models have use in maintenance and inspection as well.

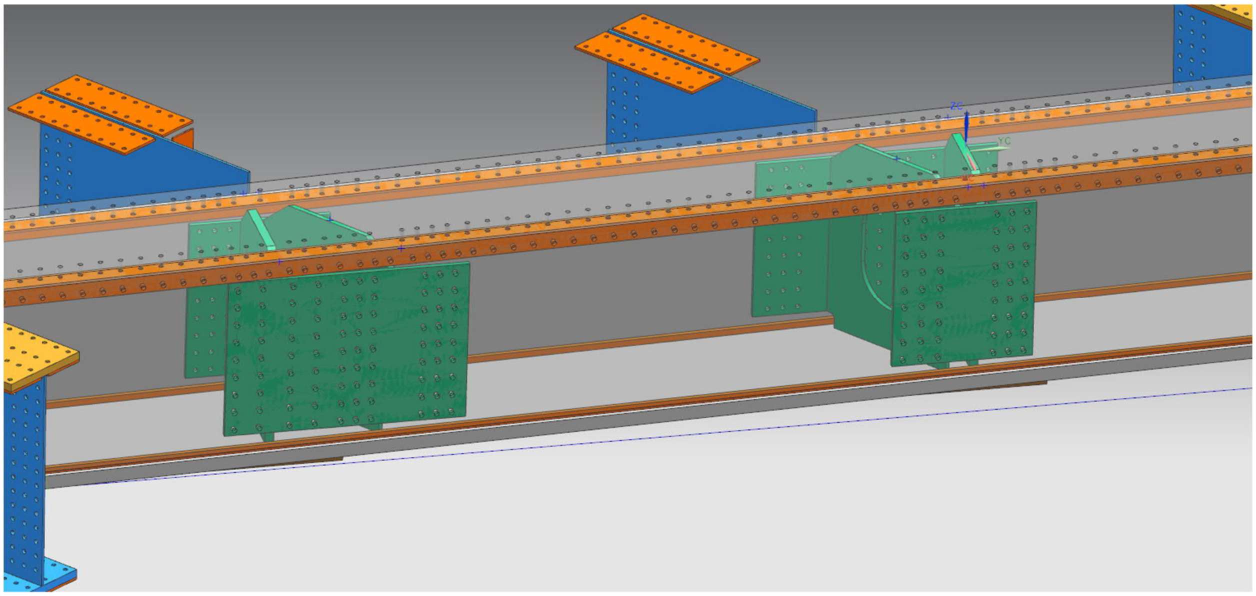


Figure 14: Shop model for an emergency construction project (Medlock, 2015).

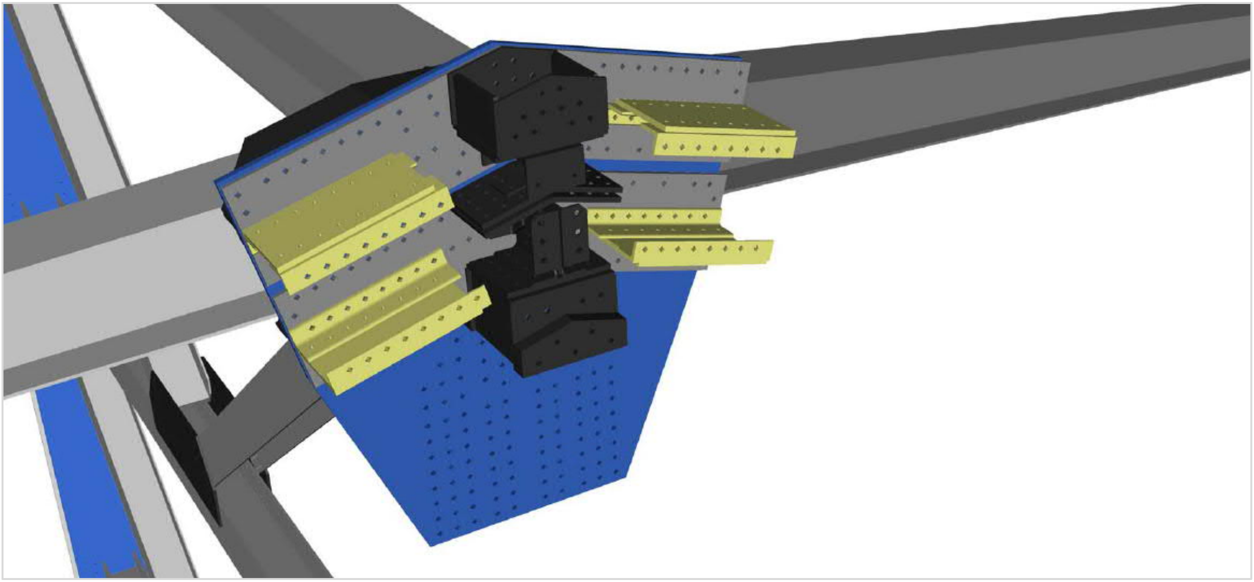


Figure 15: Virtual fit-up for the Milton-Madison Bridge (Ramkrishnan, 2014).

Another application for mitigating risk at minimal cost is that of virtual assembly, the virtual fit-up of all steel pieces by the fabricators before cutting them and sending them to the field. Virtual assembly shows all pieces fully connected and in position to allow for a bearing-to-bearing check. Such techniques cost significantly less than physical assembly with the same results. Although, physical assembly is most often required only on large, complex bridge projects, it was used on the Milton-Madison Bridge in Kentucky. (Ramkrishnan, 2014) (Medlock, 2015) One of the 3D models of a connection on this steel truss bridge is shown in **Error! Reference source not found.**.

3D models are especially of interest for use in formwork planning of concrete bridges, particularly those with complicated geometry. Teams can virtually mock-up formwork to test placement strategies before going to the field or setting up in a precast yard. Additionally, they can easily quantify the formwork required from the models. Formwork vendors have software that runs within a CAD environment to plan formwork.

2.1.5 Construction

The most significant use of 3D and 4D bridge models for construction is for planning construction to avoid issues in the field. Other construction uses relate less to 3D solid models of bridge elements, and more to 3D data, such as excavation surface models for AMG or staking data for substructure layout.

2.1.5.1 Public Information Management

Public information management is an ongoing need in delivering infrastructure projects for a broad sets of stakeholders, both technical and non-technical. In urban settings, bridges can serve a wide community who depend daily on the bridges for free access to homes, jobs, and community facilities. In rural settings, alternate routes may involve long detours that affect provision of emergency services. Visualization using 3D and 4D bridge models can enhance this process by using more readily understood diagrams.

Communicating the wider implications of construction projects visually is a valuable use of 3D and 4D bridge models, whether to win public approval or to communicate detailed concepts to a technical audience. For example, in the case of the SF-Oakland Bay Bridge reconstruction of the signature span, the use of 3D visualizations and rendered 4D simulations were central to the public outreach and approval. Caltrans even developed a driving simulator video game, the Bay Bridge Explorer, to educate the public of the planned detours. (Taylor, 2011)

2.1.5.2 As-built Records

Generating as-built records is another opportunity for 3D data, particularly lidar scans that can quickly and safely collect a point cloud to be analyzed from the office to verify construction. Lidar can be used to determine clearances and to compare the pre- and post-load conditions. Figure 16 illustrates these two uses by Caltrans. (Aguilar, 2015)

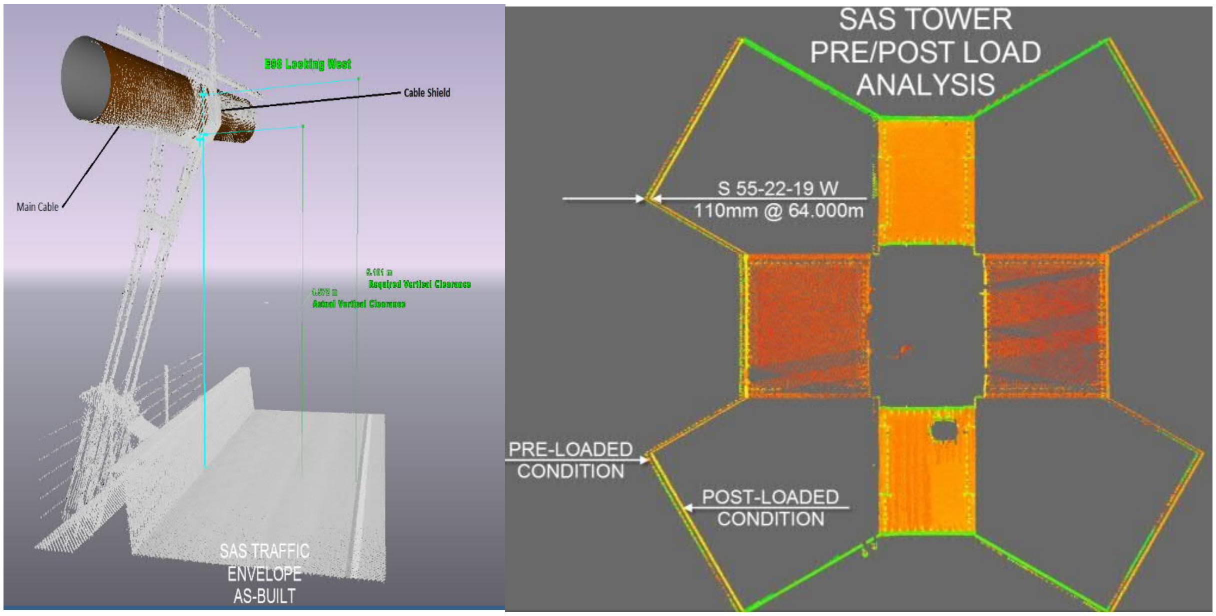
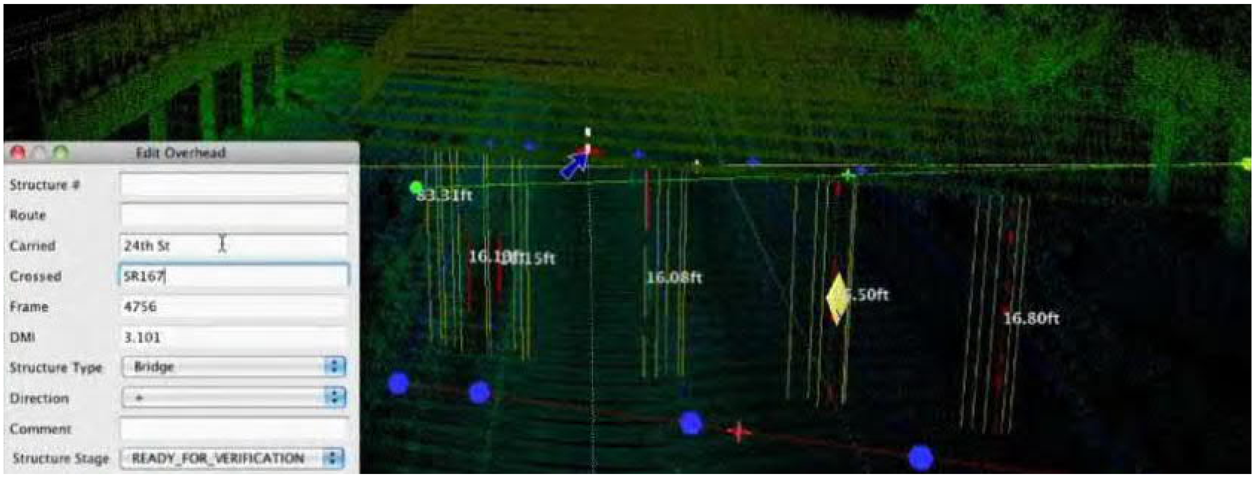


Figure 16: Uses of San Francisco-Oakland Bay Bridge lidar scans (Aguilar, 2015).

2.1.6 Operations and Maintenance

Uses for operations and maintenance are in the early emergent stage. If geometry and components are attributed during design and construction with product and installation data, the maintenance and asset management departments can extract and capture data for the BMS. Some BMS software is able to display and query 3D model elements. Other BMS software can store the design and fabrication data (including models) in a field in the database so that it can be accessed for future maintenance or rehabilitation work.



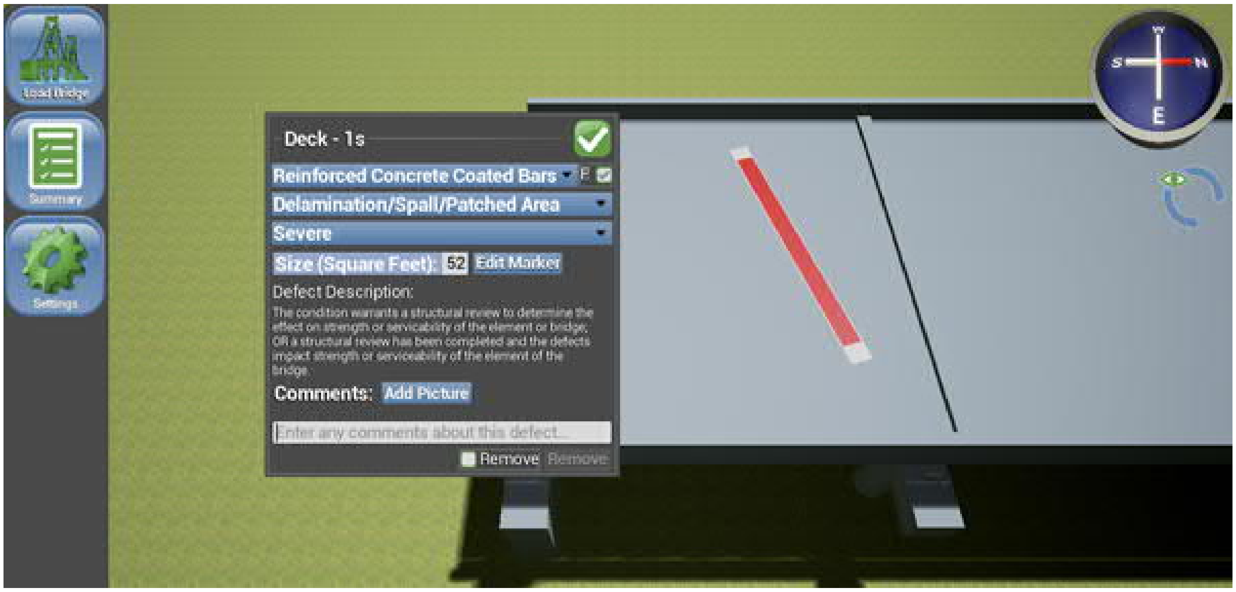
Structure #	
Route	
Carried	24th St
Crossed	SR167
Frame	4756
DMI	3.101
Structure Type	Bridge
Direction	+
Comment	
Structure Stage	READY_FOR_VERIFICATION

Figure 17: Bridge inventory data extraction from mobile lidar data (Yen, et al., 2011).

Mobile lidar is an emerging use of 3D data to collect bridge inventory data. There are larger benefits when agencies consolidate data collection for multiple assets, however, it was estimated that Washington State DOT could save $800,000 per cycle for collecting only bridge clearances with survey-grade mobile lidar (Yen, et al., 2011). Post-processing tools enable extraction of existing inventory and condition data. For example, it enables measurement of clearances or detection of cracking and spalling concrete. In Figure 17, facility, clearance, and structure type information is being extracted from mobile lidar data.

An already well-established use for 3D models and measurements in the bridge domain is for routine maintenance and inspection. Inspections and condition rating of bridges are critical for establishing proper maintenance and repair schedules. Also, the conditions assessment and accurate clearances are important factors for route planning to issue overweight/oversized load permits.

Mobile technologies are enhancing the safety and efficiency of bridge inspection activities. Michigan Tech Research Institute (MTRI) developed the 3D BRIDGE App for MDOT, seen in Figure 18. This program allows for tablet-enabled collecting and locating of defects and repairs in the field. By cutting out multiple data entry steps and coordinating any related annotation (descriptions, photos, quantities, etc.), this tool is reducing data collecting time dramatically. Interactive inspections allow the workforce to collect and report condition data at the component element level and for broader audiences to query results right on the 3D model. (Michigan Tech Research Institute, 2016)



Deck - 1s

Reinforced Concrete Coated Bars

Delamination/Spall/Patched Area

Severe

Size (Square Feet): 52

Defect Description:

The condition warrants a structural review to determine the effect on strength or servicability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element of the bridge.

Comments:

Enter any comments about this defect...

Figure 18: 3D Bridge App tablet application (Michigan Tech Research Institute, 2016).

Another quickly evolving area of inspection is that of non-destructive evaluation (NDE). NDE refers to techniques, often deployable at or near-highway speeds, which permit evaluating the condition of a bridge (delaminations, cracks and spalls) without traffic disruption. One important subset of NDE is remote sensing, like lidar or ground penetrating radar, which allows collection of bridge health data not only without stopping traffic but with greatly reduced inspection times and highly accurate results. These methods and their 3D outputs can be easily integrated with other bridge model information in the process of overall management of the bridge assets. Furthermore, they illustrate how some of the strongest drivers for 3D adoption in the bridge lifecycle stem from inspection (operations and maintenance) more than from design. (Brooks, et al., 2015)

2.2 Relevant Building Information Modeling (BIM) Practices

BIM has achieved a high level of penetration in the vertical construction industry over the past decade. At last measure by McGraw Hill's SmartMarket report, BIM adoption in North America for buildings stood at 71% in 2012, up from 17% in 2007 (Bernstein, et al., 2012).

Not all aspects of BIM relate to bridges, but some aspects of bridge design and construction have more in common with buildings than with roads. Bridges and buildings have some common functional elements, such as foundations, columns, bearings, beams, and slabs. Clashes with reinforcement and post-tensioning, and opportunities for prefabricated elements and systems are also analogous to buildings. Thus, our search for potential uses and practices related to 3D and 4D models for bridges includes a survey of BIM practices that are translatable. Discussion of those practices follows.

2.2.1 Level of Development and Model Progression Specification

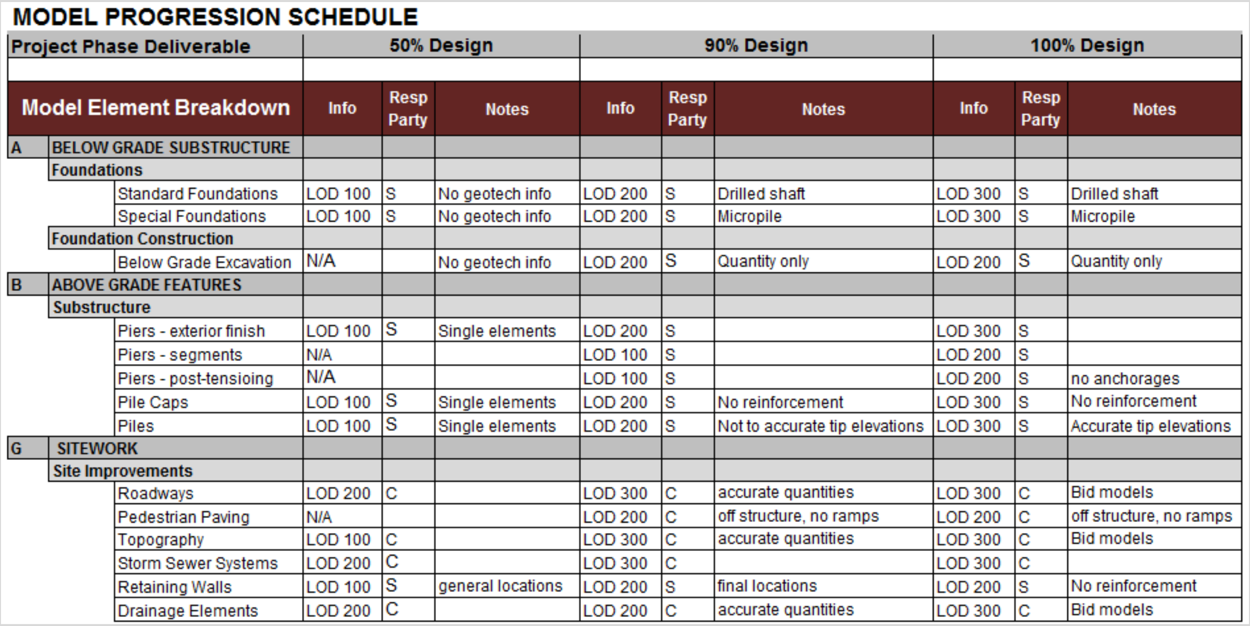
Level of Development (LOD) indicates how reliable model geometry and information is at the different phases of project development (American Institute of Architects, 2016a). It is expressly not a measure of the modeled object's detail, but rather how closely it reflects design intent and constructability. Throughout development, LOD of each model element becomes progressively more developed, from generic geometry concepts to full-specified descriptions appropriate for the intended use. Table 1 contains the AIA's LOD definitions LOD 100 through LOD 500.

The term LOD, coined by the AIA, arose in concert with a commonly used BIM management document, the Model Progression Specification (MPS). The MPS is a high level overview that outlines what model geometry, and at *what LOD,* is input by each project team member for a specific scope of work, broken down at the object type level. The specification is often a required component of project execution plans (described below). (Bedrick, 2008) The goals of the BIM use will have been determined (and documented in the project execution plan) at the beginning of the project as this will influence up to the LOD to which the model elements should be authored at all design milestones to successfully serve its purpose.

Table 1: AIA Definitions of LOD as applicable to Bridges.

LOD	Model Element Requirements	Authorized Uses
LOD 100	Overall massing indicative of height, volume, location and orientation. May be modeled in three dimensions or represented by other data.	Limited analysis Aggregate cost estimating High-level staging
LOD 200	Elements are modeled as generalized systems or assemblies with approximate quantities, size, shape, location and orientation. Attributes may be attached to model elements.	Preliminary Analysis High-level cost estimating High-level scheduling
LOD 300	Elements are modeled as specific assemblies and are accurate in quantity, size, shape, location and orientation. Attributes may be attached to model elements.	Construction documents Detailed analysis Project controls
LOD 400	As per LOD 300 plus complete fabrication, assembly and detailing information	Model-based fabrication Actual cost tracking Look-aheads Virtual mock-ups
LOD 500	Elements are as-constructed assemblies accurate in quantity, size, shape, location and orientation. Attributes may be attached to model elements.	Maintenance and planning of future construction

Responsibilities for modeling and data entry should be assigned to individuals who are part of the discipline advancing the design of the relevant elements. The assignments for model authoring to each designated LOD by project phase represent the minimum sufficient LOD to support the uses at each phase. For example, for water crossings, hydraulic design needs to be advanced to a higher LOD earlier in the overall project development to enable less conservative assumptions by the bridge engineers. In some cases, LOD can be assigned by discipline, but for bridge elements, LOD can vary to reflect the elements of the design more affected by assumptions. The MPS serves as the central point of reference for the content specification for model elements. It is a tool that enables disciplines to share information earlier, by articulating the confidence that should be placed in that information. Figure 19 is a sample MPS for substructure and site design.



MODEL PROGRESSION SCHEDULE

Project Phase Deliverable		50% Design			90% Design			100% Design		
	Model Element Breakdown	**Info**	**Resp Party**	**Notes**	**Info**	**Resp Party**	**Notes**	**Info**	**Resp Party**	**Notes**
A	BELOW GRADE SUBSTRUCTURE									
	Foundations									
	Standard Foundations	LOD 100	S	No geotech info	LOD 200	S	Drilled shaft	LOD 300	S	Drilled shaft
	Special Foundations	LOD 100	S	No geotech info	LOD 200	S	Micropile	LOD 300	S	Micropile
	Foundation Construction									
	Below Grade Excavation	N/A		No geotech info	LOD 200	S	Quantity only	LOD 200	S	Quantity only
B	ABOVE GRADE FEATURES									
	Substructure									
	Piers - exterior finish	LOD 100	S	Single elements	LOD 200	S		LOD 300	S	
	Piers - segments	N/A			LOD 100	S		LOD 200	S	
	Piers - post-tensioing	N/A			LOD 100	S		LOD 200	S	no anchorages
	Pile Caps	LOD 100	S	Single elements	LOD 200	S	No reinforcement	LOD 300	S	No reinforcement
	Piles	LOD 100	S	Single elements	LOD 200	S	Not to accurate tip elevations	LOD 300	S	Accurate tip elevations
G	SITEWORK									
	Site Improvements									
	Roadways	LOD 200	C		LOD 300	C	accurate quantities	LOD 300	C	Bid models
	Pedestrian Paving	N/A			LOD 200	C	off structure, no ramps	LOD 200	C	off structure, no ramps
	Topography	LOD 100	C		LOD 300	C	accurate quantities	LOD 300	C	Bid models
	Storm Sewer Systems	LOD 200	C		LOD 300	C		LOD 300	C	
	Retaining Walls	LOD 100	S	general locations	LOD 200	S	final locations	LOD 200	S	No reinforcement
	Drainage Elements	LOD 200	C		LOD 200	C	accurate quantities	LOD 300	C	Bid models

Figure 19: Sample MPS for substructure and site work.

2.2.3 Project Execution Plans

Project execution planning takes a process-view of BIM as a means to optimize the investment in information modeling to meet business objectives based on unique project characteristics.

A project execution plan:

- identifies favorable BIM uses;
- identifies the process flow for developing and using information;
- defines the modeling requirements by element and LOD to support the uses;
- identifies the responsible parties for model authoring;
- addresses interdisciplinary information exchange proactively; and
- describes the resources needed for support.

These plans are a means to reliably project and manage the costs of using BIM as planned. Project execution planning should incorporate careful consideration of the value realized by the BIM uses on each individual project. These plans provide a clear understanding of goals, responsibilities attached to each person, team, department, and manager. (Computer Integrated Construction Research Program, 2011)

The foundation for project execution planning is to define BIM uses for the project goals. The parties involved in identifying BIM uses should include immediate and downstream users in construction or beyond. Collectively, across the building industry, experts have rallied around a standard set of BIM uses and how they relate to design, construction and operations phases. (Computer Integrated Construction Research Program, 2011) Standardization is particularly important when the downstream users are unknown, or where the ultimate use has clear data governance processes that to consider. Figure 20 illustrates how the process applies to bridge project development.

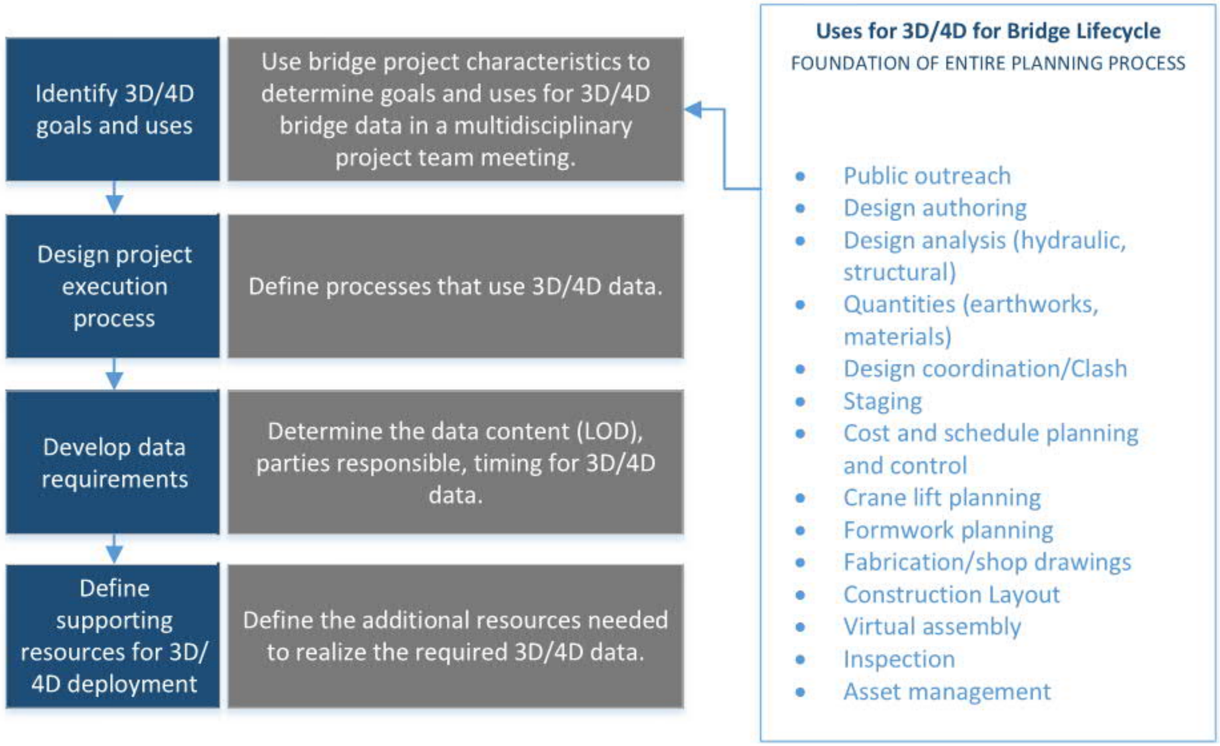


Figure 20: Project Execution Planning process as it relates to bridges.

The project execution planning approach works well for large, complex projects with a wide range of BIM uses. Standard project execution plans can be developed for smaller, more typical projects. There, the main customization will be in how extensively uses like staging and constructability analyses need to be supported, and when the best timing is to incorporate these analyses.

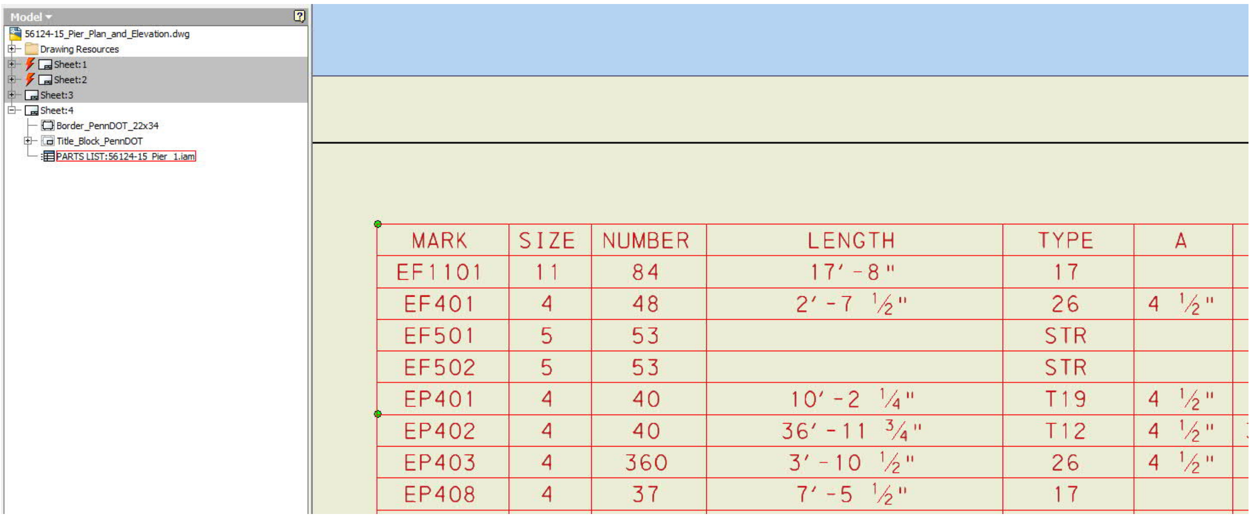
2.2.3 Uses

The BIM uses are viewed together to define lowest common LOD for each discrete element. This element-level planning then defines the 3D and 4D model contents. We will step through some of the most popular BIM uses, or applications of the information and geometry of modeled project elements.

2.2.3.1 Design Documentation

One of the earliest drivers of BIM adoption was the ability to quickly propagate design changes with automated plan updates from the parametric models. Since a parametric model forms the basis for all the plans, sections, elevations, and annotations, changes to objects propagate through the whole sheet set, significantly reducing production time. These time savings in design documentation are what enabled iterative and collaborative multidisciplinary design to avoid clashes prior to construction. The direct correspondence between the models and the plans are what gave meaning to the clash detection process.

Another leap in productivity that BIM offered is for automation in schedule generation. As the objects modeled carry graphical *and* non-graphical information, any change in the design, for example selecting a different reinforcement bar type, will immediately update in all the schedules referencing those bars. Also, since BIM enables bi-directional views of the design elements, project members can make changes from a tabular data view, such as the schedules, or a graphical (2D or 3D) view according to their convenience. Figure 21**Error! Reference source not found.** shows a segment of the bar schedule for the reinforcement detailing seen in Figure 11.



MARK	SIZE	NUMBER	LENGTH	TYPE	A
EF1101	11	84	17′-8"	17	
EF401	4	48	2′-7 ½"	26	4 ½"
EF501	5	53		STR	
EF502	5	53		STR	
EP401	4	40	10′-2 ¼"	T19	4 ½"
EP402	4	40	36′-11 ¾"	T12	4 ½"
EP403	4	360	3′-10 ½"	26	4 ½"
EP408	4	37	7′-5 ½"	17	

Figure 21: Automated reinforcement bar schedule (Brenner, 2015).

2.2.3.2 Model-derived Quantity Take-offs

BIM enables model-derived quantity take-offs. Schedules can be established that count objects of particular types, or report attributes of objects such as volumes, areas, or weights. Report-generating tools with formatting and export options are typical. The mathematical relationships in the parameters of BIM objects are not necessarily limited to geometric properties. The attributes can include pay item and specification references, material types, and material properties like densities. The schedules update dynamically with every design change. This affords designers an ability to quickly test scenarios with little additional effort.

2.2.3.3 Integrated Geometric and Structural Analysis

The functional, physical, and structural properties of buildings—and bridges—are closely related. BIM offers the opportunity to integrate physical and analytical models, by assigning analytical nodes and lines to specific locations on objects in the model. BIM models can also feed FEM analysis with both geometric and physical material properties. There is a trade off in the efficiency of specifying analysis points of interest in the BIM and the effort to exchange the information between the geometric model authoring software and the analytical modeling software. This is more seamless because IFC is the established data model and format standard for BIM under ISO 16739:2013.

The bridge industry does not yet enjoy the benefits of data format standardization, which constrains opportunities for integrating geometric and analytical modeling. There are some single-vendor applications that can be used in this way, notably the Bentley BrIM suite that includes OpenBridge Modeler, RM Bridge for complex structural analysis, and the LEAP Bridge solutions for steel and concrete bridges. Other solutions are available from Tekla, Autodesk, and other vendors. These tools have isolated pockets of use in the highway industry, especially the concrete analysis products for substructures and superstructures, however, they are rarely used for geometric modeling.

2.2.3.4 Whole Lifecycle Cost Analysis

Where once project delivery was focused only on costs through construction, reliable data exchange through IFC and dynamic change propagation enable designers to consider whole life cycle costs. In facilities, lifecycle energy and other operating costs constitute a significant proportion of life cycle costs. Facility owners are highly motivated to modify designs for energy efficiency and BIM represents an opportunity to develop meaningful return on investment analyses.

2.2.3.5 Design Review

BIM facilitates iterative design and engineering analyses at any stage of model creation, provides the ability for stakeholders to visualize decisions made during the design process. Accurate geometry in 3D models enables clash detection and virtual mockups, thus enabling collaboration, communication and decision-making in a virtual environment prior to building on-site. Design review using 3D models enables more accessible and more consistent interpretation of the design intent compared to plans. Visual reviews are effective for identifying omissions, such as the missing pipe supports in Figure 22.

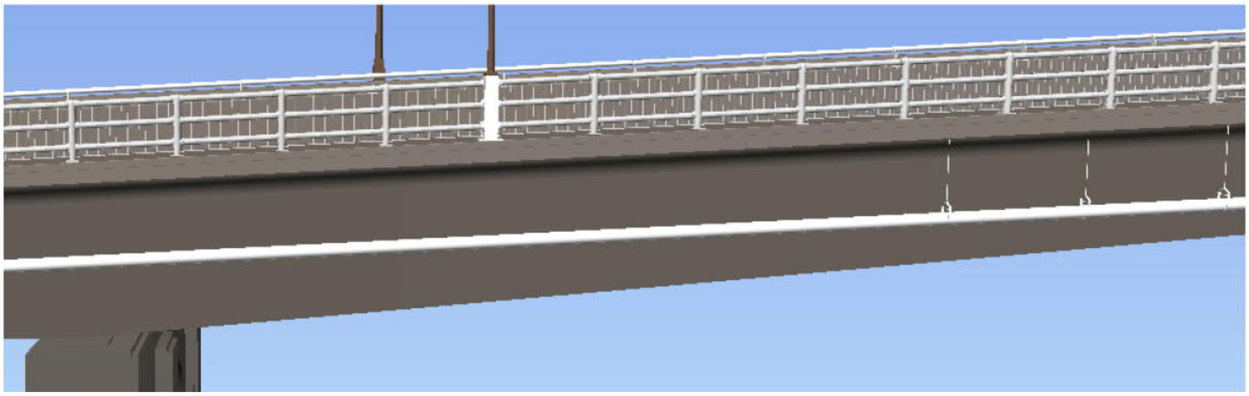


Figure 22: Visual review identifies missing pipe supports.

BIM has opened up vast new ways to visualize projects by virtue of 3D rendering tools. BIM tools often include powerful rendering engines capable of photo-realistic images. When simulations of lighting and airflow (using CFD), both commonly performed BIM-type analyses, are undertaken, one output might be renderings, as a way to report the outcomes. In fact, the growth of BIM and 3D rendering technology together has raised client expectations and placed additional pressure on teams to produce visually striking exhibits that accurately depict the latest iteration of a design. New rendering tools are leading to greater and more frequent demands for such renderings.

Design models are constantly evolving documents to be used collaboratively between contributors from different disciplines. (American Institute of Architects, 2016b) Building design involves many disciplines fitting their design elements in very congested and constrained spaces. Real-time collaboration as well as routine clash detection at regular milestones expedites the design process and leads to more predictable construction outcomes. The MPS is the resource that grounds decision-making using real-time dynamic interdisciplinary coordination.

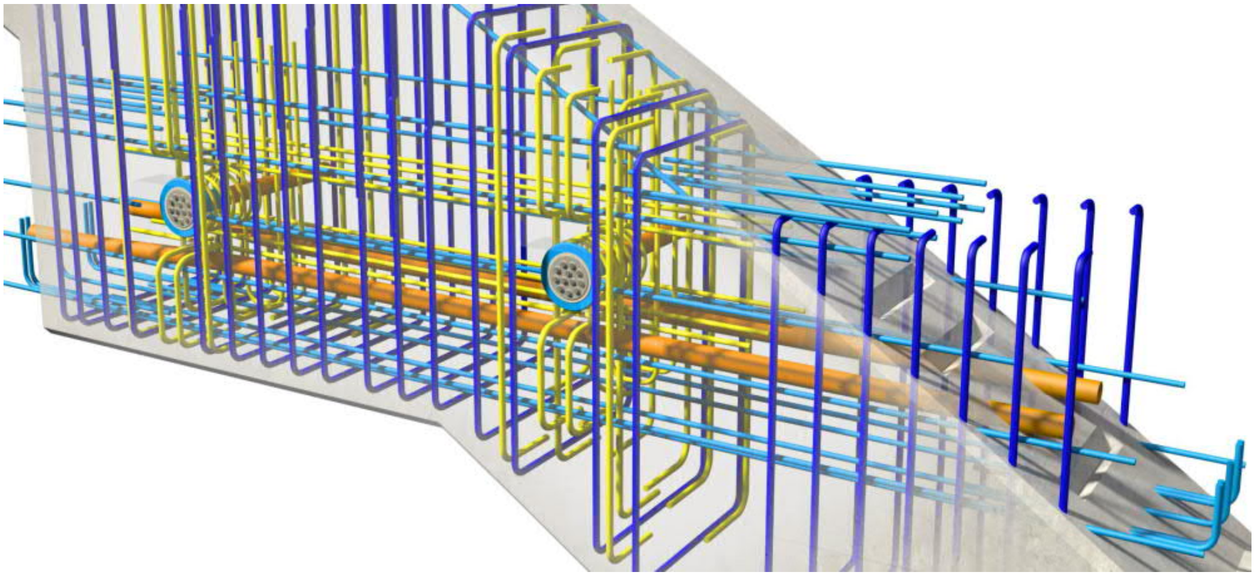


Figure 23: Coordination of rebar and post-tensioning in a concrete arch.

The extent to which this use translates to bridge design is highly dependent on the complexity. Clashes between reinforcement and post-tensioning are possible in concrete bridges, though the areas of concern may be highly localized, such as the areas seen in Figure 23. Interdisciplinary clash detection may be beneficial. However, where existing subsurface utilities are concerned, the clash detection needs to consider the confidence of the subsurface utility locations.

Traditionally, building codes are checked manually during the building design and at the design certification milestone. BIM development and data format standardization offered opportunities to digitize the rules that form building codes and automate the code-checking process. Rule-based systems can check a design model against building codes and standards. They indicate where the needed data is incomplete, overlapping or missing. Again, consistency between the BIM models and the contract plans is an essential point that gives meaning to automated code checking process.

Currently IFC, an official standard (ISO 16739:2013) containing geometric and non-geometric data, is one of the most widely used formats in automatic code-checking systems (buildingSMART, 2016). IFC acts as a bridge between modeling software and model checkers. It supports interoperability by transforming paper document-sourced rules into digital ones, thus accessible in model checkers. There are already efforts underway to expand the realm of IFC from buildings to reinforced concrete and pre-stressed concrete bridges (Yabuki, et al., 2006). While design tools implement codes such as the AASHTO LRFD, these automated checks could help design reviewers feel confident that the codes were correctly applied.

2.2.3.6 Fabrication

Steel fabricators for many decades have operated on the leading edge of technology and machinery. 3D BIM design files are able to generate the basis for fabrication models and shop drawings. In other words, BIM is directly informing digital fabrication, defined as the process that uses digitized information to in turn fabricate construction materials or assemblies, such as sheet metal, structural steel, pipes and even prototypes. Thus, BIM based fabrication workflow result in a downstream manufacturing process with fewer ambiguities and sufficient information to fabricate with less waste.

Creating and extracting computer numeric control (CNC) files from 3D BIM files is a longstanding established workflow. Integration with BIM has greatly simplified the fabrication process and reduced the time required going back and forth between shop drawing reviews. In fact, fabrication stands to gain greatly from the development of new data exchange methods, which promise to further the seamless integration between design models and machine files used to process the steel. If designers and fabricators could use a shared model, rather than sending data to the next contractor to convert to their own systems, design details, instead of being lost, can be dynamically updated with each new design change.

In the case of steel bridges, a model can generate shop drawings for use in fabrication shops; while connection details only occur infrequently in large lengths of uninterrupted span, the accuracy is critical enough to warrant a 3D approach. Similarly, in the case of precast concrete bridges, model files can produce integrated shop drawings showing concrete, rebar, and post-tensioning details for the casting yard, resulting in significant time and cost savings for the project. BIM assisted fabrication could better manage the complicated formwork required for more irregularly shaped concrete bridge designs. One can even send integrated model-based, accurate data to the rebar factory production line, thus minimizing the cutting and bending on site and reduce material waste.

2.2.3.7 Construction

Use of BIM in concert with schedules, to create 4D information or models, has become an established tool for contractors to check construction sequences and site layout and logistics. Tools allow teams to apply filters to show objects across multidisciplinary federated project models by construction phase or even by trades or discipline to organize, coordinate and visualize sequencing scenarios. This can identify issues from trades working near to each other in time or space. For these exercises it is important to include temporary works like formwork, scaffolding, equipment and earthworks. Bridges, especially those near live traffic, would greatly benefit from such 4D analysis for site layout and erection sequencing.

The term “Scan to BIM” has casually emerged and refers to the process of capturing existing or mid-construction conditions via lidar and then generating some idealized model geometry based on extracted features. Scan to BIM can be used at any time, for instance to create existing condition models prior to design, or to as-built in-progress construction for on-going space/time clash detection and construction sequencing. It could potentially be used to verify the screed information if there is support to responsively register and process the data. For instance, point cloud to 3D model comparison is relatively quick (and could be done with an unregistered point cloud if there are enough common reference points), compared to trying to extract locations from a point cloud.

2.2.3.8 Asset Commissioning

The customizable non-geometric attributes of parametric models creates an opportunity to improve the asset commissioning process. Establishing agency-specific BIM object standards enables models to be generated with pre-populated asset information needed for maintenance and asset management business systems.

The manual collection of asset and maintenance management systems information is an onerous task that involves mining paper-based design and construction information, or locating the assets to collect their attributes. Many enterprise business systems that receive the BIM-based tabular asset data can maintain the link to the 3D model which allows visualization by the facility team and a bi-directional link in order to maintain that asset model updated as repairs and equipment replacement occurs.

To this end, a data exchange protocol was developed by the Army Corps of Engineers to facilitate this data transfer from the model to downstream target databases systems: Construction Operations Building Information Exchange (COBie). COBie transforms information in paper documents into data that can be used throughout the electronic design/build/operate process. (East, 2007) Such is its effectiveness, COBie has seen its acceptance by the larger building industry. (Scarponcini & Nisbet, 2013) The current COBie data structure is illustrated in Figure 24.

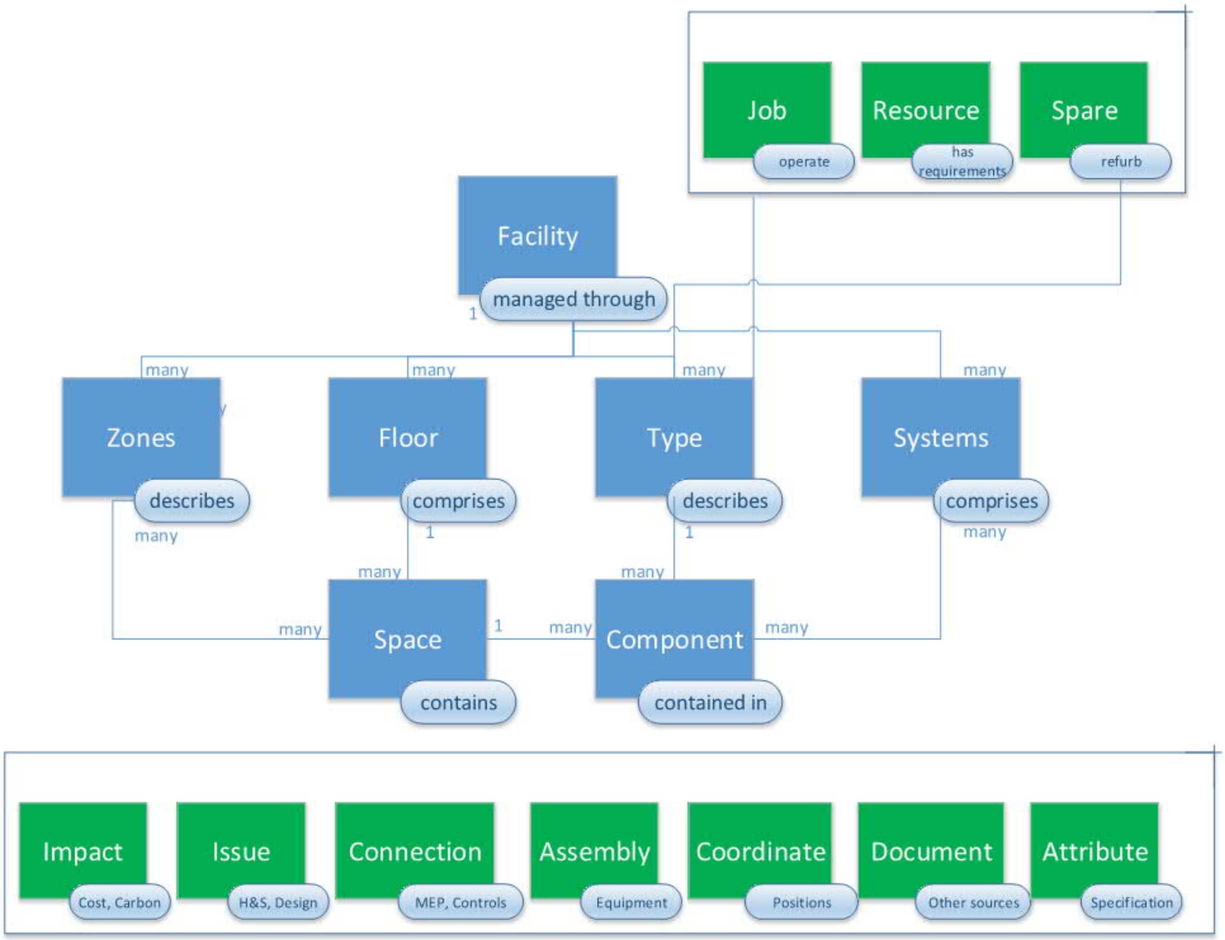


Figure 24: COBie data structure (East, 2007).

There are efforts to extend the COBie data structure to better support linear, civil infrastructure projects. Linear and geospatial locations were two of the problems identified when evaluating how COBie can be extended to support the UK Government's BIM mandate. Another issue was the concept of variable asset attributes, which allow attribute values to vary along the length of a linear asset without segmenting that asset into multiple assets. (Scarponcini & Nisbet, 2013) This would be important to support bridge element condition information.

2.2.3.9 Operations and Maintenance

At an enterprise level, agencies are beginning to realize the benefits of incorporating BIM into operations and maintenance workflows. This allows owners or facility operators the ability to answer key questions such as, what do we own, or when was the last service performed on this component? The incentive of being able to access such intelligence proves invaluable for managing a collection of assets, small or large. Asset information models may be used to view and organize monitored data across a portfolio of assets. For example, moisture sensors and air quality sensors can be placed within facilities and linked so that the measurement data feeds to the asset models in order to enable monitoring and analysis of real-time conditions. Off-site access to such information can help management teams detect safety issues before they become critical.

2.3 Data Interoperability and Durability Considerations

In this section, the various data formats and exchange schemas used in the bridge and buildings industries are detailed and a summary of the schemas reviewed by the FHWA is presented. The intent is to identify the most favorable data deliverable formats for MDOT to invest in when developing a framework for 3D and 4D bridge models and plans.

2.3.1 Data Formats and Exchange Schemas in use for Bridges

A number of data formats were identified in *Figure* . These are included, as are emergent data format and schemas for bridges, such as the Bentley OpenBridge schema and the IFC standard being explored by FHWA and AASHTO.

2.3.1.1 Plain Text Formats

XML refers to the eXtensible Markup Language, which is a markup language that defines a set of rules for encoding documents that is both human-readable and machine-readable. Data is typically described in data schemas that defines the organization of data and how they relate to each other. XML format files do not display data on their own, rather they rely on other software programs (such as AutoCAD or MicroStation or other Bentley Programs) to format and display the information contained within. This format allows the transfer of design and other data from one platform to another, and a schema is necessary to interpret the markup language and extract the data.

Examples of XML format schemas widely used in the bridge industry include LandXML for terrain and roadway geometrics, MathCAD for structural analysis, LEAP Bridge Enterprise for structural analysis, AASHTOWare Trns*port for bidding and construction inspection data, and TransXML, a data schema that was proposed and studied, but not implemented. (Ziering, et al., 2007) XML is a potential exchange format for AASHTOWare Bridge analysis products. (Shirole, et al., 2008) The MDOT 3D BRIDGE App uses XML as the file format. (Michigan Tech Research Institute, 2016)

Other plain text format files that are in common use include the Comma Separated Values (CSV) and other formatted text formats. CSV files are often used for survey points and tables of data, such as quantities and schedules.

2.3.1.2 Plain geometry formats

DXF is a neutral file format for interoperable exchange of CAD graphical content such as lines, points, arcs, 3D solids and meshes, text, dimension lines, and other vector graphics. Software vendors have implemented good support for proprietary CAD graphics formats, such that DXF is rarely used. Bentley’s .dgn format is well supported by other CAD software applications in the highway market. Neutral plain geometry formats for 3D models emerged to support mechanical design and drafting. The .STEP file format was adopted as a standard (initially ISO 10303-21:1994, currently ISO 10303-21:2016). (Industry Standards Organization, 2016) These are not common in the highway market, but are supported by CAD software applications.

2.3.1.3 Formats supporting both data and graphics

As the industry turns towards object models for design development, proprietary file formats store graphics, object parameters, and the rules that define the relationships between the two. This presents challenges for data durability and data interoperability, as correctly interpreting the data may rely upon using specific software, and even a specific version of that software. However, with a lack of data standard for the highway industry in general and specifically for bridges, vendors have reached a point where they must invest in schema development to provide the software tools that users demand.

The most notable proprietary data format and schema as it relates to MDOT is the Bentley OpenRoads and OpenBridge schemas, supported by the .dgn file format and readable by MicroStation V8i SS4 and later software. Much of the desired seamless data exchange enjoyed by the vertical construction industry is being implemented for bridge structural analysis, parametric design, and plans production. Figure 25 shows how many of the functional areas of bridge design development are supported with seamless data flow in the proprietary Bentley data schemas.

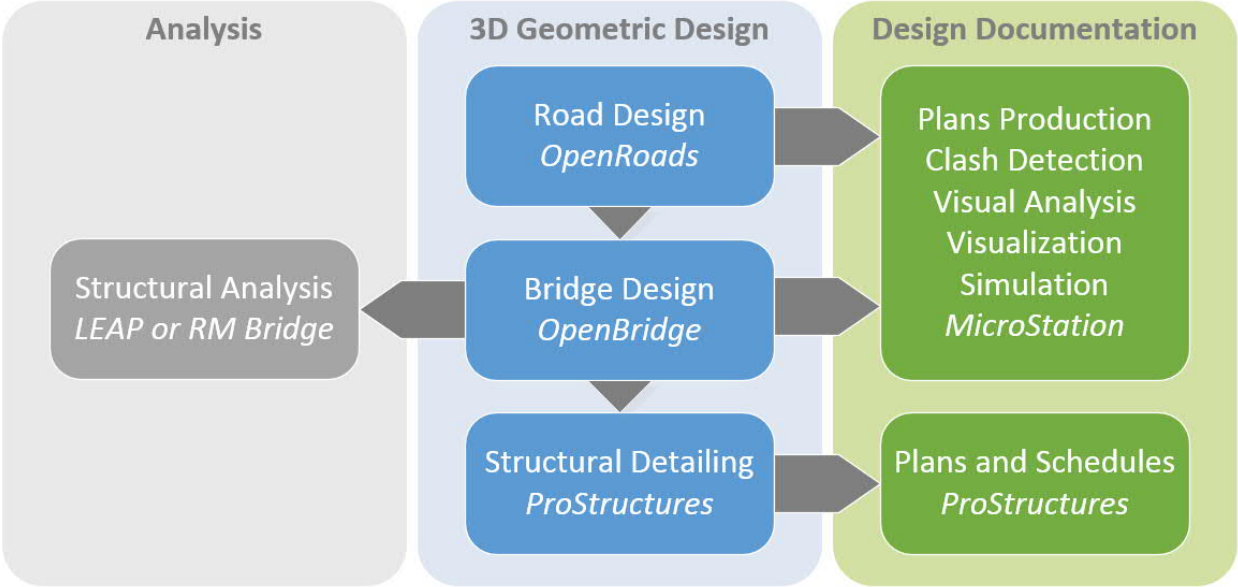


Figure 25: Design production within the Bentley proprietary schemas.

The problem with proprietary schemas is that it limits the data exchange to the software products that support it, in this case a single vendor. However, MDOT's current standard for road design and for all drafting is compatible with this schema. The most limiting aspect is integration with structural analysis, and this is an optional part of the workflow. An agency may have significant data governance issues with reliance on a proprietary data format. It may be especially limiting to aspirations to replace contract plans with contract models, either for fabrication or more broadly.

The Industry Foundation Classes (IFC) data model is a platform-neutral, open file format specification that is intended to describe building and construction industry data. It is an object-based file format with a data model developed by the buildingSMART Alliance, which also develops the National BIM Standard. The IFC model specification is open and available. Unlike other schemas such as LandXML, it is registered by the International Standards Organization (ISO). (International Organization for Standardization, 2013)

As an international standard and endorsed by legitimate industry organizations such as the AIA, the IFC data model is supported by all major software vendors in the building industry. The format has undergone several generations of vendor validation and certification and consequently meets the ISO criteria map for all of validation, verification, conformance and interoperability. This avoids concerns for data interoperability and durability, and provides the most flexibility regarding software applications.

The main challenge with IFC is that it is not well supported for roadway data, in particular roadway parametric models and alignment-based layout. (Grant, et al., 2015) Stubs (or extensions) proposed to IFC version 4 provide some support for geospatial coordinates and civil elements. IFC-Alignment and other proposals to be introduced in IFC version 5 address many of the roadway and bridge-specific needs to make IFC viable for bridges. The IFC-Infra roadmap is supported by Autodesk, Bentley, and Trimble vendors (amongst others), as well as a large contractor (Kiewit). (Liebich, 2015)

2.3.2 Progress of Schema Standardization for Bridge Industry

There have been several industry efforts to explore data standardization for bridges over the past decade. These have been supported by the FHWA, AASHTO, and NCRHP.

2.3.2.1 Schemas Reviews

The Open Bridge Information Model (OpenBrIM) was developed as a framework of an open data model. The OpenBrIM 2.0 schema supports models of components of bridges using several generic data structures. Specific meaning of objects depends on understanding particular object types of reserved identifiers, which are not defined within the schema. The data schema itself contributes a minimal role in validation of such file, while specific custom validation would be required to enforce correct usage of attributes and string encodings. For example, the flange width of a beam would be captured as a Parameter, and the 3D volume would consist of data structures that reference this parameter. The naming of such parameters also needs to be standardized for software applications to extract such information consistently. The OpenBrIM specification defines such standard set of objects.

The primary advantage of an OpenBrIM schema is that the parametric nature is conducive to describing high-level design parameters and could be leveraged to develop reusable component templates such as deck and pier types. However, the requirement for custom validation to enforce correct usage of attributes means that the schema does not meet the ISO criteria map for validation, verification, conformance and interoperability. The creators identified a need for legitimate schema governance as a critical factor in its success. (Chen & Shirole, 2013)

Further research continued to develop OpenBrIM 3.0 as a community-driven, free, cloud-based collaboration system. (Red Equation Corp, 2015) At the conclusion of the project, there were still significant gaps in the objects and functions necessary for comprehensive bridge design. (Bartholomew, et al., 2015) A lack of clear schema governance, and the availability of a near-complete open and well implemented standard in IFC, means OpenBrIM is unlikely to be widely developed.

Concurrently with the development of OpenBrIM, a study evaluated the completeness of the IFC schema for the construction of two typical “workhorse” bridge types, one concrete and one steel. Other than the need for alignment-based layout, provided by the proposed IFC-Alignment for IFC5, the extensions proposed to fulfill the functionality for bridge design were non-critical and related to repetitive pile/rebar layout, derivation of camber, and documented use of constraint-based parameterization. (Grant, et al., 2015) While the research focused on information exchanged from design to construction (via contract plans), it is worth noting that IFC has already been adopted by many fabricators.

The suitability of LandXML for bridges has also been evaluated. LandXML supports terrain and roadway alignments, as well as cross-sections and pipe networks to some extent. It is also well supported by software commonly used in highway designs. However, LandXML does not manage complex 3D geometry. Indeed, its support for utility structures is incomplete. LandXML did not meet the ISO criteria map for verification or conformance, but did meet the criteria for validation and interoperability.

The general steps moving forward involve creating a comprehensive map of data exchanges to develop a data dictionary, mapping the data dictionary to established data schemas (most likely IFC), systematic testing, industry adoption by vendors (including software certification), and ultimately deployment by the bridge industry through establishing data standards.

The topic of schema governance for bridge data has been championed by the AASHTO T-19 Committee, which is part of the Subcommittee on Bridges and Structures (SCOBS). The T-19 Committee has been educating SCOBS members on BrIM and collaborating with other AASHTO and Transportation Research Board committees. (Becker, 2015) AASHTO T-19 Committee has yet endorsed any one path to bridge data standardization.

3. Current Practices

This section summarizes the state of the practice for using 3D and 4D models and plans within MDOT and peer agencies. The intent is to coordinate this research with ongoing national efforts and to align the research to the most favorable emerging areas for development. The practices of Iowa, New York, Wisconsin, Utah, and Connecticut DOTs and Caltrans, are described as they were communicated in the planning for and execution of a web-based peer exchange hosted by the FHWA. (Federal Highway Administration, 2016a) Other resources shared by these agencies, such as NYSDOT presentations to AASHTO's T-19 committee (Soka, 2015) meeting in 2015 and Iowa DOTs implementation plan, (Jeffers, 2015) are also referenced.

3.1 Peer Agency Standard Practices

Wisconsin DOT uses a variety of Autodesk and Bentley products for design development. On large construction programs, such as the Southeast Freeways project, Roadway and Bridge discipline models are consolidated into a single, federated model that includes all disciplines. Within this federated model, the level of detail was limited to external faces, with clash detection of footings, utilities, piles and abutments made possible. Several utility/pile clashes and utility/lighting clashes were found.

The Southeast Freeways project has used a combination of Bentley LEAP software and rapid geometric modeling software tools to develop bridge models. LandXML was used to import roadway geometrics into LEAP to create a model oriented to project coordinates. Wisconsin DOT uses FEM analysis for certain complex structure types. When a complex structure type requires FEM, the designer is required to deliver the FEM model. The FEM models could be used for structure rating during asset management, but software interoperability and data durability are concerns.

Utah DOT utilizes a combination of in-house designers and consultants for design work. Some consultants have developed 3D models for more complex bridges for internal use, whereas designs for simpler workhorse type bridges do not use 3D analysis tools.

NYSDOT uses substructure models for quantity take-off, both for excavation earthworks and concrete volumes. (Soka, 2015) Bridge models are feature-based, which means that they contain MicroStation CAD elements. Examples are shown in Figure 26. These are not parametric models, which means that design changes do not propagate automatically. However, they are developed in project geospatial coordinates consistent with the roadway models. The models are used for geometric analysis and detailing, and are not integrated with structural analysis. The models aid in plans production, quantity take-off, and interdisciplinary coordination.

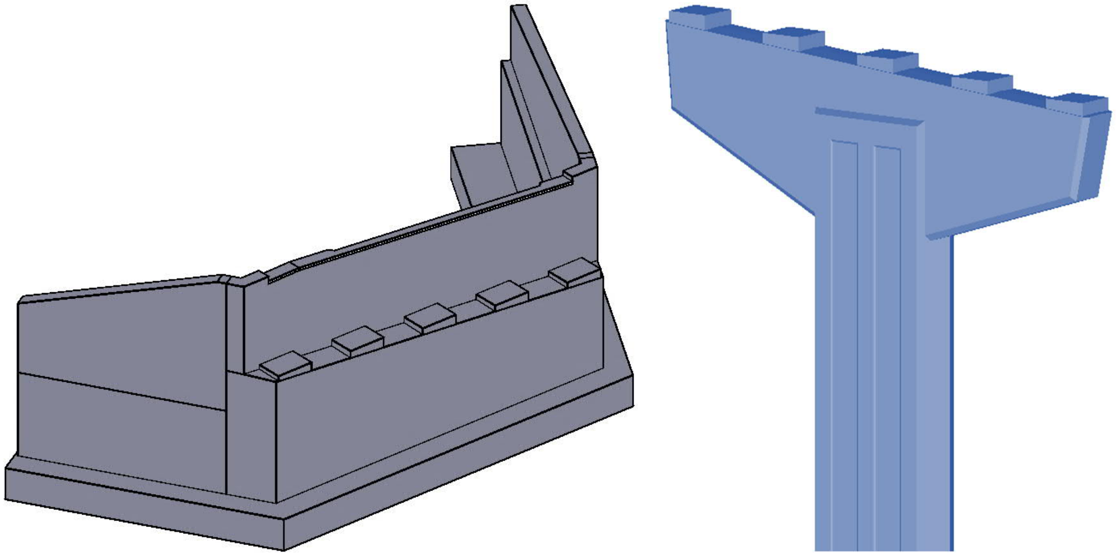


Figure 26: Examples of an abutment and a pier (Soka, 2015).

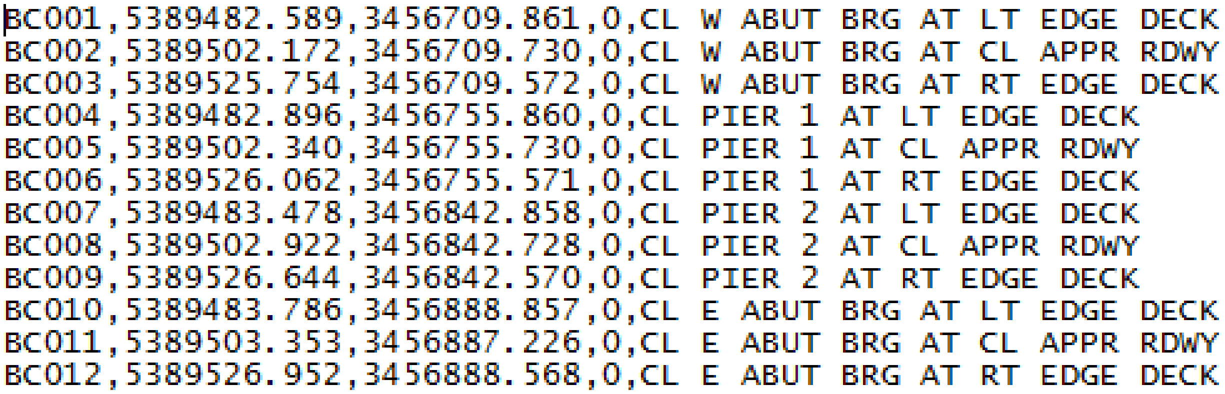
NYSDOT has incorporated requirements and guidance for 3D models of substructures into their Bridge Manual. (New York State Department of Transportation, 2014) The modeling standard makes extensive use of the MicroStation model feature. Models within MicroStation are analogous to sheets in an Excel spreadsheet file. It is a means to segment and name individual 3D model content. However, this is a unique function of MicroStation and requires MicroStation software to access all but the current model. Bridge files may have over two dozen models within them. While these files are made available to contractors with other 3D data as part of the bid reference documents, the ability to use them requires advanced knowledge of MicroStation and access to the software to export each model individually.

3.2 Peer Agency Pilot Efforts

The Iowa DOT has used several free and open source software tools to extend the range of software available to them for visualization. The Little Silver Creek Bridge, an ABC project, was the pilot for applying these tools. (Iowa Department of Transportation, 2016)

Iowa DOT also had a consultant use 4D modeling to visualize complex staging at the Council Bluffs Interchange project. Here, the visualizations were more rudimentary as the target audience was technical. A number of contract coordination issues meant that there was a need to closely coordinate contract milestones. A 4D model with low detail graphics was an effective solution to manage the risks associated with staging and coordination. (Federal Highway Administration, 2016d)

On a project along I-80 in Iowa, while consultant designers will provide the 3D models, Iowa DOT is piloting generating stake-out information to provide to contractors electronically. Figure 27 is an example of the bridge staking data to be provided. Iowa DOT is also evaluating using OpenBridge Modeler to consume the OpenRoads models created by the Roads department. (Jeffers, 2015)



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BC012,5389526.952,3456888.568,0,CL E ABUT BRG AT RT EDGE DECK
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Figure 27: Bridge staking data (Jeffers, 2015).

While Utah DOT is still early on in the process of 3D models for structures, they intend to move from a plans and model-based deliverable to a consumable digital data deliverable achieved through a database approach. Further, they'd like to receive these models back from construction for asset management purposes with the same digital data format.

With a pilot project along Route 125, Caltrans will model bridges in 3D. Within this project, four "workhorse" type standard Caltrans concrete bridges are being modeled using Revit Structures. The software will be used to model, among others, abutments as well as rebar detailing. The bridge models are scheduled to start at the substructure level, but there is an overall plan to model the superstructures as well. Caltrans would like the finished model that they provide to the contractor to be in IFC format, with source data such as the table of parameters in Excel. Further, while the parameter data would be in Excel, the mathematical relationships would be in Dynamo, a scripting application within Revit.

Caltrans is currently seeking funding to market the BIM process to project managers. Ideally, they'd like project managers to implement BIM in the planning process. Caltrans has already added OpenBridge Modeler and OpenRoads to the list of approved software and are trying to integrate Bentley ProConcrete for rebar detailing.

Visualization is a separate outreach activity that Caltrans is actively looking to enhance and develop an expertise in. Caltrans has already been using 3D models and visualization to support design and stakeholder communications for several years. For instance, in the San Francisco-Oakland Bay Bridge program, construction on Yerba Buena Island had four separate contracts working adjacent, and, in some cases, sharing staging areas. Caltrans wanted to better understand how those four contracts would interface and as such, requested that the 3D models be repurposed and used to produce a 4D simulation of this area. The four contracts were merged into a single master schedule. The model was broken down into components based on the activities in that schedule. The two were connected using software, and a 4D simulation was produced.

The 4D construction simulations that Caltrans used on the San Francisco-Oakland Bay Bridge allowed all of the contractors working on Yerba Buena Island to better understand activities that would be happening concurrently. The model was used in meetings with the various contractors when planning for access and construction areas on the island. Eventually, later activities were planned and presented to stakeholders using the 4D model, including models for temporary structures from contractors. (Federal Highway Administration, 2015a)

Connecticut DOT used 3D visualization and 4D simulation to support construction planning and management on the I-95 New Haven Harbor Crossing Corridor Improvement Program. These models were used for technical analysis, project communication, visualization of construction sequences, and illustrations for the public's better understanding of the project. (Federal Highway Administration, 2015a)

NYSDOT is currently undertaking a research project that is looking at 3D data-driven design in fabrication and shop drawing review. The project was initiated starting with MicroStation InRoads files and then transferring in steel elevations. There was a focus on ensuring data integrity within the model over developing the visual side of the model and file compatibility was an important consideration. One of the challenges was the fact that the design showed the final position of the girders, which is not the load state used for fabrication. An addendum to the project took the data to fabricate a full-scale girder and do a laser scan to verify that the beam was fabricated as per the requirements. The benefits were found to be reduced likelihood of errors reentering data from plans, as well as efficiencies.

3.3 MDOT Practices

MDOT’s primary opportunity for generating 3D and 4D bridge models and plans is during the preconstruction process. The general process is described in Figure 28, which shows to project development phases, key activities, and the outputs.

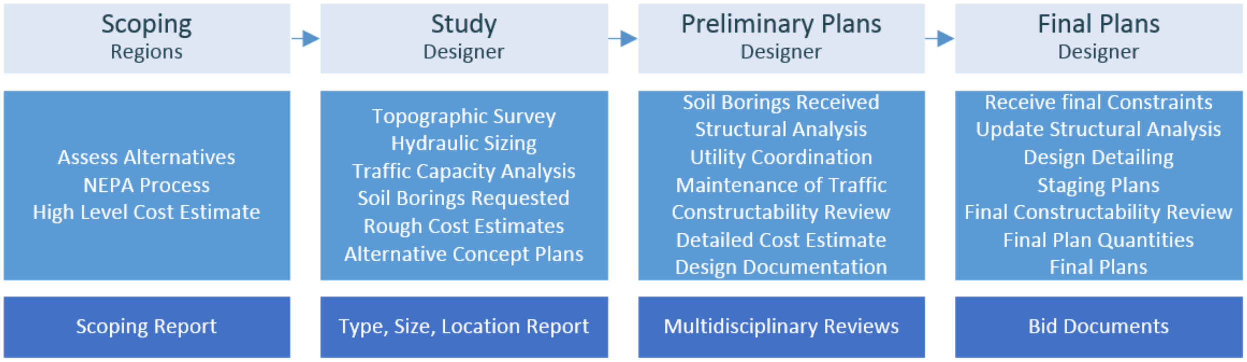

Figure 28: MDOT bridge project development process (MDOT, 2009).

Most bridge projects qualify as Categorical Exclusions under the NEPA process, but for larger, less common bridge projects there are opportunities to use 3D models for visualization during the NEPA process. For the majority of MDOT’s bridge projects, the first use of 3D data is in the Study phase, when topographic survey is collected and alternatives are considered to a level of detail that includes exploring clearances and sizing some of the main structural elements to the extent needed to make a rigorous assessment of the best type, size, and location.

3.3.1 Study Phase

The Study Phase is intended to be the point at which the final design criteria are solidified. Often, the best alternative is clear at the Study Phase. The main difference between the Study Phase and Preliminary Plans is that different design alternatives are considered in the Study Phase. Normally, MDOT's Regions have done a robust Scoping before adding the project to the STIP, often narrowing down, for instance, if a superstructure replacement or whole structure replacement is needed.

The Study Phase often includes refined information, such as survey, initial hydraulics to determine open area, and geotechnical constraints sufficient to develop foundation assumptions. (Retaining wall heights and footing depths may change as the design advances.) The Study Phase essentially narrows down issues such as whether the structure will be a culvert or a bridge (i.e. structure length along the centerline), whether the superstructure will be concrete or steel, the beam depth, and whether or not ABC will be used. The products of the Study Phase are general site and structure plans for about three alternative design concepts. The study phase will soon also include documenting major project impacts such as utility conflicts or relocations and right-of-way impacts.

The study phase is used to refine decisions on geometry such, as under-clearances, which affects both the road profiles and the structure depths. It is possible that Corridor Models could help the process if Road used templates of simple beams or girders that are parallel to the alignment. A section such as that shown in Figure 29 could be created from a corridor model, which would update dynamically to width, elevation, cross-slope, or superelevation changes. Setting up dynamic templates for corridor models for various beam configurations would be time-consuming, however. Software like OpenBridge Modeler is designed to evaluate different superstructure and substructure configurations quickly and would make 3D models more accessible for a range of structure types.

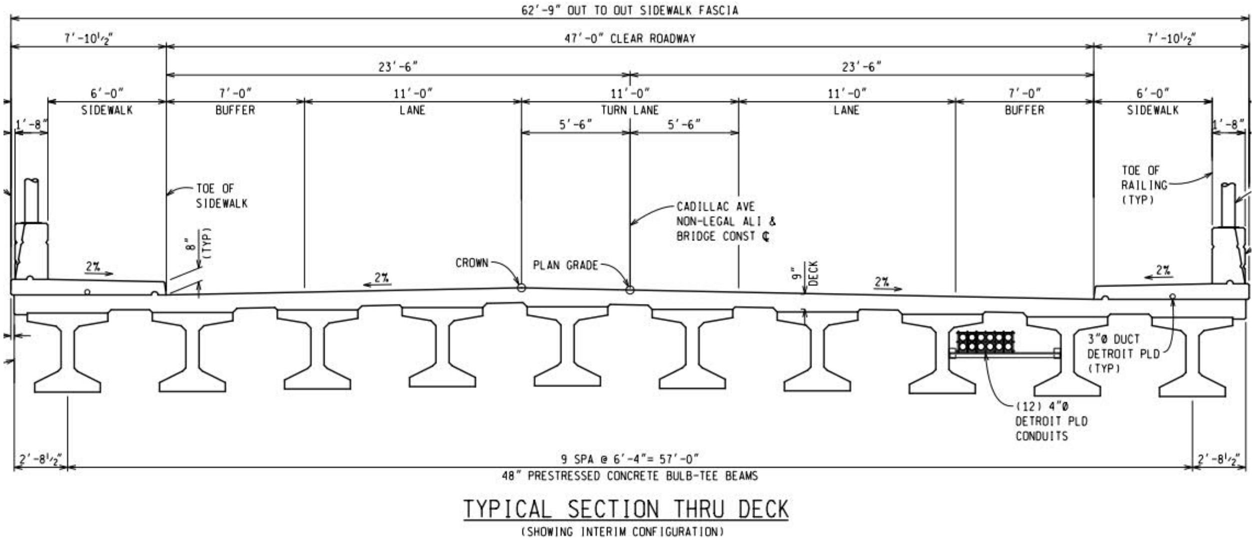

Figure 29: Corridor models can help automate creating sections.

MDOT uses an in-house Visual Basic for Applications (VBA) routine to automate the process of extracting cross-sections for HEC-RAS to be used in bridge hydraulic modeling. The tool uses the terrain data, MicroStation geometry of the river alignment and cross-section locations, and exports a .csv file to generate the HEC-RAS model.

Over the past several years, MDOT has been able to rely on institutional knowledge in-house and in the consultant community to optimally deploy evolving survey technology to safely and efficiently collect the topographic information needed for bridge studies and designs. As key members of the survey workforce have aged into retirement or moved into new areas, MDOT recognizes a need to refresh standards for survey data collection, processing, and deliverables.

MDOT is aware of opportunities to use static lidar for bridge survey data collection. Static lidar is more expensive than other methods of survey data collection and processing, but it can be deployed with less traffic control and less exposure of surveyors to the motoring public. These benefits, as well as a more detailed, more accurate, and more complete picture of the existing conditions, as illustrated by Figure 30, can give a favorable return on the investment.

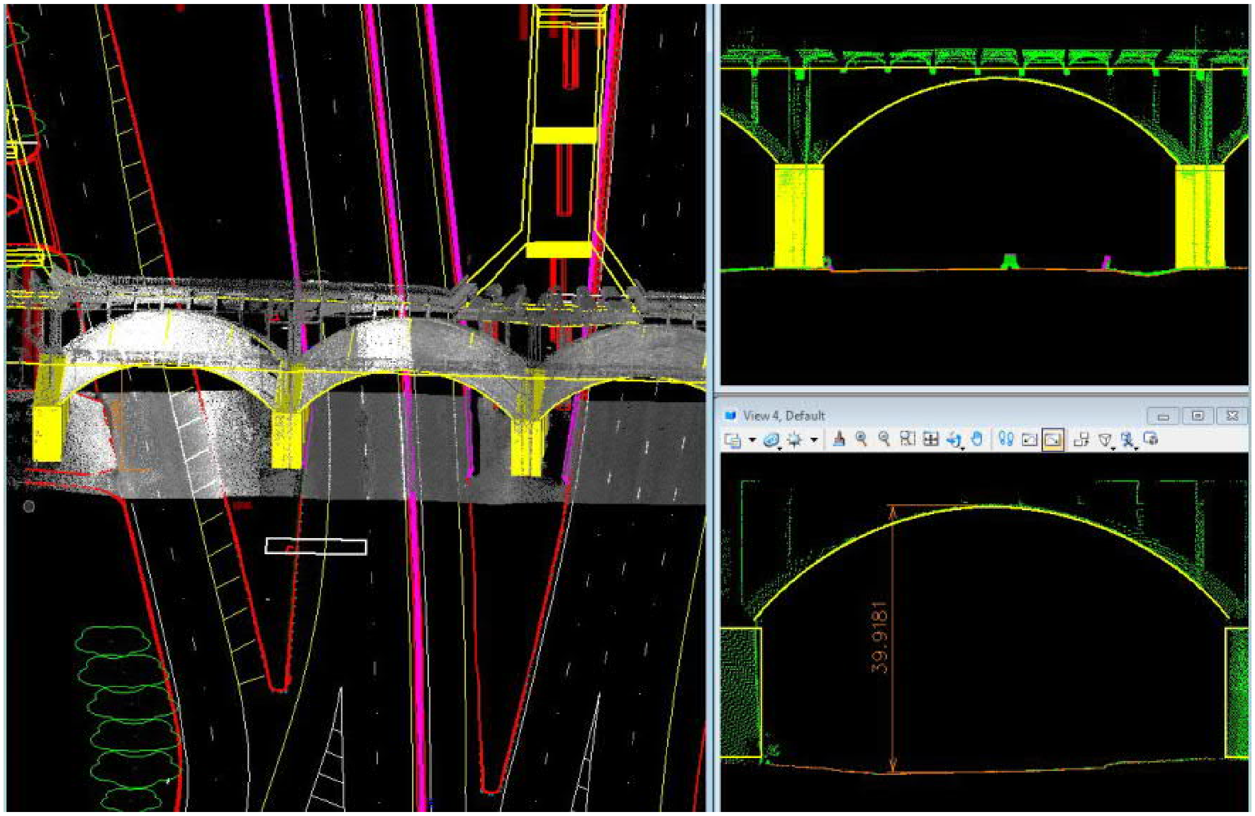

Figure 30: A lidar survey of a bridge (Fisher, et al., 2012).

Static lidar can collect the normal features, such as existing roadway geometrics, locating the ends of the decks, joints, trees, utility poles, etc. and inferring the locations of the reference points and reference lines. The more complete picture of under clearance is a significant benefit of lidar survey; traditional methods of determining the under clearance collect measurements at a discrete points, but not indicate where in the lane or off the pier that the measurement was taken. Having a complete point cloud could give the designer confidence that clearance requirements will be achieved with the recommended profile modifications.

Another benefit of static lidar is the ability to use scan-to-BIM technology to extract solid primitives of the visible substructure and superstructure elements. Figure 31 shows the application of scan-to-BIM for an existing highway interchange. The resulting solid models can be used for staging analysis, evaluating options for demolition, taking off demolition quantities, and 4D simulation. MDOT has TopoDOT software which has functionality to automate some scan-to-BIM extraction for substructures and beams.

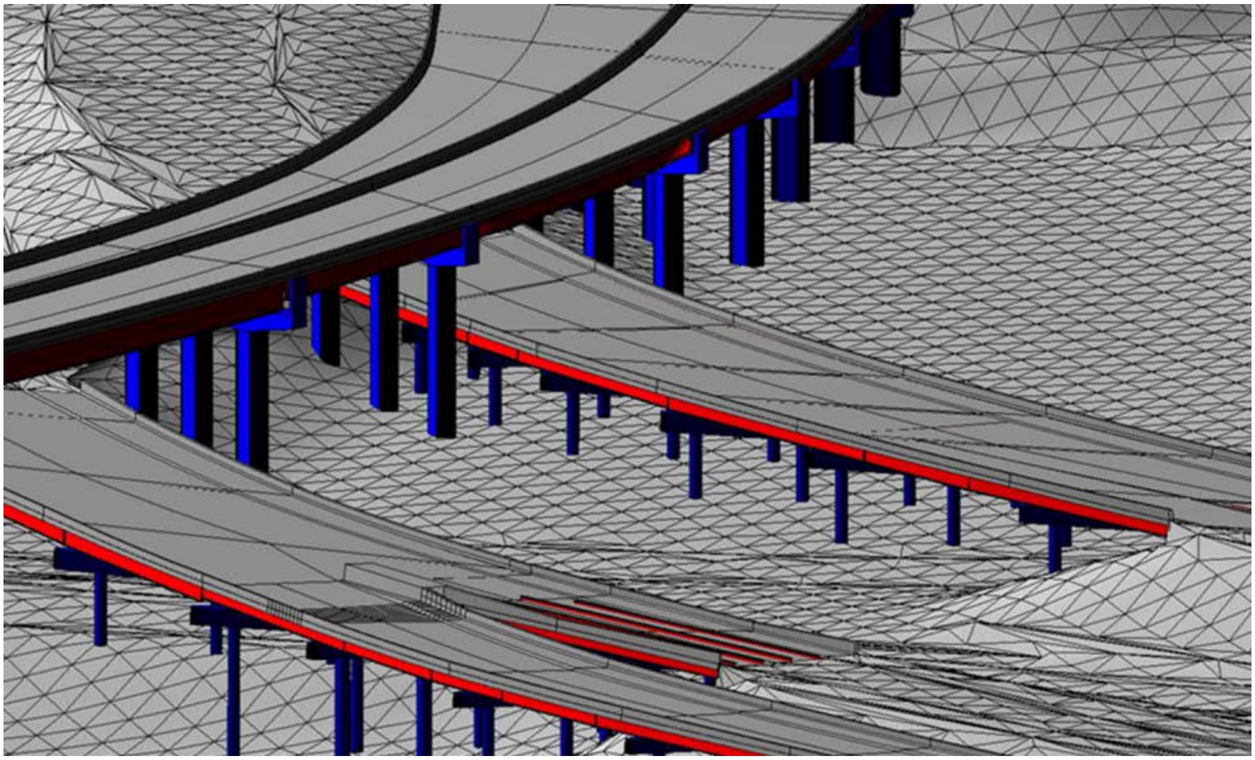

Figure 31: Scan-to-BIM for a highway interchange (Fisher, et al., 2012).

MDOT is discussing with FHWA the purpose of the Study phase in order to refine the process of preparing a Type, Size, & Location (TS&L) report. Most projects are sufficiently constrained that the Study Phase does not add significant value and the Preliminary Plans phase is effectively an exercise in producing more plans to document the selected alternative. The ability to rapidly generate 3D models may make the study phase more meaningful through developing options and more detailed review of the alternatives. A larger investment in 3D modeling in the Study Phase would need to have improve plans production efficiency to add value. If OpenBridge Modeler is able to automate creation of some types of plan sheets, then it would be a valuable tool for the Study Phase.

3.3.2 Design Phase

MicroStation feature modeling has been piloted in the past, but there was no automation to the process. Each step had to be completed manually and as such, the pilot did not seem to be adding value. While modeling substructures was found to be relatively easy, decks were harder to model properly; in particular, the modeling of crowns, haunches and horizontal and vertical curvature.

Change propagation is one of the biggest issues for MDOT's technicians and designers. Typically, quality information is not available at the time when design needs to advance and design documentation needs to start. Assumptions regarding maintenance of traffic staging happen early and the design usually proceeds based on preliminary foundation recommendations. The impact of change propagation depends on how advanced the design is when the change is received. Sometimes the changes cannot be fully propagated and only dimensions change on plans without updating the plan graphics.

Reacting to change is further complicated by the fact that Bridge design is performed in Lansing while Road design is performed within the regions. Over the past 3 years, MDOT has implemented several process refinements into the bridge design workflow. MDOT's document management and collaboration tool is ProjectWise. ProjectWise enables collaboration between Bridge and Road as designs progress for both disciplines. In the past, the Bridge and Road deliverables were staggered, but now they are more integrated. For instance, plan view drawings are now in project coordinates, enabling one common set of reference files to be shared between Road and Bridge. This allows updates to propagate through both sets of plans. Some of MDOT's Roadway designers have started to model bridge abutments using Geopak linear templates and corridors.

The reference points (at each substructure unit) and reference lines, seen in Figure 32, define the layout for the bridge. The reference line falls along the bridge centerline, with a crossing line either at the centerline of a pier or the back side of the abutment. For rehabilitation and partial replacement projects, often the reference line locations are assumed based on existing plans or as-built drawings and cannot be determined clearly until the abutment is exposed during construction. This can lead to design changes in construction. Parametric models with dynamic change propagation to plan sheets would significantly improve response times.

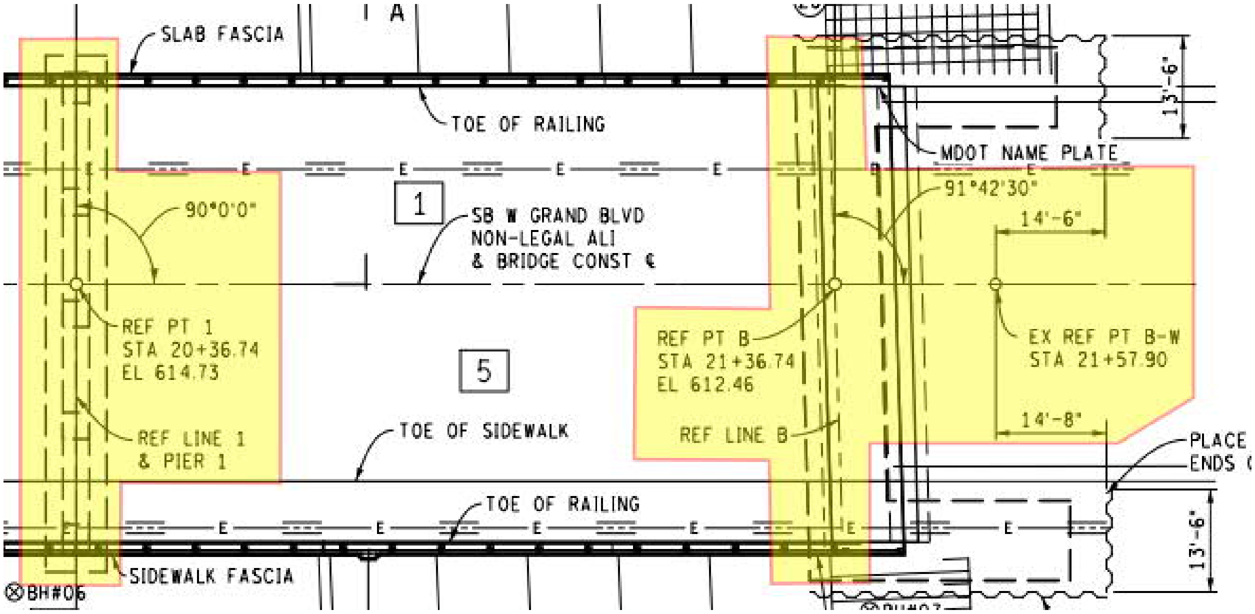

Figure 32: Reference points and lines.

New requirements for Road to produce 3D model deliverables has helped set the foundation for 3D modeling to be adopted across the department. MDOT recognizes the potential for additional process improvements from 3D parametric modeling for designers. How others will benefit is not yet clear to MDOT. The greatest opportunities for parametric models appear to be for detailing, especially for rebar (e.g. with ProConcrete) and tensioning strands in prefabricated bulb tee beams (e.g. with LEAP Bridge Enterprise). In addition to Bentley tools, there are software tools that read and write to the IFC file format.

There is a desire to model the whole structure in 3D and use that model to create plans. Past experience with LEAP Bridge Enterprise was disappointing because it could not be customized to MDOT-specific elements and used a different design methodology for piers that is not compatible with MDOT's standard. It was also cumbersome to have to propagate design changes through LEAP Bridge Enterprise rather than directly in the MicroStation environment. OpenBridge Modeler is promising because it seems to address these concerns and will integrate with the Bentley structural analysis products. The opportunity for visual design coordination is valuable, but the ability to use the models for plans production needs to be carefully explored.

Final Plans can include complicated superstructure drawings, especially when there is superelevation on the deck. Haunches are usually specified with a general height and are only detailed if unusually high requiring additional reinforcement. Haunches do need to be shown in cross-sections. OpenBridge Modeler will need to model haunches and bolster elevations on pier caps to bring good value. If these details need to be added manually then the change propagation efficiencies that OpenBridge Modeler has are eroded. OpenBridge Modeler does not yet compute cambers, though LEAP Bridge Enterprise does. Engineers typically use spreadsheets to compute cambers.

Modeling earthwork at abutments would be beneficial for the purposes of checking constructability and computing earthwork quantities. Bridge calculates the structural backfill and excavation quantities using a 1:1 slope match line with the Road embankment quantities. The Bridge quantities are usually paid according to plan quantities and there is some concern that these are routinely overestimated due to the complexity of calculating accurate quantities. There are challenging angles and corners that are time-consuming to compute manually. This is not a primary objective of 3D modeling, but it is another area where 3D modeling can enhance with increased accuracy and efficiency.

An in-house analysis software called Bridge Design System (BDS) is used to design the most common bridge types on the MDOT highway system. Amongst its outputs, BDS produces a table of deck elevations for the slab & screed tables. The AutoDraw program developed in-house has also been used to provide some automation for plans production, consuming BDS data and generating MicroStation line work. MDOT's consultants do not use BDS. Instead, MDOT's consultants use a range of proprietary analysis products suitable for the structure type and in-house developed spreadsheets and templates. Generally speaking, more complex designs involving structure types not supported by BDS are completed by MDOT's consultants.

While MDOT does not often have projects with very sophisticated detailing, structural detailing is a laborious and time-consuming process. Parametric modeling to layout the reinforcement and generate the schedules would introduce significant efficiencies. MDOT already has software that helps, but it can be cumbersome. Reinforcement details need to be shown in plan, elevation, and section views. The efficiencies from using a single model that propagates change, generates the details, and provides schedules and quantities can be significant.

MDOT feels that 3D models would be very beneficial for construction staging. Without the ability to visualize the staging fully it is hard to make sure everything will work out. Designers have fielded calls and RFIs in construction, and there have been contract change orders because design could not fully identify and resolve staging issues with traditional methods. MDOT needs to design staging based on constraints associated with maintaining lanes. Seeing the full picture of slope impacts would help tremendously, as fill slopes sometimes conflict with maintained lanes. The ability to visualize these in the design plans would limit contractors' perceived risk. Design may show temporary sheeting locations, but 3D models would help to provide slopes at temporary conditions and also to create details for how to maintain slopes.

MDOT has reached out to Contractors for their inputs and to identify benefits of 3D modeling for bridges, but has not received much response. MDOT's contractors do not appear to use 3D models in construction of standard bridge types. Contractors have requested 3D coordinates for reference points, which have been added to plan sheets, but have not expressed a desire for other substructure layout information.

4. Requirements for the Framework

The objectives of Phase II are to provide recommendations to advance 3D and 4D bridge modeling as a standard agency practice. These recommendations will include a complete framework that can be utilized for the development of 3D and 4D bridge modeling at the right time, in the right format, and at the right level of detail to add value to design, construction, and/or operations. This section identifies constraints and evaluation criteria to be used in Phase II to develop the framework for 3D and 4D bridge models and plans.

4.1 Data Integration

MDOT needs to be able to read and write the types of 3D and 4D bridge models that MDOT staff and consultants develop. This is a large practical constraint, however, MDOT has a lot of software available under a Bentley Enterprise License Agreement. MDOT's ProjectWise server can host data of any format. Thus, MDOT can screen down options for software and data deliverables to the current Bentley data formats and open data formats such as IFC and XML. One significant consideration is the in-house developed and maintained BDS software, currently being updated in a separate research project.

Primary data integration considerations include:

- Must produce data that can be stored on ProjectWise
- Must produce data that can be consumed by MicroStation for plans production
- Must organize the 3D models into different levels or other segments for each structural element, e.g. a level for beams, a level for bearings, etc.
- Able to consume MicroStation 3D solid and mesh objects
- Able to consume OpenRoads data
- Able to produce 3D models that can be used for visualization
- Able to produce 3D models that can be used for clash detection
- Able to produce 3D models that can be used for staging and lift planning

Secondary data integration considerations include:

- Able to produce data that structural analysis software can consume
- Change propagation preserves staging decisions, e.g. slopes and segmentation
- Can store views and annotations for review comments
- Models are extensible, i.e. can be progressed e.g. for fabrication models
- Can export data for MiB^{RIDG}E and MDOT BRIDGE App
- Able to produce 3D models that can be used to replace/supplement plan sheets
- Able to read and write data to exchange with BDS software

4.2 Adds value to workflows

An important part of the framework is to provide information project managers can use to forecast the returns they can expect from their investment in 3D and 4D models. These returns will occur in design, construction, or later. Returns for the design phase are clear inclusion factors for selecting 3D and 4D modeling strategies. Returns that would occur later, or which might be less tangible, will require judgment from the design project manager to select appropriate 3D and 4D modeling strategies. These returns may be efficiencies, quality improvements, or risk identification and management improvements. Finally, the framework for 3D and 4D bridge models should be consistent with MDOT's knowledge management, e-Construction, and Civil Integrated Management initiatives.

Some efficiencies that should be assessed are:

- Increased automation of plan sheet production
- Automation of change propagation through plan sheets and models
- Automation of quantity take-off for some pay items
- Efficiencies in reinforcement design and quantity take-off
- Efficiencies in generating shop drawings for fabrication
- Opportunities for shop model reviews (as a replacement for shop drawings)
- Opportunities to replace/supplement plan sheets with a 3D Model Deliverable

Some quality enhancements that should be assessed are:

- Rapid evaluation of different alternatives for a more refined design
- Generate more accurate quantities, e.g. earthwork, rebar
- Add more detail to the designs, e.g. provide 3D RIDs
- Ability to review designs in more detail, e.g. slope impacts and staging
- Ability to automate clash detection
- Producing images and videos to communicate with stakeholders and the public

Some risk identification and management enhancements that should be assessed are:

- Reducing manual workflows that could introduce errors
- Increased clarity of the design intent
- Ability to plan lifts to optimize equipment mobilization
- Ability to review staging in detail, e.g. slope intercepts and maintenance of traffic
- More consumable staging information, e.g. 3D images and 4D simulations in RID

4.3 Usability

This research identified a wide range of opportunities for creating and using 3D and 4D bridge models. However, the time and training resources required to learn any new tools is a challenge and it is unsustainable to create a large training burden to maintain skill sets. The 3D and 4D modeling tools need to be quickly usable, as do the resulting 3D and 4D models.

First, the framework needs to:

- Support existing workflows and institutional knowledge
- Prioritize an intuitive user experience to minimize training needs

- Be customizable to MDOT standards for components and documentation

Secondly, the framework needs to provide meaningful data:

- With a defined, appropriate LOD for the intended uses
- That is consistent with current and evolving data governance standards
- That is consumable in construction by MDOT’s inspectors and contractors

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Appendix 5. Phase 2 Report

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1. Introduction

This research project is conducted by WSP | Parsons Brinckerhoff on behalf of the Michigan Department of Transportation (MDOT). The four phases to this research are shown in Figure 1. The first phase was completed in October 2016 during which the research team refined a framework that guides the 3D and 4D bridge modeling process. This report documents the process and outcomes of the second phase of the research, which prioritized the specific uses of 3D and 4D models to explore in the framework, and lays out the framework and its implementation. In Phase III, the research team will develop sample bridge models, and in Phase IV a workspace and documentation will be delivered to support implementation of 3D and 4D bridge modeling policies and practices at MDOT.

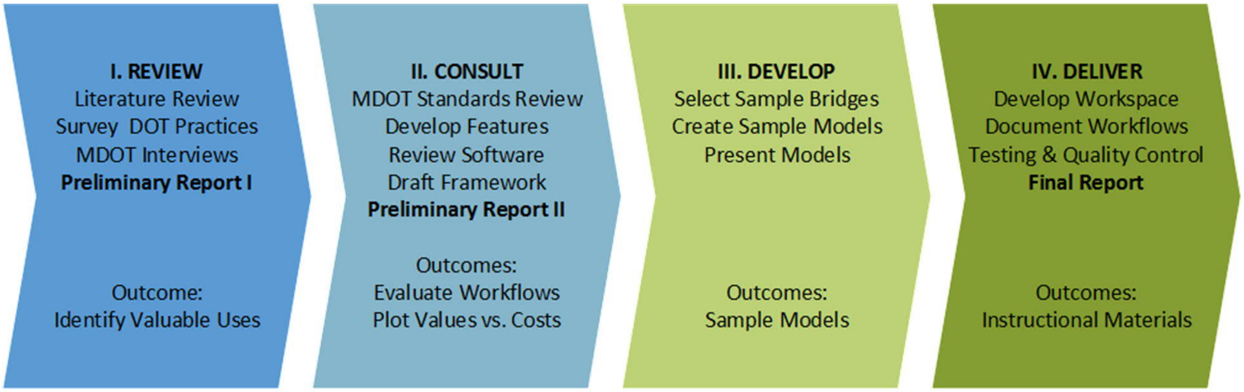


Figure 1: Research phases.

1.1 Background

MDOT's policies for designing and constructing road projects using 3D modeling and e-Construction continue to mature. MDOT and contractor partners are benefiting from the predictability, repeatability, and reliability of standardized roadway data delivered from design to construction that is accessible in the field from mobile devices. MDOT is now engaged in determining the best course to effectively use 3D and 4D models for bridges.

The value of extending 3D models to bridges could be realized in many ways, which vary based on lifecycle phase, type of project, intended uses of the 3D model, the detail in the model, and the accuracy of the model. There is more variety in 3D workflows for bridges than there is for roadways. The tools used to model bridges vary by structural type and whether the bridge is new, being replaced, or being rehabilitated or modified. The framework for defining when and how to model bridges is expected to be more complex than that developed for roadways.

Bridges vary greatly in structural type, which significantly affects the parametric rules that govern layout. Although the layout rules are relatively simple for the majority of structural types, the software development efforts and market are fragmented. The absence of a standard data format for bridges is significant, making it difficult to use different software in series to increase detail of the design without data degradation. While industry is advancing towards adopting IFC as the data standard for bridges, under a hybrid stewardship model, but no decision has been made yet. (Mlynarski & Hu, 2016) The framework developed in this report is intended to be adaptable as efforts to advance data standards for bridges mature.

MDOT objectives for investigating and implementing 3D and 4D models for bridges are as follows:

- Streamline and begin to automate generation of bridge plan details.
- Aid designers to size and place components
- Confirm fit-up of precast elements
- Identify conflicts
- Demonstrate staging for part-width, multi-stage, and accelerated bridge construction
- Better quantify and identify limits of earth disturbance for all projects requiring earthwork and more accurately identify extents of items such as retaining walls and return walls at substructures
- Communicate information in the plans to coordinate and demonstrate project activities
- Provide standardized models that can integrate with operational needs, including inspection, rating, and management.

1.2 Objective

The first phase of this research explored emerging practices and research efforts nationally to set the context for developing a framework in the next phase. This included identifying potential valuable uses for 3D and 4D models for bridges, regardless of their current state of adoption among departments of transportation and their consultant and contractor partners.

This stage is to create the framework of a decision tree for bridge designers to identify modeling priorities based on each structure's unique features. Some have simple designs but challenging locations with high traffic volumes, limited space for staging, and environmental impacts from noise, vibration, and emissions. Others have accessible sites but challenging design features. The data needs and uses in construction vary as well. For example, 4D models for staging and public involvement need low detail and accuracy; fabrication of steel I-girders does not require a model at all but rather tables of deck geometry and key elevations; and concrete structures could use highly accurate and detailed models to plan formwork or to prefabricate bridge elements and systems.

1.3 Scope

In Phase II, the WSP | Parsons Brinckerhoff team first filtered the many uses of 3D models identified in Phase I down to 20 feasible and potentially favorable uses. Second, the team conducted a survey of MDOT's bridge community to assess the priority, obtain perceived value, and provide input on their perspectives of these 20 uses of 3D bridge models. The results were analyzed to identify the emerging highest priority and highest value uses. These uses were then assessed against the screening criteria identified in Phase I. A framework was developed for MDOT's bridge engineers to clearly identify and articulate the model requirements, how to manage horizontal distance distortions implicit to state plane coordinates in a state that contains three state plane zones, and project selection criteria for 3D model uses. Finally, a set of selection criteria were identified for the sample models in Phase III.

1.4 Methodology

The team prepared a handout and a spreadsheet-based screening tool, and delivered a webinar to MDOT's bridge community to solicit feedback on the 20 identified uses of 3D bridge models. The webinar was recorded, and the survey materials were shared with the recording on two occasions. Twenty-six inputs were received and analyzed. The most favorable uses were evaluated to determine how they fit into the process of bridge project delivery and asset management. The framework was advanced to support the most urgent and highest value uses.

1.5 Organization of Report

This report is organized in four primary sections: uses for screening, screening process, framework development, and implementation into MDOT's policies and standards. The framework and implementation sections will be further developed in the final report (Phase IV), taking into consideration lessons learned while producing sample models (Phase III).

1.6 Acronyms and Definitions

This section introduces some of the acronyms used in this report.

3D: Three-dimensional. Has properties that are defined for three axes, nominally x, y, and z, in a Cartesian coordinate system.

4D model: Four-dimensional model. A 3D simulation of change over time. For example, a 3D model that has been connected to a construction schedule to produce a simulation of the construction process, or a 3D simulation of deterioration.

AASHTO: American Association of State Highway and Transportation Officials. A standards-setting body for specifications, test protocols, and guidelines. Voting members are representatives of U.S. State highway and transportation agencies.

AIA: American Institute of Architects. A professional organization that produces a collection of Digital Practice Documents, some of which relate to standard practices for use of Building Information Modeling.

BIM: Building Information Modeling. A process involving the generation and management of digital representations of physical and functional characteristics of places.

BMS: Bridge Management System. An information system for managing bridges, usually including asset inventory and condition data at the element level, as well as predictive algorithms for bridge conditions used to optimize the type and timing of preservation and replacement activities across the system.

CADD: Computer-Aided Design and Drafting. A category of computer software that is used to develop roadway designs. CADD software typically uses an object-oriented approach to apply mathematical rules that automate the process of drafting roadway designs. 3D digital design data is a common output of the application of CADD software.

FEM: Finite Element Method. A method of structural analysis that uses accurate representation of complex geometry in 3D.

FHWA: Federal Highway Administration. An agency within the U.S. Department of Transportation with a mission to provide national leadership and innovation to improve mobility on the nation's highways.

IFC: Industry Foundation Class. A platform-neutral, open data model and file format specification that is intended to describe building and construction industry data. It is an international standard for BIM (International Organization for Standardization, 2013).

Lidar: (Portmanteau of "light" and "radar"). Remote sensing technology that measures distance and other information by recording information about laser reflections. Typically, lidar machines consist of rapidly pulsing lasers that are capable of taking millions of measurements in a short time. Information that can be gathered by such devices includes x,y,z coordinates of objects that the laser strikes and intensity of the returned beam. Commonly, a camera captures simultaneous images to extract RGB color of the remote object as well and assign it to the point.

LOD: Level of Development. A qualitative designation that communicates the degree of engineering intent behind a 3D model that defines the authorized uses. Normally the LOD will increase through the design development process.

MPS: Model Progression Specification. A specification that defines how the LOD for individual model elements increases over the project milestones. The MPS will assign a specific, minimum LOD to each model element for each milestone. The LOD typically increases from milestone to milestone.

PS&E: Plan, Specification, and Estimate. The construction contract documents prepared by the designer.

XML: Extensible Markup Language. A text-based, human-readable and machine-readable structured data schema.

2. Uses for Screening

The Phase 1 report took a comprehensive view of potential uses of 3D and 4D bridge models across the bridge asset lifecycle. These were reduced to the following list of 20 feasible and potentially favorable uses for screening.

2.1 Visualization and Public Outreach

Description: A visually accessible model that is not necessarily geometrically detailed or accurate. Quick to generate, but not useful for plans production. A fly through or drive through video of the proposed construction helps to inform the non-technical people at public meetings, stakeholder meetings, and during right-of-way acquisition.

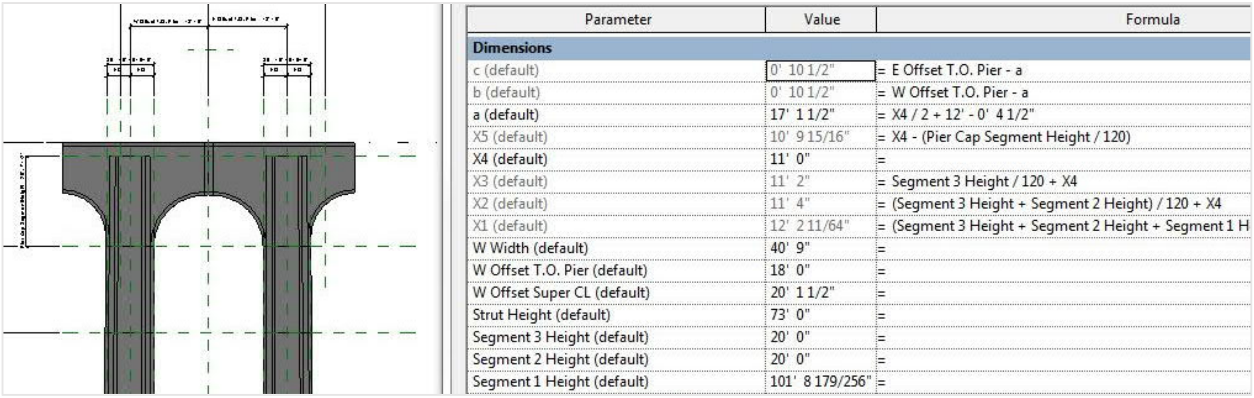
Timing: Just-in-time model creation or a more detailed model created during the Study phase that is intermittently updated and new renderings and videos produced just-in-time.

Figure 2: A visualization model.

2.2 Model-based Plans Production

Description: Use parametric models of the exterior faces to create 2D contract plans. Sheets are dynamically connected to the model to automatically propagate changes between the model and the plan graphics and annotations.

Timing: Model development begins in the Study phase. Detail is added through design production. Model can be updated to reflect as-built conditions.



Parameter	Value	Formula
Dimensions		
c (default)	0' 10 1/2"	= E Offset T.O. Pier - a
b (default)	0' 10 1/2"	= W Offset T.O. Pier - a
a (default)	17' 1 1/2"	= X4 / 2 + 12' - 0' 4 1/2"
X5 (default)	10' 9 15/16"	= X4 - (Pier Cap Segment Height / 120)
X4 (default)	11' 0"	=
X3 (default)	11' 2"	= Segment 3 Height / 120 + X4
X2 (default)	11' 4"	= (Segment 3 Height + Segment 2 Height) / 120 + X4
X1 (default)	12' 2 11/64"	= (Segment 3 Height + Segment 2 Height + Segment 1 H
W Width (default)	40' 9"	=
W Offset T.O. Pier (default)	18' 0"	=
W Offset Super CL (default)	20' 1 1/2"	=
Strut Height (default)	73' 0"	=
Segment 3 Height (default)	20' 0"	=
Segment 2 Height (default)	20' 0"	=
Segment 1 Height (default)	101' 8 179/256"	=

Figure 3: A parametric model for plans production.

2.3 Site Plan and Excavation Design

Description: Most work accomplished with roadway design tools and referencing existing ground, roadway final, and interim ground surfaces. Model the abutment interim and final surfaces, excavation surfaces, and interim works such as stock piles and sediment basins if applicable (e.g., designated locations due to site constraints). Used for quantity take-off and plan production.

Timing: Begins in Study phase and developed as the design evolves.

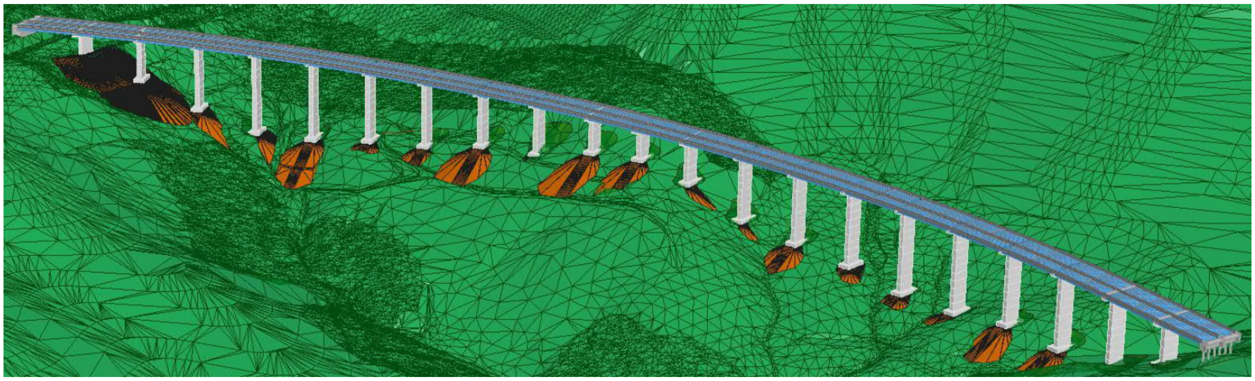


Figure 4: Using 3D models for site and excavation plans.

2.4 Visual Design, Sizing, and Placing of Components

Description: 3D model used to inform engineering judgment to better make preliminary decisions on substructure locations earlier in the design process. May include information from other disciplines (e.g., roadway, subsurface utilities). Could use to better understand access and staging.

Timing: Model created during the Study phase that is intermittently updated to reflect the current design concept (e.g., at design review milestones or while developing staging plans).

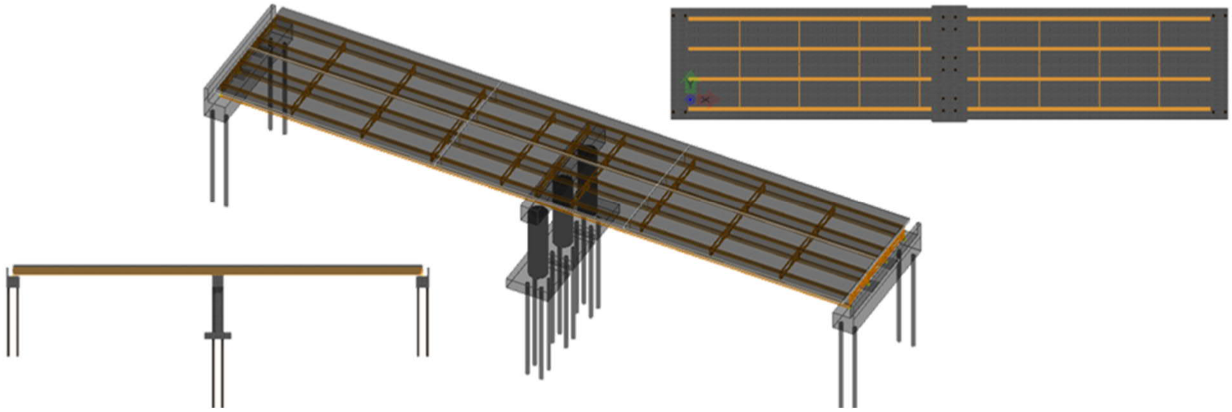


Figure 5: A low detail model to assess sizing and placing of components.

2.5 Visualize Substructure Staging

Description: A low detail 3D model of existing and proposed substructure components, existing and interim excavation and embankment surfaces, and generic temporary works and equipment. Components are displayed in combinations to reflect staged construction.

Timing: Just-in-time model creation for single use (e.g., while developing staging plans), or a model created during the Study phase that is intermittently updated and new renderings and videos produced just-in-time for constructability reviews and Final Plans.

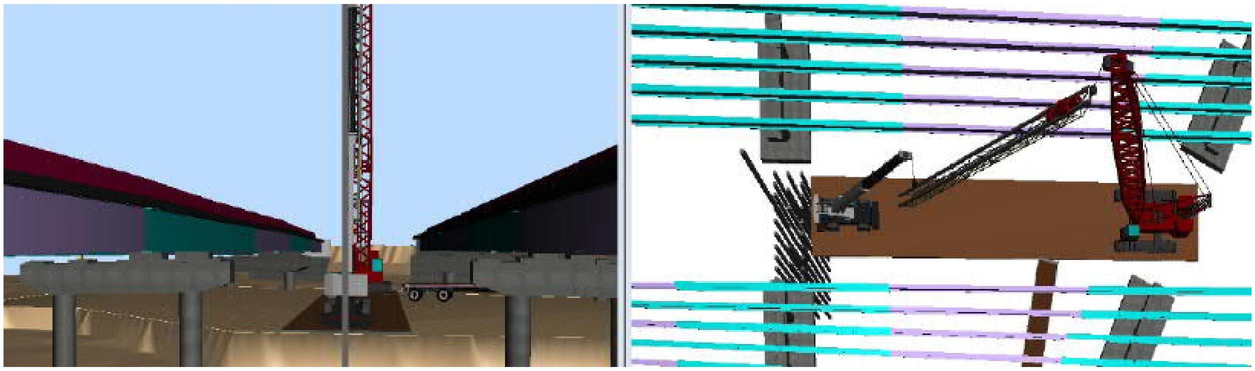
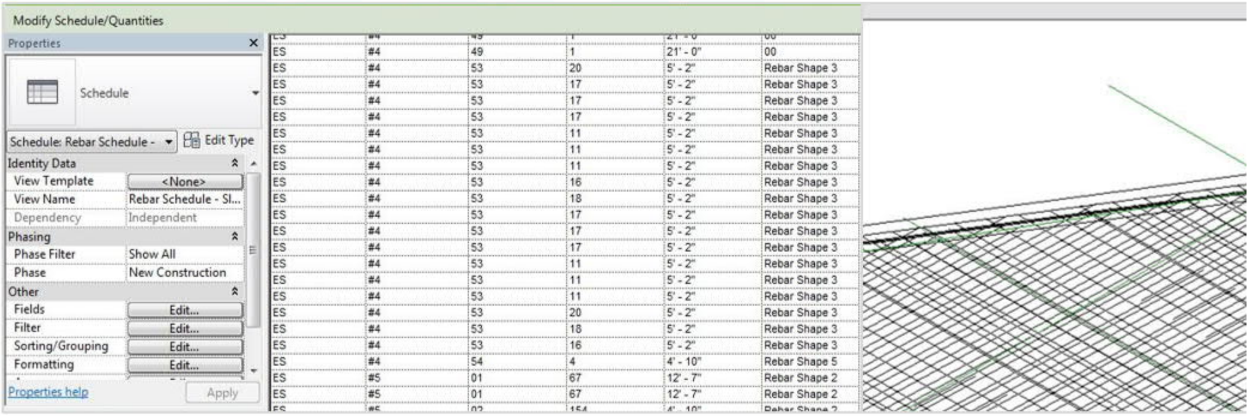


Figure 6: A 3D model used to visualize substructure staging from two angles.

2.6 Parametric Models for Detailing

Description: 3D model of concrete components with reinforcement placed automatically using pre-defined rules. Used to create detail drawings and annotation with the ability to automatically propagate changes in model to plans. Quantity take-offs and schedules can be automated. Also applicable to post-tensioning design and steel detailing.

Timing: A library of standard components is adapted for each project at the start of detailed design. Custom components are created during detailed design using pre-defined rules for rebar placement.



Schedule: Rebar Schedule -

Identity Data
View Template: <None>
View Name: Rebar Schedule - Sl...
Dependency: Independent

Phasing
Phase Filter: Show All
Phase: New Construction

Other
Fields
Filter
Sorting/Grouping
Formatting

ES	#4	49	1	21' - 0"	00
ES	#4	53	20	5' - 2"	Rebar Shape 3
ES	#4	53	17	5' - 2"	Rebar Shape 3
ES	#4	53	17	5' - 2"	Rebar Shape 3
ES	#4	53	17	5' - 2"	Rebar Shape 3
ES	#4	53	11	5' - 2"	Rebar Shape 3
ES	#4	53	11	5' - 2"	Rebar Shape 3
ES	#4	53	11	5' - 2"	Rebar Shape 3
ES	#4	53	16	5' - 2"	Rebar Shape 3
ES	#4	53	18	5' - 2"	Rebar Shape 3
ES	#4	53	17	5' - 2"	Rebar Shape 3
ES	#4	53	17	5' - 2"	Rebar Shape 3
ES	#4	53	17	5' - 2"	Rebar Shape 3
ES	#4	53	11	5' - 2"	Rebar Shape 3
ES	#4	53	11	5' - 2"	Rebar Shape 3
ES	#4	53	11	5' - 2"	Rebar Shape 3
ES	#4	53	20	5' - 2"	Rebar Shape 3
ES	#4	53	18	5' - 2"	Rebar Shape 3
ES	#4	53	16	5' - 2"	Rebar Shape 3
ES	#4	54	4	4' - 10"	Rebar Shape 5
ES	#5	01	67	12' - 7"	Rebar Shape 2
ES	#5	01	67	12' - 7"	Rebar Shape 2

Figure 7: Automated reinforcement bar schedule (Brenner, 2015).

2.7 Macro-scale Clash Detection

Description: Computer algorithm-based clash detection using 3D models of macro-scale components (e.g., structure and foundation units, existing and proposed utilities, and drainage features). Clash detection can identify hard physical clashes (direct hit) and soft clashes (clearance violations).

Timing: Model created at design review milestones and intermittently updated either when there is new or better quality information that triggers a need for repeating the clash detection.

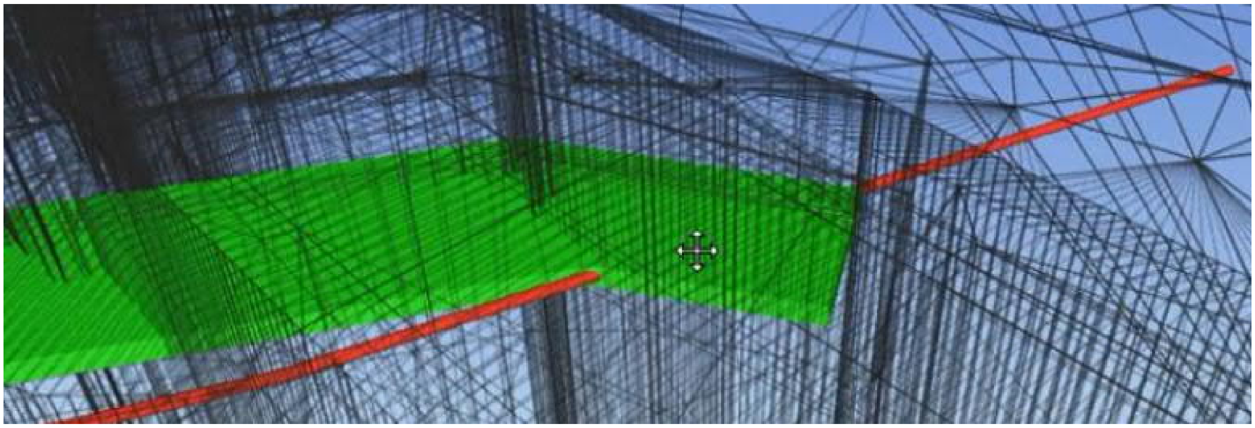


Figure 8: Macro-scale clash detection locating a pipe through a footing.

2.8 Micro-scale Clash Detection

Description: Computer algorithm-based clash detection using 3D solid models of micro-scale components (e.g., post-tensioning anchorages in the transverse direction of a slab conflicting with conventional longitudinal reinforcement). Soft clashes could be used to check for minimum bar spacing and clearances.

Timing: During detailing for Final Plans.

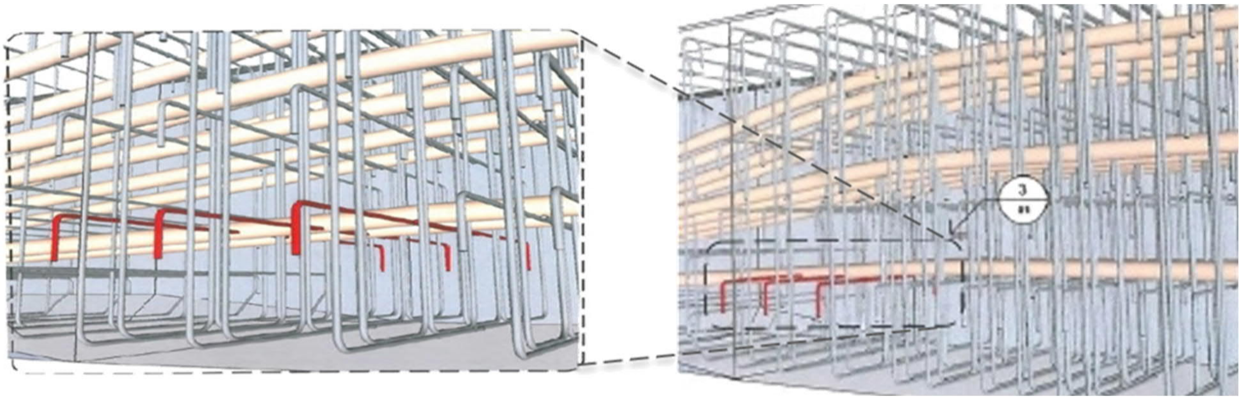


Figure 9: Micro-scale clash detection locating rebar through post-tensioning.

2.9 Structural Analysis and Design

Description: Finite Element Method (FEM) can give engineers more confidence in the analysis of complex geometry. New software makes creating the 3D FEM models more accessible and enables the models to be used for other purposes as well, such as detailing, plans production, clash detection, and visualization.

Timing: Model created in the Study or Preliminary Plans phase and intermittently updated for significant design changes or at milestones (if used in detailing/Final Plans).

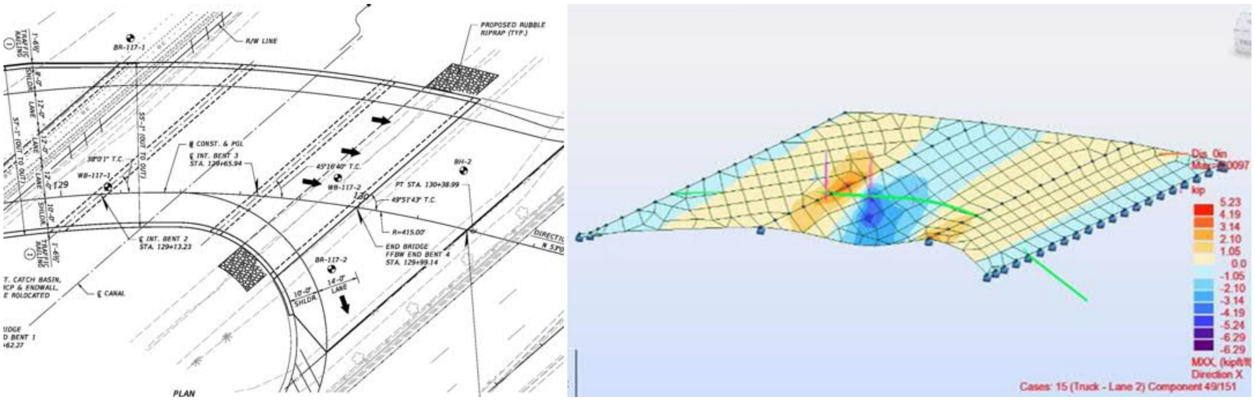


Figure 10: Structural analysis and design using one 3D model (Brenner, 2015).

2.10 Point Clouds of Existing Bridges

Description: Different types of lidar and photogrammetry can collect high density point clouds with high local accuracy, providing a detailed picture of existing bridges. These can be used in a variety of ways for planning and design. For example, the exact minimum vertical clearance height and location (including lane location and controlling girder location), horizontal clearance information, other physical site constraints (trees, overhead obstructions), and on-structure utilities.

Timing: Routine bulk geospatial data collection for programmatic asset inventory (mobile lidar) or Study phase (static lidar or small unmanned aircraft systems photogrammetry or lidar).

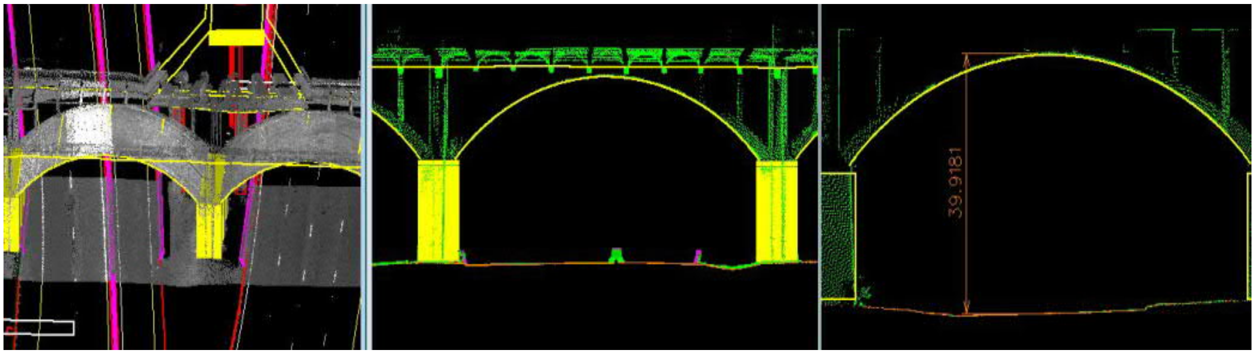


Figure 11: Examples of a point cloud of an existing bridge (Fisher, et al., 2012).

2.11 Visual Renderings and Lighting Analysis

Description: Bridge deck lighting and shadow analysis for structures carrying a Single Point Urban Interchange.

Timing: Just-in-time model creation or a more detailed model created during the Study phase that is intermittently updated and new renderings and videos produced just-in-time for milestones such as design reviews and public or stakeholder meetings.

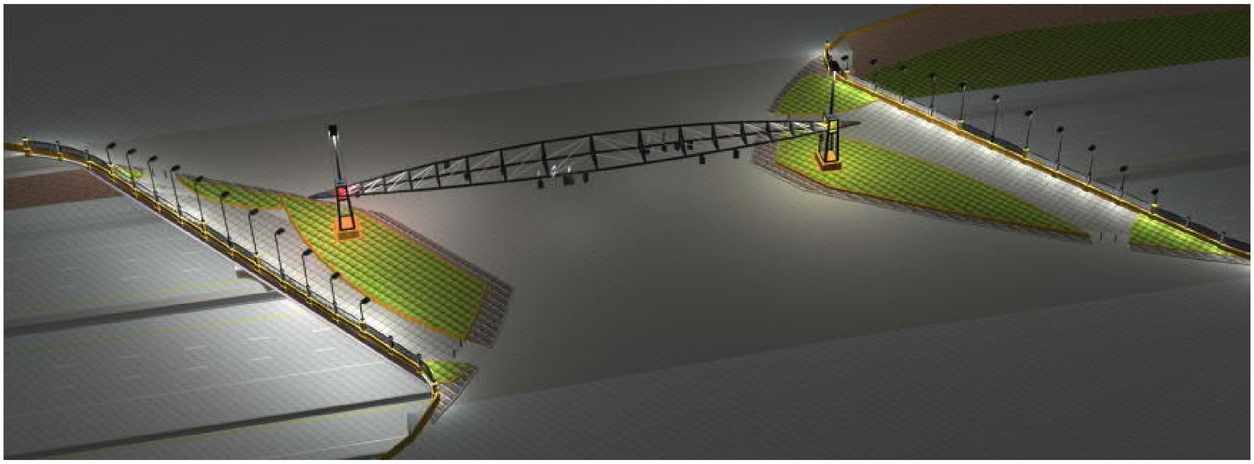


Figure 12: Using a rendered 3D model for lighting analysis.

2.12 Virtual Fit-up of Precast Components

Description: Check that precast elements can be assembled within a virtual model as a constructability review. Could be done as a feasibility assessment, a design review, shop drawing review, or pre-construction quality control check using lidar as-built models. All relevant design details would be modeled, contractor means of construction incorporated if/when available, and potentially verified against as-built fabricated lidar point cloud.

Timing: Just-in-time model creation for single use (e.g., shop model review) or a more detailed model created during the Study phase that is intermittently updated at major milestones.

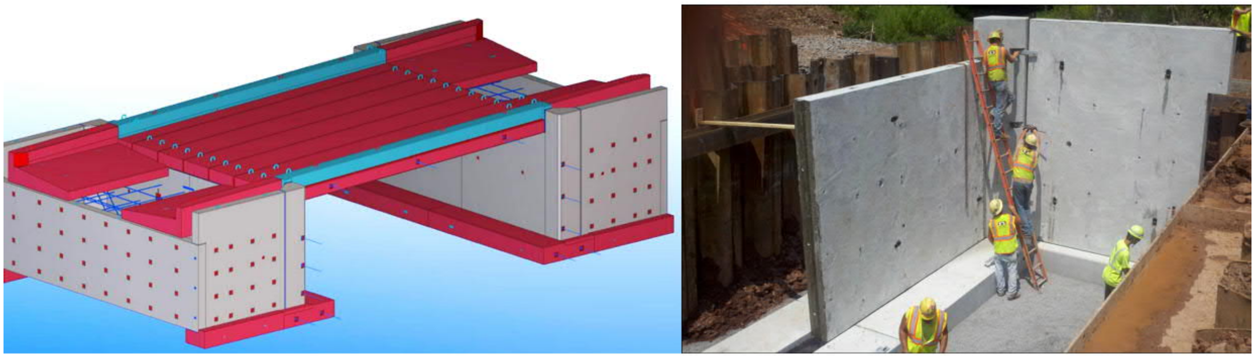


Figure 13: A virtual fit-up model and the precast elements (Dickson & Reffner, 2014).

2.13 Virtual Fit-up of Steel Components

Description: Check that steel elements can be assembled within a virtual model as a constructability review. Could be done as a feasibility assessment, a design review, shop drawing review, or virtual assembly (where warranted). All relevant design details would be modeled and additional information of interim steel positions (e.g., camber ordinates at different dead load applications). Fabrication and erection means and methods could be included if/when available (e.g., in contractor shop model submittal).

Timing: Just-in-time model creation for single use (e.g., shop model review) or a more detailed model created during the Study phase that is intermittently updated at major milestones.

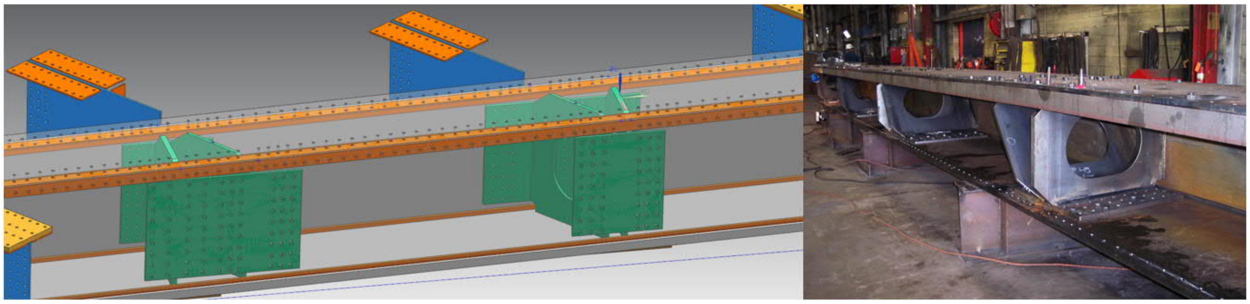


Figure 14: A virtual fit-up model and the steel on the fabrication floor (Medlock, 2015).

2.14 Visualization of Congested Details

Description: Isometric views on 2D plans of congested details (e.g., post-tensioning anchorages and conventional reinforcement stirrup details). Intended to communicate design intent. May be generated from a parametric detailing model.

Timing: Final Plans.

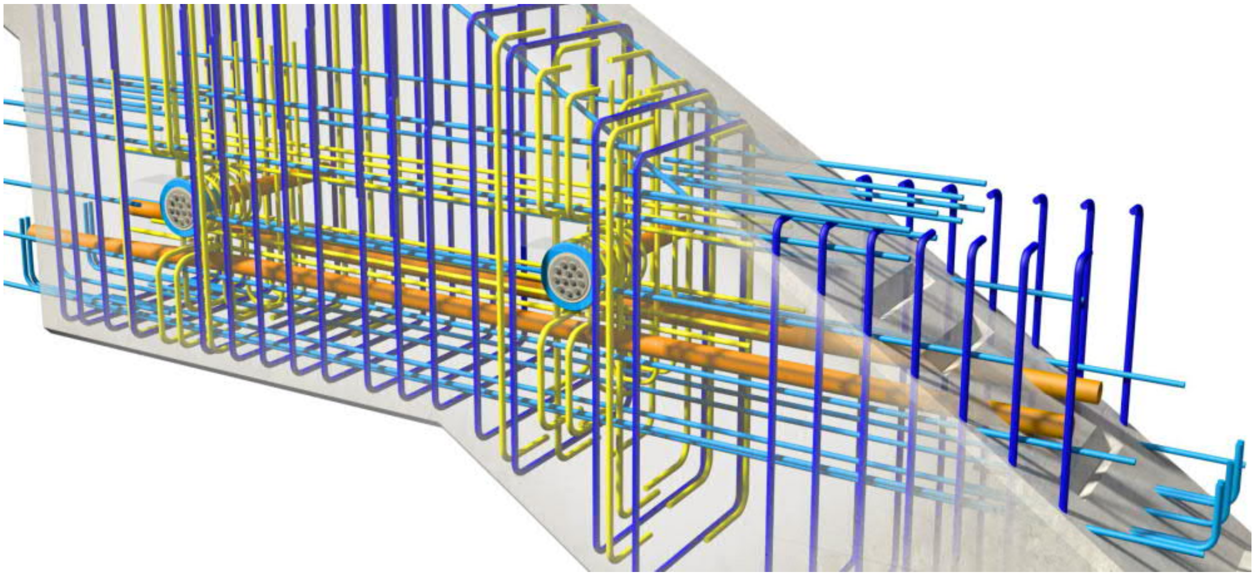


Figure 15: Using 3D models to visualize congested details.

2.15 Construction Verification and As-Built Recording

Description: Use as-designed solids model (or surfaces) and compare to lidar as-built survey to verify construction outcomes. Check pre-loading and post-loading deflections at key locations. Can also track structure deflections over time.

Timing: Final Plans (solids/surface models) and Construction (as-built survey).

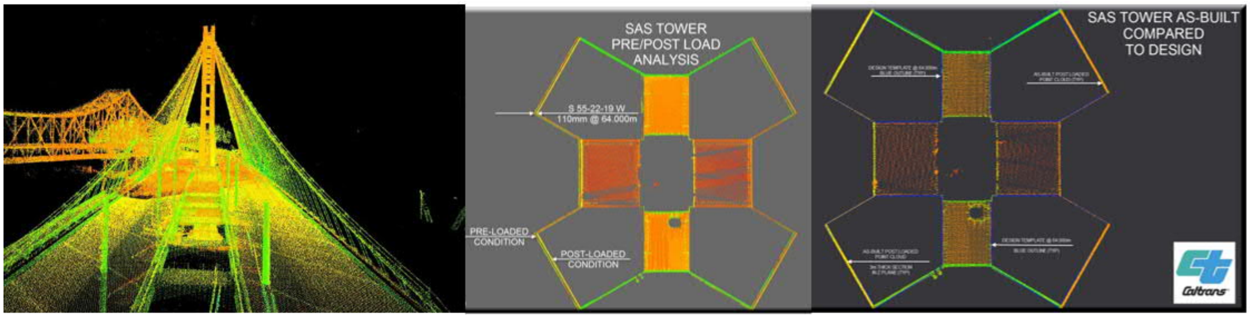


Figure 16: Using 3D data to create as-built records (Aguilar, 2015).

2.16 Construction Simulation (4D Models)

Description: Model tied to contractor schedule for virtual construction planning of project for logistics, efficiency, and safety. Can be used in design to better understand staging, communicate with stakeholders and the public, or communicate constraints to contractors. Contractors can use 4D models to develop means and methods of construction. Depending on the intended use and scope of the simulation, may need the original conditions and nearby areas, as well as temporary works and interim conditions to be modeled. Level of geometric accuracy and detail varies by intended use.

Timing: May be created during the Study phase or at any other point in the project development process and then be intermittently updated with new renderings and videos produced just-in-time.

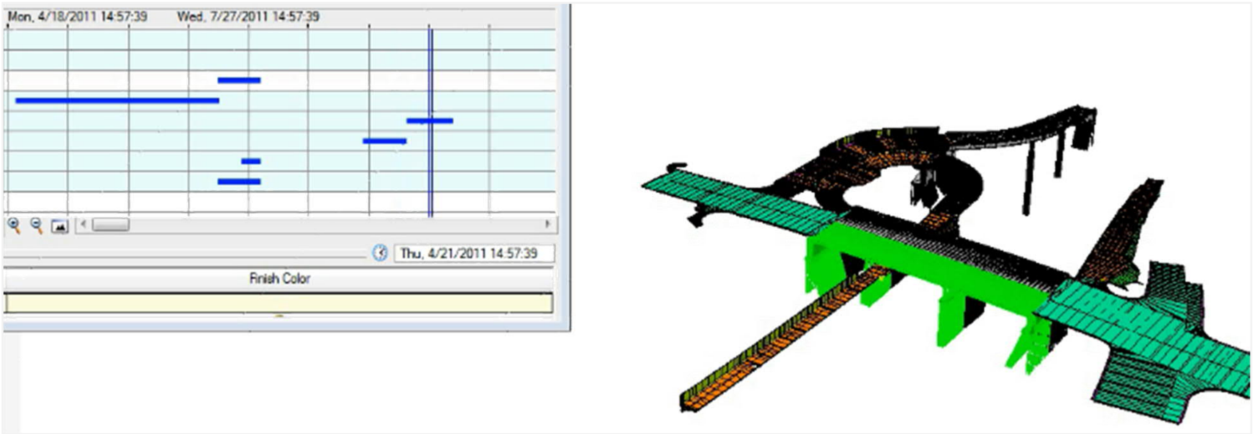


Figure 17: A 4D construction simulation (DiGiacobbe, 2014).

2.17 Crane Mobilization and Lift Planning

Description: Use simple geometric representations of bridge components with software that is preloaded with the available equipment, including properties related to clearance envelopes, reach lengths, and lift capacity. Combined with geometric properties and weights of the structural elements, crane movements and lift sequences can be planned to determine which cranes to mobilize and when.

Timing: Bid and post-award, possibly during Study phase or Preliminary Plans if hard decisions need to be made due to site access constraints.

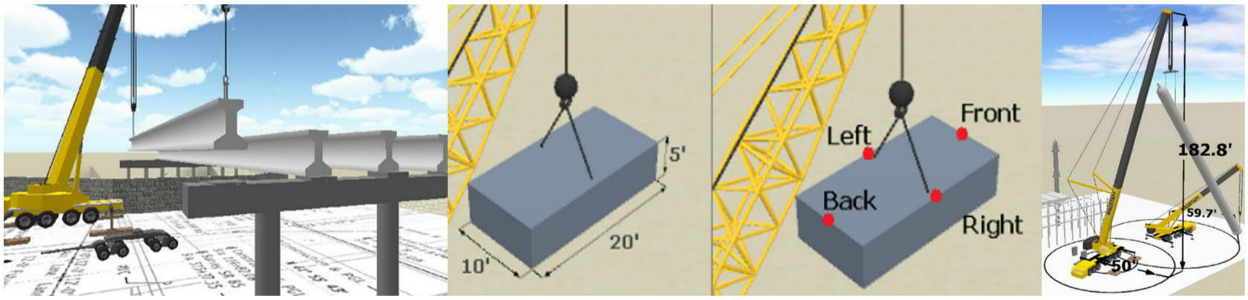


Figure 18: Using 3D models to plan lift sequences and rigging (Ramkrishnan, 2014).

2.18 Formwork Planning

Description: Regardless of whether the structure will be precast or cast-in-place, 3D models can be used to aid formwork planning in construction. The model needs to be a geometrically accurate representation of the external concrete faces. It could be developed as part of other processes, such as parametric models for detailing or plans production.

Timing: The models could be provided at Final Plans for the contractors' use in bidding and construction, or provided by the contractor as part of their Plans and Working Drawings submittals.

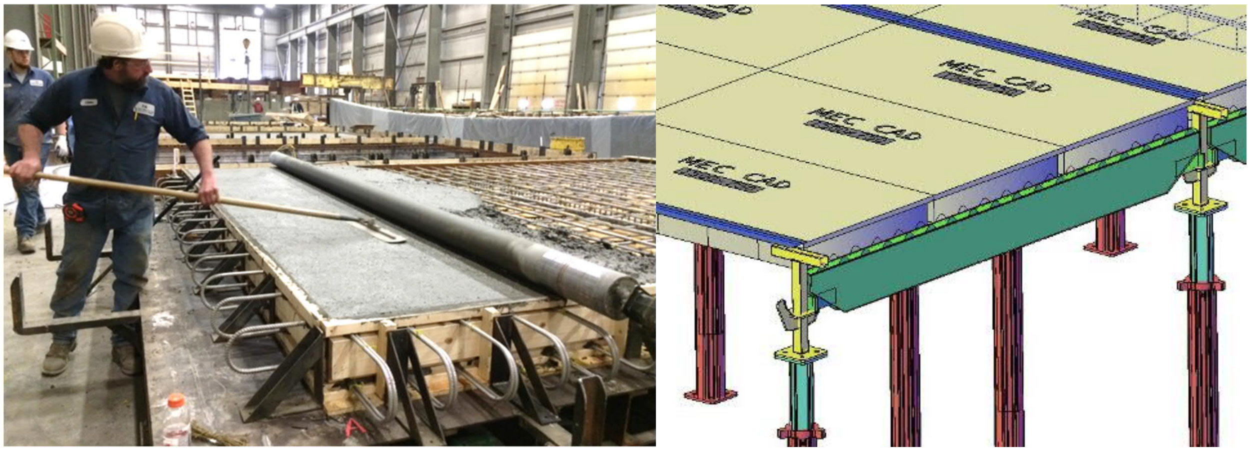
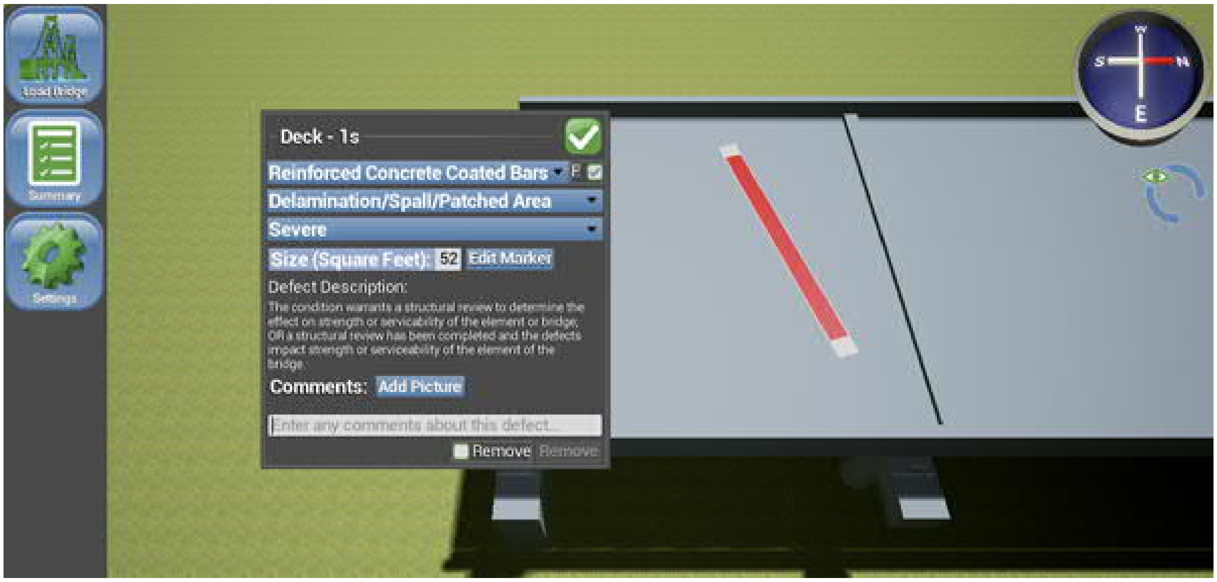


Figure 19: Using 3D models to plan formwork for off-site fabrication.

2.19 Routine Inspection

Description: Inspectors using tablets can use a model to collect more detailed and complete information of current bridge conditions. Using the B^{ridg}e App being developed for MDOT, inspectors can document the location and extent of distress on a 3D model. Currently, the models pull the structure information available in the MiB^{RIDG}E database, but more detailed models could be consumed in the future if they are developed in design or construction and stored in the MiB^{RIDG}E database.

Timing: Model created just-in-time from MiB^{RIDG}E data using the MDOT B^{RIDG}E App.



Deck - 1s

Reinforced Concrete Coated Bars

Delamination/Spall/Patched Area

Severe

Size (Square Feet): 52

Defect Description:
The condition warrants a structural review to determine the effect on strength or servicability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element of the bridge.

Comments:

Enter any comments about this defect...

Figure 20: The MDOT B^{ridg}e App (Michigan Tech Research Institute, n.d.).

2.20 Rating and Routing

Description: Preservation of the design and construction information in a location and format that is accessible can add value to supporting the work of operating the bridge. As long as the 3D design and construction information is well documented, it could support rating and routing for overweight/oversize vehicle permits. The effort for the designer is to define the origins and limitations of the 3D models being preserved and to store the information in a durable and accessible format.

Timing: Design and construction professionals would need to store metadata with durable formats of the 3D models they create. The metadata would include pertinent information to others on the assumptions and basis for the 3D models, such as the geospatial metadata (grid/ground coordinate system definitions), intended uses of the 3D models, approximations and simplifications (e.g., removing minor curvature from analysis models), and saving the data in a durable format (e.g., LandXML, Industry Foundation Class (IFC), DGN). Analytical models would need to be stored in a format that is compatible with MDOT rating software.

3 Screening Process

The information in Chapter 2 was provided as a handout with instructions and a data capture spreadsheet, shown in Figure 21, to collect feedback. MDOT identified the target audience to receive the screening tool from internal bridge engineers, technicians, surveyors, road designers, construction, inspection, and asset management staff, as well as MDOT’s consultant community. Consultation with construction partners including Michigan Infrastructure & Transportation Association (MITA) will occur in Phase III or Phase IV when the sample models are available.

Number	Use	Description	Timing	Priority (select one)	Value (select one)	Engineer Time (Days)	Technician Time (Days)	Notes
1	Visualization & Public Outreach	A visually-accessible model that is not necessarily geometrically detailed or accurate. Quick to generate, but not useful for plans production. A fly through or drive through video of the proposed construction helps to inform the non-technical people at public meetings, stakeholder meetings, and during right-of-way acquisition.	Study, Preliminary Plans, and/or Final Plans	High priority	High value	2	5	Not applicable to all projects. Would be more accessible if model was available from e.g. model-based plans production.
2	Model-based Plans Production	Use parametric models of the exterior faces to create 2D contract plans. Sheets are dynamically connected to the model to automatically propagate changes between the model and the plan graphics and annotations.	Study, updated through Preliminary Plans and Final Plans					
3	Site Plan and Excavation Design	Most work accomplished with Roadway design tools and referencing existing ground, roadway final and interim ground surfaces, etc. Model the abutment interim and final surfaces, excavation surfaces, and interim works e.g. stock piles and sediment basins if applicable (e.g. designated locations due to site constraints). Used for quantity take-off and plan production.	Study, updated through Preliminary Plans and Final Plans					
4	Visual design, sizing, and placing of components	3D model used to inform engineering judgement to better make preliminary decisions on substructure locations earlier in the design process. May include information from other disciplines, e.g. roadway, subsurface utilities. Could use to better understand access and staging.	Study, updated through Preliminary Plans and Final Plans					
5	Visualize Substructure Staging	A low detail 3D model of existing and proposed substructure components, existing and interim excavation and embankment surfaces, and generic temporary works and equipment. Components are displayed in combinations to reflect staged construction.	Study, Preliminary Plans, and/or Final Plans					

Figure 21: Feedback spreadsheet with sample row completed.

For each of the 20 defined uses, respondents were asked the following:

- Identify their perceived priority from a set of five options ranging from “not a priority” to “urgent priority”
- Identify their perceived value from a set of four options ranging from “not valuable” to “high value”
- Indicate the maximum amount of engineer time in days that they would invest in realizing the use
- Indicate the maximum amount of technician time in days that they would invest in realizing the use
- (Optionally) provide notes that qualify or explain any of their inputs

The team received 26 responses and collated them into a single spreadsheet. The priority and value fields were converted to number scales for the purpose of computing an average and for charting. Two hundred and twenty-six (226) unique notes were provided, which were considered in identifying project selection criteria. There were insufficient responses to the amount of engineer and technician time to draw meaningful conclusions.

3.1 Prioritization

Figure 22 through Figure 25 chart the results of the use prioritization and urgency feedback. “Priority” and “Urgency” each have two charts. The first shows the range of the responses and the average. The second chart shows the number of responses received for the extreme values. Each chart identifies the top five uses based on the average (Figure 22 and 24) or the most responses at the highest level (Figure 23 and Figure 25). Only three uses had sufficient responses of “urgent priority” to warrant identification. The top five (or three, in the case of urgency) uses were advanced into the final list. Some uses appeared in multiple lists. As a result, the following seven uses emerged:

- Site Plan and Excavation Design
- Model-based Plans Production
- Parametric Models for Detailing
- Visualization of Congested Details
- Structural Analysis and Design
- Visual Design, Sizing, and Placing Components
- Routine Inspection

These uses support the primary functions listed in Table 1. Most of the uses relate to design activities. Thus, they will be evaluated to determine how they are complementary.

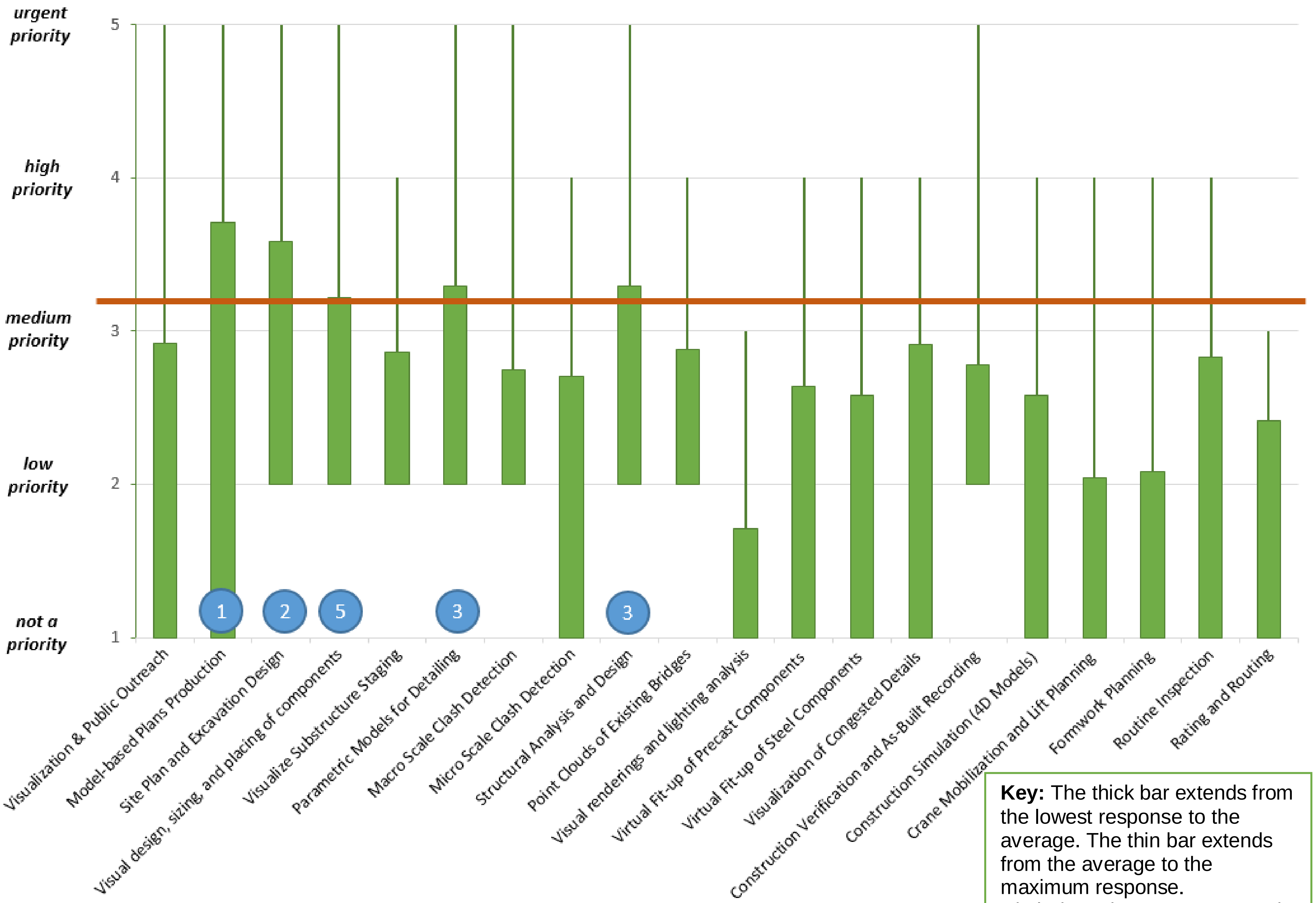
Table 1: Priority uses and their associated primary functions.

Use	Primary Functions
Site Plan and Excavation Design	Geometric Design, Design Documentation
Model-based Plans Production	Geometric Design, Design Documentation
Parametric Models for Detailing	Geometric Design, Design Documentation
Visualization of Congested Details	Geometric Design, Design Documentation
Structural Analysis and Design	Analytical Design
Visual Design, Sizing, and Placing Components	Analytical Design, Geometric Design
Routine Inspection	Asset Management

3.2 Acceptable Investment

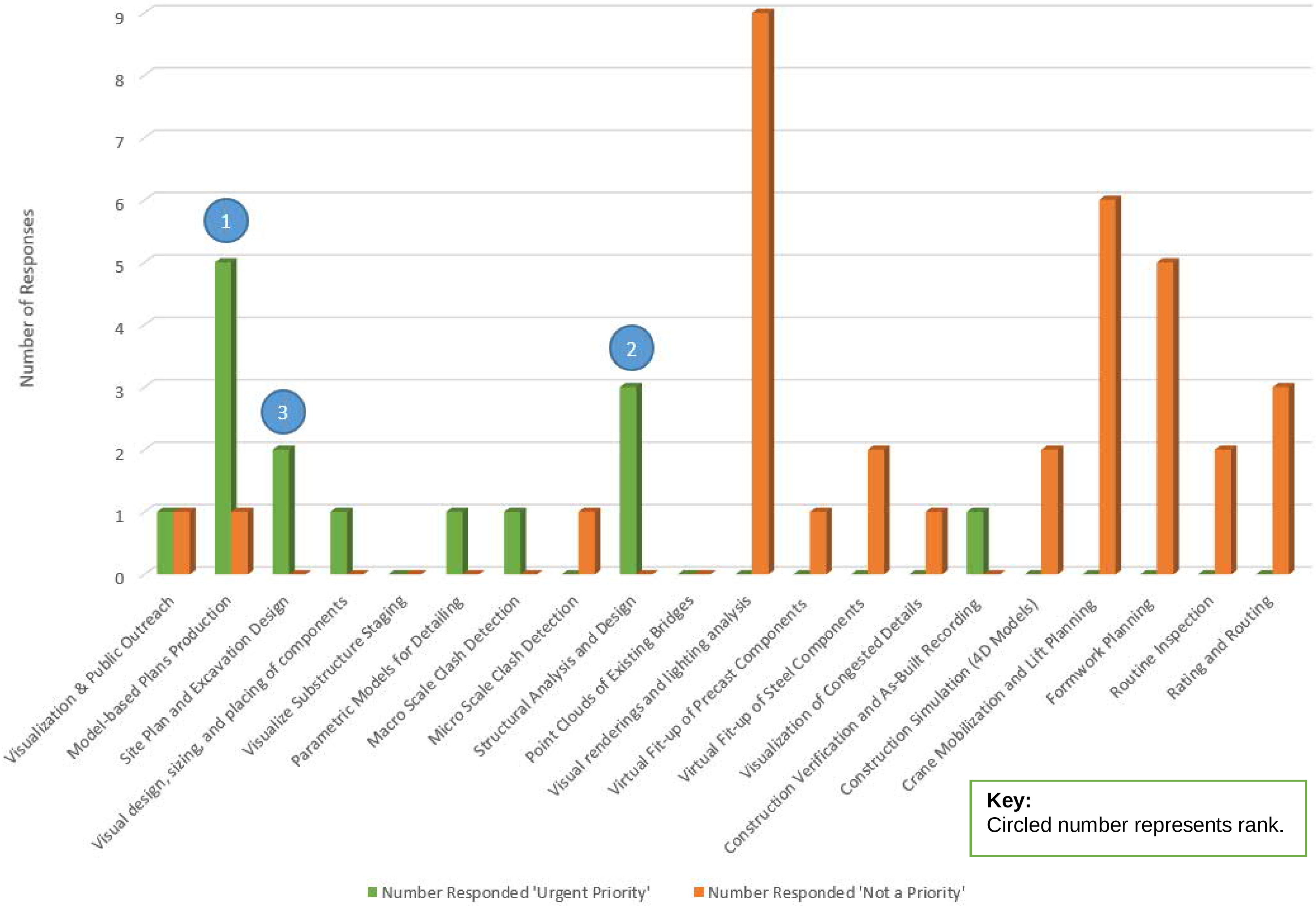
There were few responses to the maximum acceptable investment in engineer time (eight responses) and technician time (seven responses). These were plotted to show the range and average as above. Figure 26 shows the responses for engineer time, and Figure 27 shows the responses for technician time.

Respondents were asked to report the time in days. There was a wide range of responses and a low sample rate, making it difficult to draw meaningful conclusions. This topic could be revisited once sample models are available and the concept is less abstract.



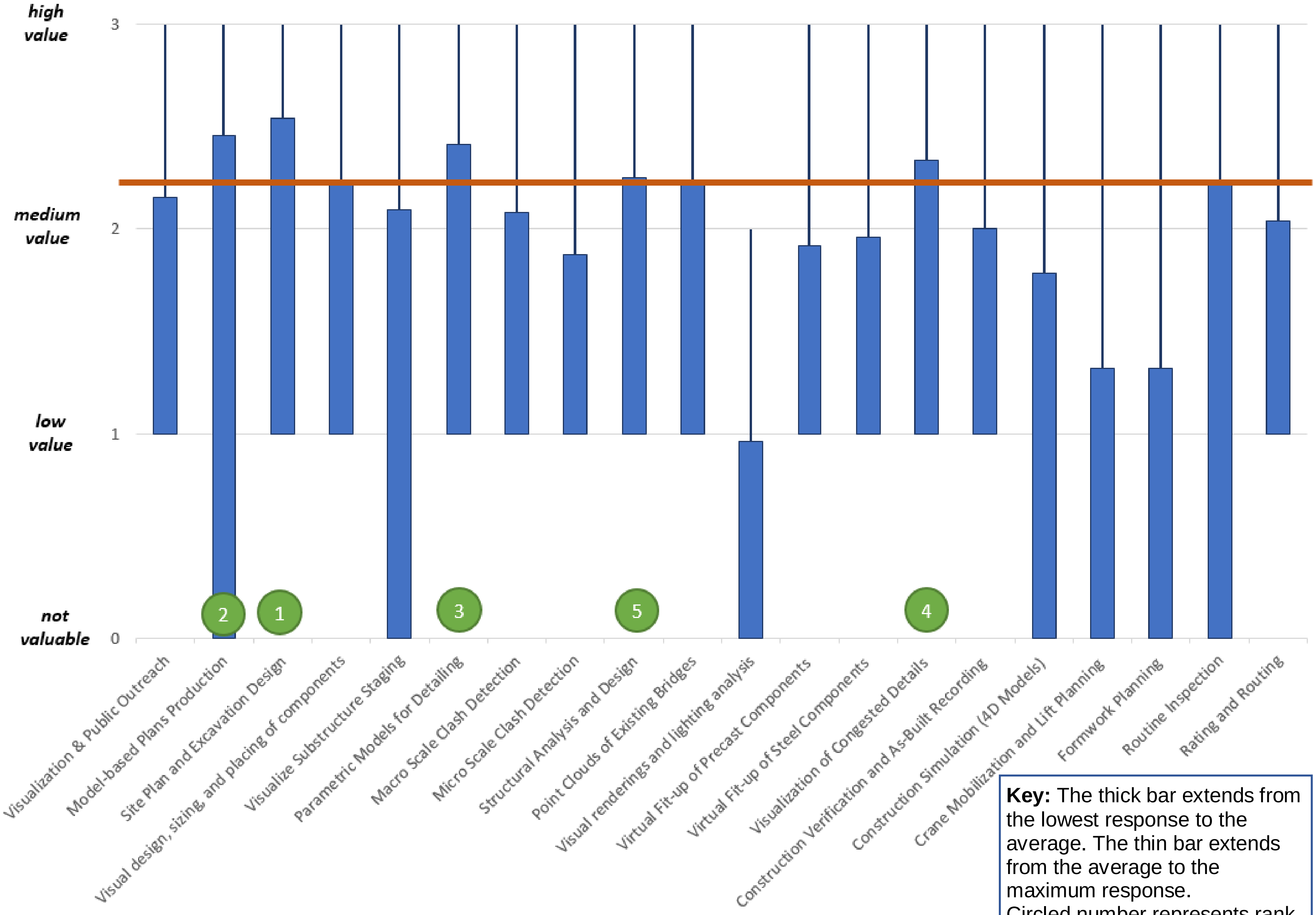
Key: The thick bar extends from the lowest response to the average. The thin bar extends from the average to the maximum response.
Circled number represents rank.

Figure 22: 3D Bridge Model Priority Ranking.



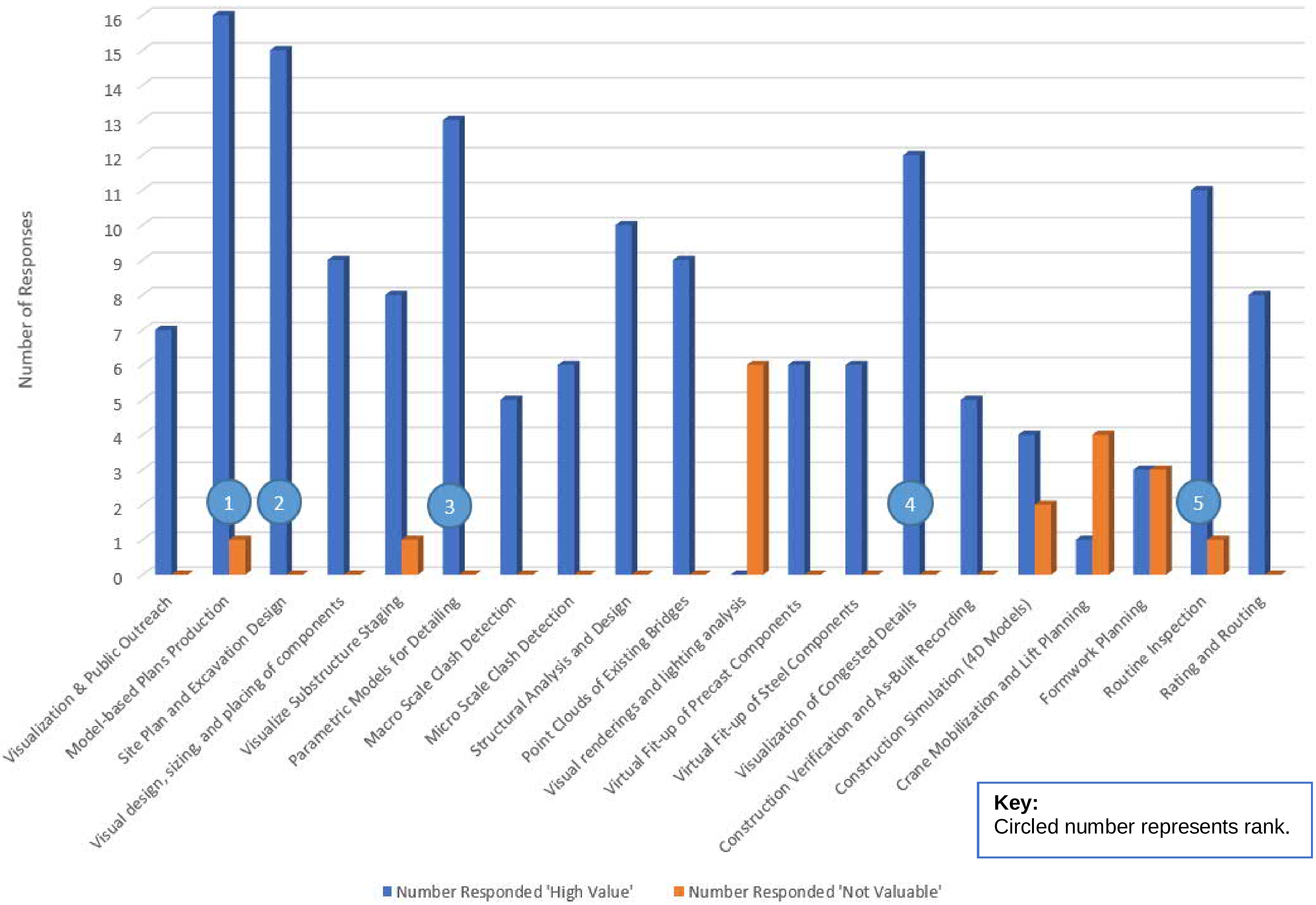
Key:
Circled number represents rank.

Figure 23: 3D Bridge Model Urgent and Non-Priority Responses.



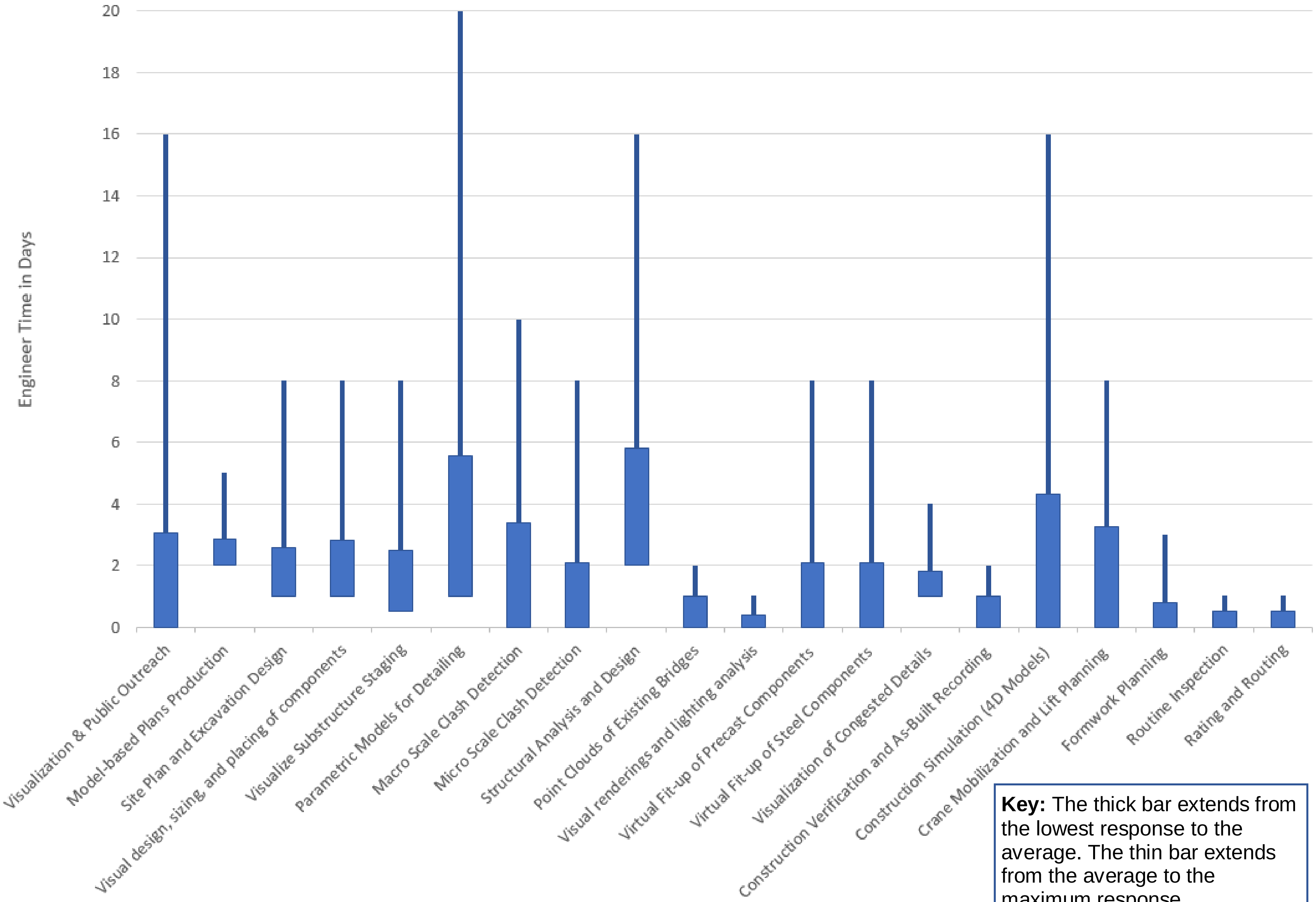
Key: The thick bar extends from the lowest response to the average. The thin bar extends from the average to the maximum response.
Circled number represents rank.

Figure 24: 3D Bridge Model Value Ranking.



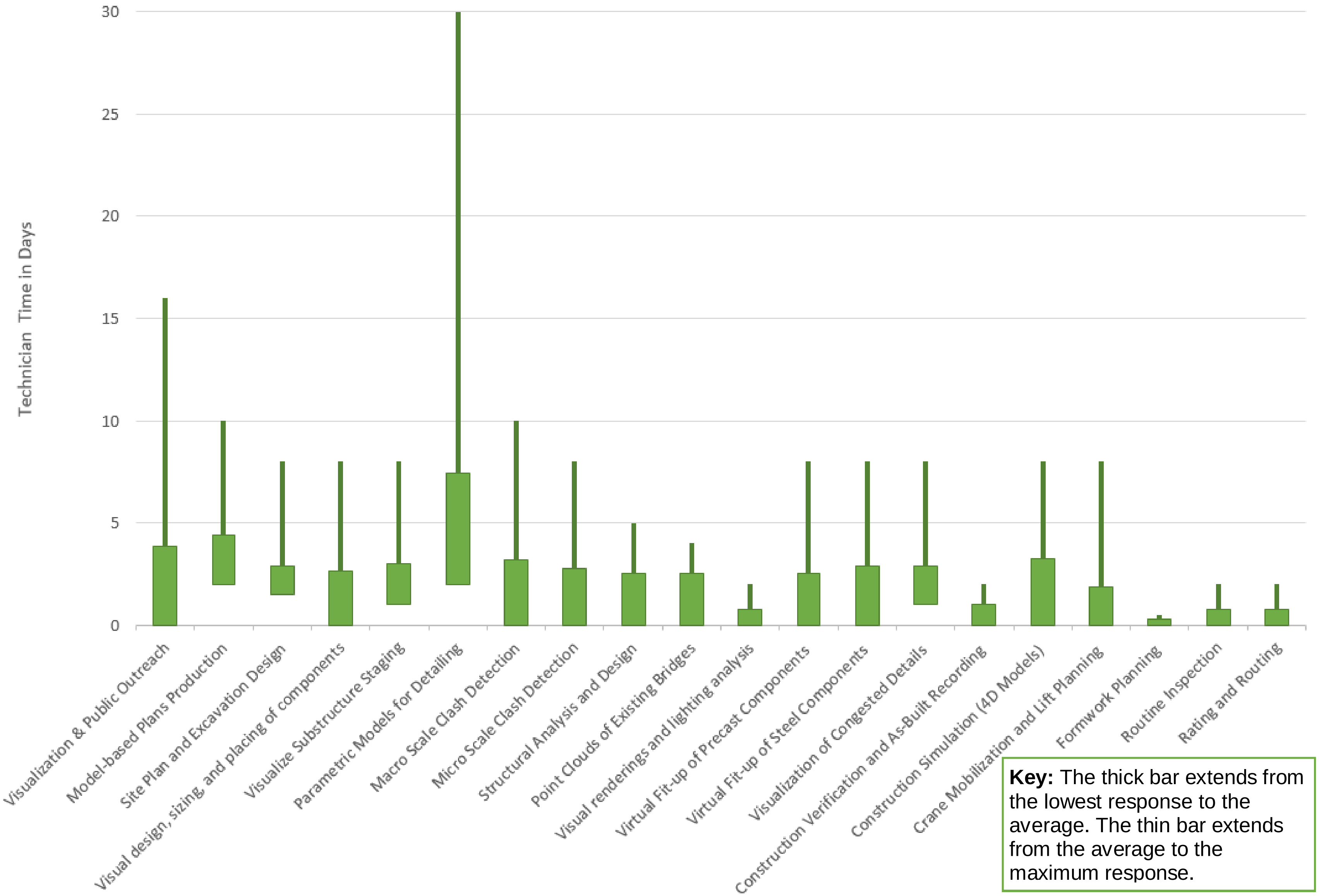
Key:
Circled number represents rank.

Figure 25: 3D Bridge Model High and No Value Responses.



Key: The thick bar extends from the lowest response to the average. The thin bar extends from the average to the maximum response.

Figure 26: Maximum Acceptable 3D Bridge Modeling Engineer Time Investment.



Key: The thick bar extends from the lowest response to the average. The thin bar extends from the average to the maximum response.

Figure 27: Maximum Acceptable 3D Bridge Modeling Technician Time Investment.

3.3 Framework Requirements

This section tests the highest priority and most valuable uses against the constraints and evaluation criteria created in Phase I to develop the framework for 3D and 4D bridge models and plans.

3.3.1 Data Integration

When a bridge model can be reused for multiple purposes, an opportunity exists to create significant efficiencies by eliminating redundant data entry and manually propagating change. The bridge data flowchart in Figure 28 was created in the Phase I report. The seven priority uses identified through consultation are identified by orange boxes in **Error! Reference source not found.**. This illustrates the inter-relationships between the different uses.

Data must flow between Analytical Design and Geometric Design, and from Geometric Design to Design Documentation. Opportunities for data integration between these functions would create efficiencies. The priority use that is an outlier is using 3D models for inspection. At this time, MDOT has a plan for creating 3D models to enhance the process of documenting inspection data using the 3D B^{RIDG}E App.

Ideally, we could map data exchange standards for each arrow on Figure 28, which indicates a data exchange. Unfortunately, standards for data exchange are not yet fully developed. MDOT has some in-house tools that take output from Bridge Design System (BDS) to MicroStation via the AutoDraw program. AutoDraw automates sheet production by creating abutment, pier, superstructure, deck overlay, and slab-and-screed sheets. Bentley has some proprietary data integration through its various software products. The most complete open format for data exchange of bridge data is IFC, but it is not comprehensively supported in the bridge software market. It also does not support data exchange between structure models and civil models (such as corridor models and terrain models).

Figure 29 shows the priority uses on a flowchart that maps data flow between different types of 3D models and the primary functions in the design, construction, and operations phases. A look at the different model types shows that the number of data exchanges is reduced. For example, abutment grading and excavation modeling is most easily accomplished with a tool such as Power GEOPAK. The terrain model is visible in MicroStation along with a bridge model, but you would not use the same software to model the bridge as the site plan. Either the bridge engineers and technicians can work with the roadway engineers or technicians to create the terrain models for the site plan, or the bridge engineers or technicians can learn a small set of Power GEOPAK skills to accomplish these tasks.

MDOT needs to be able to read and write the 3D and 4D bridge models that MDOT staff and consultants develop. Currently, MDOT has a wide range of software available under a Bentley Enterprise License Agreement. MDOT's ProjectWise server can host data of any format. Thus, MDOT currently needs models to be delivered in the current Bentley data formats or open data formats such as IFC and Extensible Markup Language (XML).

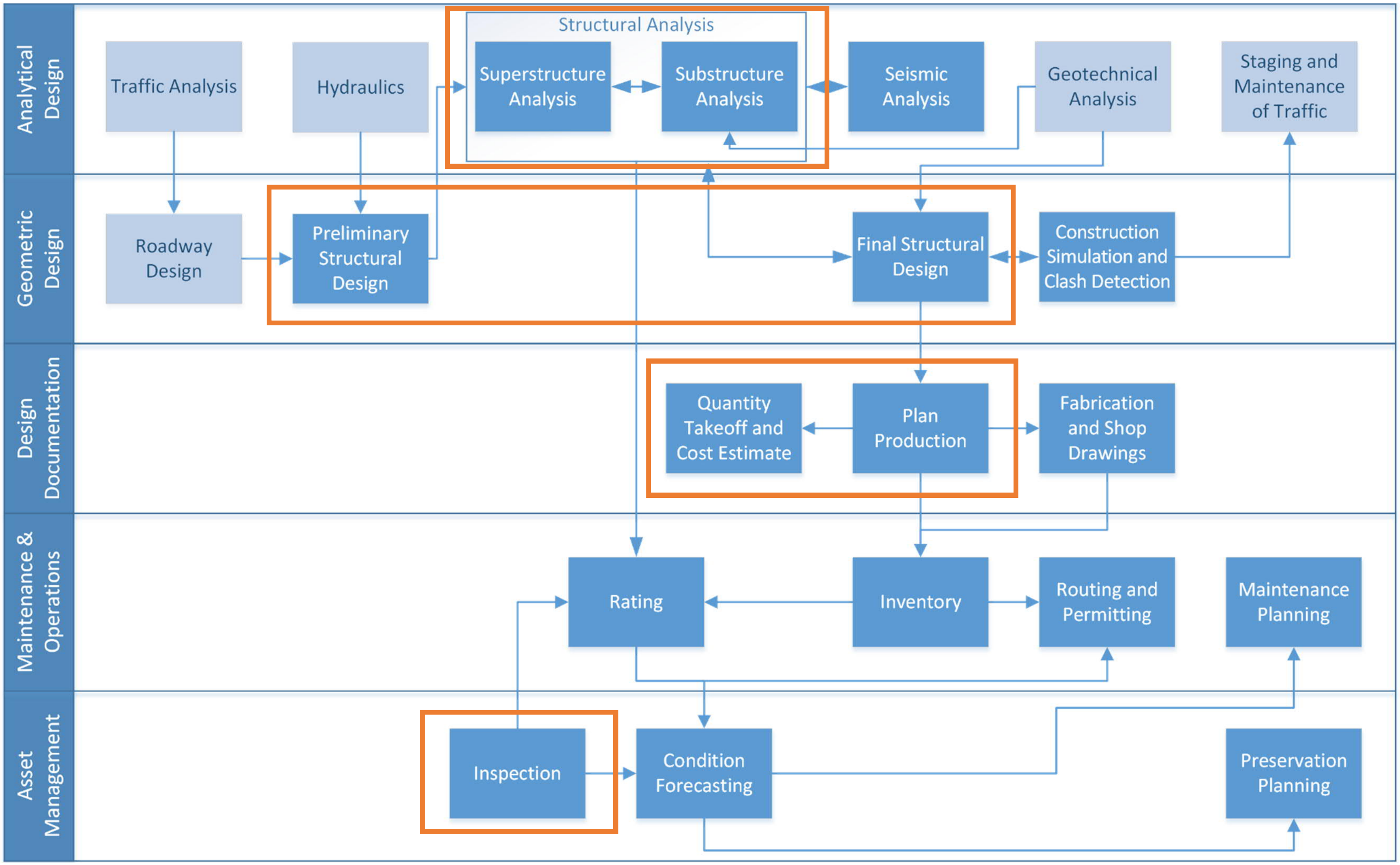


Figure 28: Priority uses identified on bridge data flowchart.

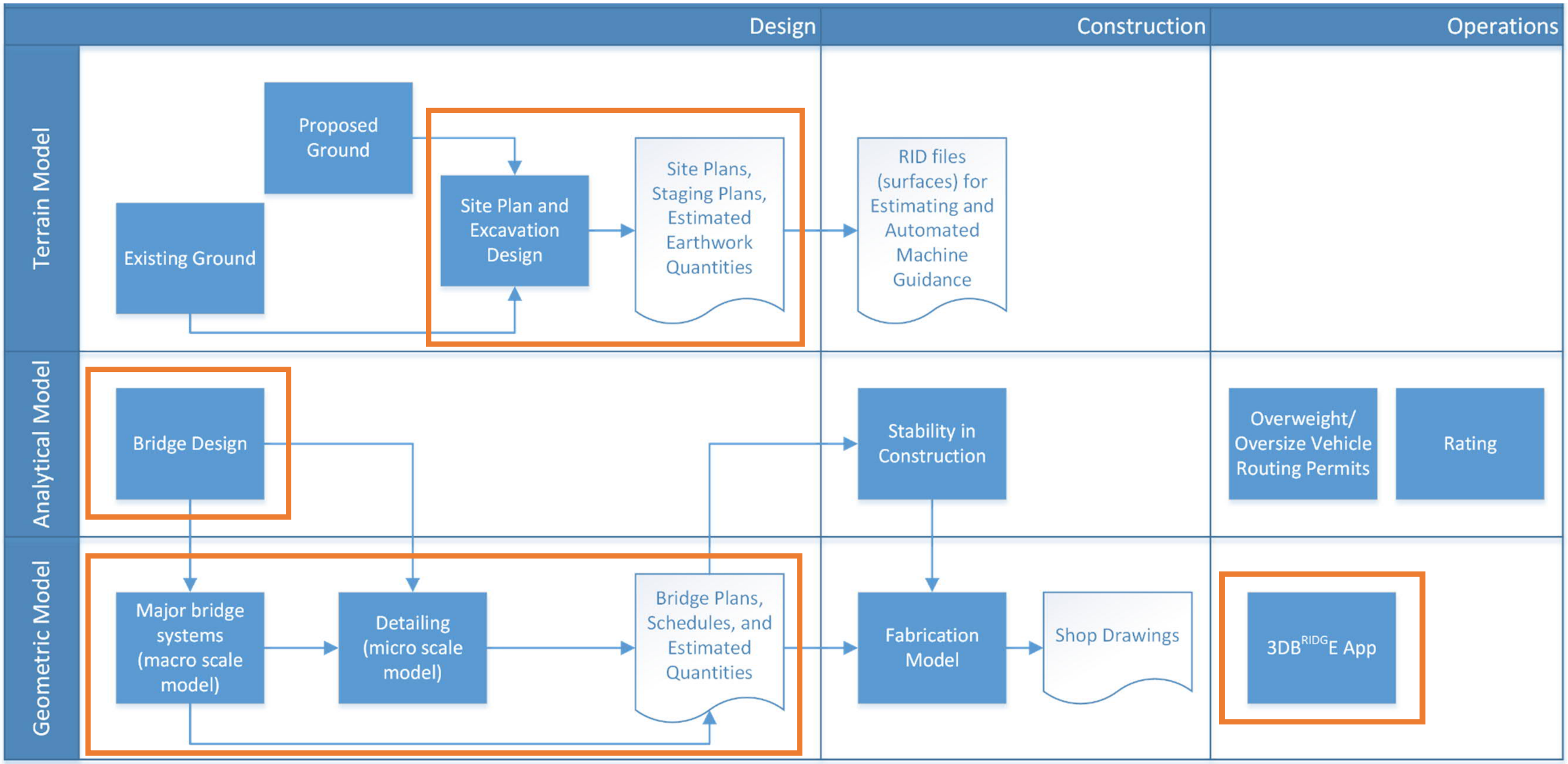


Figure 29: Bridge data flow by model type with priority uses identified.

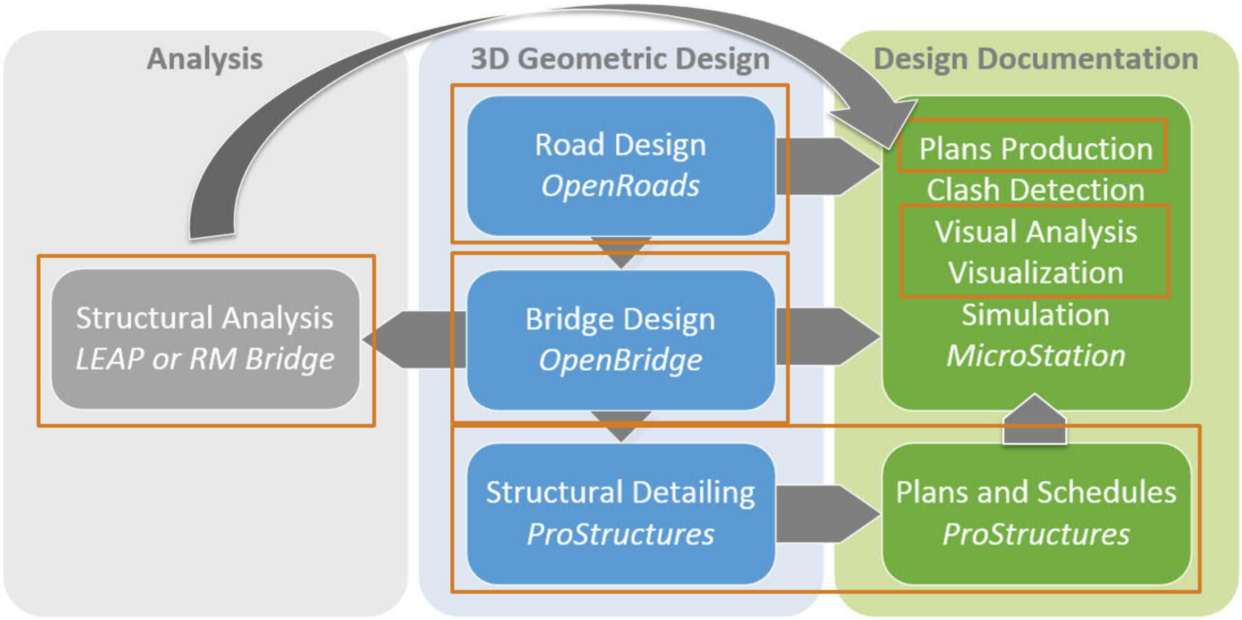


Figure 30: Priority uses and the Bentley software workflow.

Figure 30 shows how all of the priority uses, with the exception of inspection, are supported in the Bentley bridge modeling workflow. There are some 3D analysis tools—LEAP products primarily—that can work either stand-alone or with OpenBridge Modeler to create a 3D bridge model that can be used for visual design and analysis. MDOT's engineers and consultants already use LEAP products to check some designs performed with BDS and for other designs not compatible with BDS.

LEAP can create 3D models in MicroStation mesh format that are relatively aggregate but that can be used for visualization and to look at high-level design coordination. **Error! Reference source not found.** is an example of a 3D model created in LEAP Bridge Steel. OpenBridge Modeler is the central hub for bridge data in the Bentley workflow. The OpenBridge Modeler model exchanges data with ProStructures for detailing and scheduling. The extent to which LEAP, OpenBridge Modeler, and ProStructures work seamlessly to exchange data will be evaluated in more detail in Phase III.

Conceptually, the priority uses can be supported with the Bentley workflow and satisfy the primary data integration considerations identified in the Phase I report, which are:

- Must produce data that can be stored on ProjectWise
- Must produce data that can be consumed by MicroStation for plans production
- Must organize the 3D models into different levels or other segments for each structural element (e.g., a level for beams, a level for bearings, etc.)
- Able to consume MicroStation 3D solid and mesh objects
- Able to consume OpenRoads data
- Able to produce 3D models that can be used for visualization

- Able to produce 3D models that can be used for clash detection
- Able to produce 3D models that can be used for staging and lift planning

The secondary data integration considerations identified in the Phase I report are revisited in Table 2.

Table 2: Assessment of the secondary data integration considerations.

Secondary Consideration	Assessment
Able to produce data that structural analysis software can consume	Bentley workflow already supports this with its analytical tools. Integrating BDS would require developing a translator. Other commercial analysis tools would rely on maturing bridge data standards.
Change propagation preserves staging decisions (e.g., slopes and segmentation)	This relates to 3D model organization and will be explored further in Phase III.
Can store views and annotations for review comments	MicroStation can save views with numerous presets. Furthermore, these saved views are preserved in 3D PDFs. The value of 3D PDFs for design review should be evaluated in Phase III.
Models are extensible (i.e., can be progressed) such as for fabrication models	This did not emerge as a priority use. However, it may emerge when MITA and the concrete and steel trade associations are engaged in Phase III or Phase IV.
Can export data for MiBRIDGE and MDOT 3D BRIDGE App	This did not emerge as a priority use. Using 3D models in inspection is a priority. Ensuring that 3D models are standardized, with a durable file format and organized to support element-level inspection organization should be sufficient that MDOT can evaluate how to leverage these models for inspection in the future.
Able to produce 3D models that can be used to replace/supplement plan sheets	Plan production emerged as a primary use. Phase III model selection criteria will prioritize geometrically accurate models that can be sectioned and displayed for plan production.
Able to read and write data to exchange with BDS software	MDOT is already evaluating the workflow to integrate automation between BDS and plans production, including via OpenBridge Modeler.

3.3.2 Adds Value to Workflows

The survey identified how the various uses add value to the core functions. Some of the feedback received indicated that the respondents were not familiar with modern software capabilities, especially for parametric modeling. For example, some expressed doubt that it was possible to create 2D plans from a 3D model, while others indicated they were “not opposed” to this process, as long as it was not onerous. It would be beneficial to conduct outreach with MDOT’s bridge community once the sample models are available after Phase III.

Respondents mostly identified immediate value that accrued to the phase creating the model. Secondary benefits were not a strong factor in the prioritization. The opportunities to realize secondary benefits from cross-functional uses of the model depend on standardization of the models, with thoughtful organization of the data in the models. This is explored in more depth in the next section. The feedback comments are summarized for the seven priority uses in isolation in Table 3.

Table 3: Summary of feedback on value of priority uses in isolation.

Use	Value Added
Site Plan and Excavation Design	• An efficient way to generate accurate earthwork quantities, especially where there is complex geometry. Currently, MDOT pays plan quantities making accuracy a priority. It is important for situations that are urban and/or congested sites, as well as in hilly or mountainous terrain. • Modeling bridge excavation and backfill limits is important to fully explore part-width construction staging. • Modeling can support verifying final grading and bottom of footing checks. • This change would be most useful, easiest to implement, and least time consuming.
Model-based Plans Production	• Dynamic change propagation and the ability to reuse content can lead to an overall reduction in effort for plans production. • Greater flexibility to make design changes late in the design process, thanks to dynamic change propagation. • The time investment varies with the complexity of the project and the ability to reuse standard model libraries. • Using standard model libraries will lead to quality improvements and more efficient review processes.
Parametric Models for Detailing	• Similar benefits to above regarding efficiency and quality, especially related to using standard model libraries. • Ability to automate, or semi-automate, bar schedules will offset any additional time required to model complex or non-standard geometry. It would also improve the accuracy of the bar schedules. • Detailing takes place late in the project; this approach would give designers a lot more flexibility.
Visualization of Congested Details	• Valuable for designers laying out complex details. • Valuable for contractors and field staff for all congested details, especially pier caps and proper bolster elevations.
Structural Analysis and Design	• More sophisticated modeling could lead to more accurate and more efficient structural designs. • Using refined analysis techniques could aid quality and efficiency in design, e.g. analyzing stresses under different interim construction stages could change how we build. • Valuable for complex structures with unique design features.
Visual Design, Sizing, and Placing Components	• Useful in projects with medium-to-high complexity, or for a unique construction access situation. • Aids engineering judgment and troubleshooting.
Routine Inspection	• Easier to document inspection findings in the field (i.e. assign noted defects directly to components of model). • Low-hanging fruit, since the models are easily created with general detail that is useful in the field.

Plans production models were identified to have the most potential for secondary uses. These secondary uses that did not rise to the top may be accessible. It is helpful to identify primary uses and the available derivative or secondary uses of a model of that type, as shown in Table 4. It is important to consider the relationships between primary and secondary uses in combination with the Level of Development (LOD) discussion below.

Table 4: Relationship between different primary and secondary uses.

Primary Use	Secondary or Derivative Uses
Visualization	Constructability reviews, construction simulation (4D or 5D models), Inspection
Structural Analysis	Visualization and simulation, macro-scale clash detection, constructability reviews, rating and routing
Plans Production	Visualization and simulation, design coordination, macro-scale clash detection, constructability reviews, inspection
Detailing	Visualization of congested details, micro-scale clash detection, constructability reviews, inspection
Fabrication	Visualization, micro-scale clash detection, virtual fit-up, inspection

Table 5 lists comment feedback received that relates to the value added when a model is used in a combination of ways.

Table 5: Summary of feedback on value of priority uses in combination with other uses.

Use	Value Added
Site Plan and Excavation Design	• Would help to identify if there are any obstructions that need to be addressed or avoided. • Well suited to projects that include roadway and bridge designs, especially new build projects. On combined projects, a roadway designer could lead this task. • Beneficial for storm water management design and collaboration between engineers and landscape architects. • Some roadway designers are already modeling substructure units to reconcile excavation limits between road and bridge backfill quantities. • There is value in being consistent with how roadway design works, especially on projects that involve both road and bridge design.
Model-based Plans Production	• Would save time propagating changes to the roadway geometry. • Field staff may also be able to react faster to any issues that require design modifications, or evaluating different options.
Parametric Models for Detailing	• Models might be repurposed for structural analysis since they will have the required level of detail. • Integration with model-based plans production would add even more benefits with change propagation.
Visualization of Congested Details	• In combination with parametric models for detailing it would be a small level of effort to create these visualizations. • An ability to show how conflicts found during clash detection are resolved would help limit Requests for Information (RFIs).
Structural Analysis and Design	• There is additional value when the 3D analysis model can also be used for plans, detailing, clash detection, and visualization.
Visual Design, Sizing, and Placing Components	• Some analysis software automatically generate these types of models. • This could also be achieved with a model created for plans production. • This model could be used for macro-scale clash detection to locate conflicts with roadway components and utilities.
Routine Inspection	• Models created for other purposes, which are more detailed and accurate than the MDOT B^{ridg}e App models, would add even more value. • If design models are preserved and then added to with inspection information, this provides a very rich document of the existing conditions for future maintenance or design.

Table 6 assesses the seven priority uses against the enhancement categories identified in the Phase I report.

Table 6: Assessment of enhancements and priority uses

	Site Plan and Excavation Design	Model-based Plans Production	Parametric Models for Detailing	Visualization of Congested Details	Structural Analysis and Design	Visual Design, Sizing, and Placing	Routine Inspection
Efficiency Enhancements							
Increased automation of plan sheet production	X	X	X				
Automation of change propagation through plan sheets and models	X	X	X				
Automation of quantity take-off for some pay items	X	X	X				
Efficiencies in reinforcement design and quantity take-off			X	X			
Efficiencies in generating shop drawings for fabrication		X	X				
Opportunity to replace/supplement shop drawings with a 3D model		X	X				
Opportunity to replace/supplement plan sheets with a 3D model	X	X	X				
Quality Enhancements							
Rapid evaluation of different alternatives for a more refined design		X			X	X	
Generate more accurate quantities (e.g. earthwork, rebar)	X	X	X				
Add more detail to the designs (e.g. provide 3D model RIDs)		X	X	X			
Ability to review designs in more detail (e.g. slope impacts, staging)	X	X	X	X		X	
Ability to automate clash detection	X	X	X				
Producing images and videos to communicate with stakeholders	X	X	X	X		X	
Risk Identification and Management Enhancements							
Reducing manual workflows that could introduce errors	X	X	X		X	X	
Increased clarity of the design intent	X	X	X	X		X	
Ability to plan lifts to optimize equipment mobilization		X				X	
Ability to review staging in detail (e.g., slope intercepts, traffic)	X	X				X	
More consumable staging information (e.g., images, simulations)	X	X	X	X		X	

3.3.3 Usability and Scalability

The priority uses identified through consultation are coordinated and supported by what is conceptually an integrated workflow. This will be evaluated in further detail in Phase III when developing sample models. Given that the time and training resources required to learn any new tools are a challenge and that it is unsustainable to create a large training burden to maintain skill sets, usability and scalability will be priorities for developing the final recommendations in Phase IV.

The following will be considered in selecting the sample models and the modeling tools to create them for Phase III:

- Does the process leverage existing workflows and institutional knowledge?
- Does the software have an intuitive user experience to minimize training needs?
- Does the workflow improve the utilization of MDOT’s internal resources?
- Is it customizable to MDOT standards for components and documentation?
- Does the process enable a defined, appropriate LOD for the intended uses?
- Is the process consistent with current and evolving data governance standards?
- Are the resulting models compatible with the emerging industry data standards?
- Is the model consumable in construction by MDOT inspectors and contractors?

4. Framework Development

The framework will be finalized in Phase IV, taking into consideration lessons learned from creating sample models in Phase III. This phase focuses on creating tools for bridge engineers to clearly define 3D model requirements that meet the intended use and clearly articulate the limitations of 3D models based on their specifications. Consideration is given to the organization of the information in the models, the level of development of the model elements, the visual quality of the model, how to manage geospatial distance distortions effectively, and how to clearly articulate the desired outputs from the models.

4.1 Documenting Model Requirements

A Model Progression Specification (MPS) is like the ReadMe file for the model. It defines what is included in the model, when the content is developed, who is responsible for that part of the model, and the LOD of each part at each milestone. This provides everyone the information that they need to manage their expectations at the key milestones. People responsible for creating content know what they need to create. People who rely on receiving information know what quality information they will receive, and when. This allows multidisciplinary teams to plan when to invest their own efforts based on the quality of the information they have on hand. The MPS is normally developed in an early, multidisciplinary planning meeting. A sample MPS is provided in Figure 31.

Traditionally, the MPS is part of a Project Execution Plan that lists the primary contacts and the milestone dates, as well as documents the planned and authorized uses of the model content. The milestones are normally defined by data exchanges, drive much of the decision-making about the LOD. In bridge projects, the milestones are defined by the end of a project development phase. The levels of development for design information at these milestones are documented in MDOT's policy documents. Table 7 shows these milestones, how they relate to the MPS, and the guiding policy documents.

Table 7: Bridge development milestones and policy references.

Milestone	Considerations for MPS	Policy Reference
Scoping	Articulate the needs for the project	Bridge Design Manual and Project Scoping Manual
Scope Verification	Select the right level of survey and SUE data needed to fit the future project needs	Bridge Design Manual
Study	Defines elements for the model inventory or MPS	Bridge Design Manual
Preliminary Plans	Define LOD for reviewers	Bridge Design Manual
Final Design	Define LOD for reviewers	Bridge Design Manual
RID	Define authorized uses of the information for the bidders and/or contractor	Bridge Design Manual
Construction	Verify or update the reference lines Provide fabrication models/drawings	Standard Specifications
As-Built	Verify or update the reference lines, bridge geometry, and/or the fabrication details	Standard Specifications

Category	Element	Sub-Element	Study Plans			Preliminary Plans			Final Design			RID			Construction			As-Built		
			LOD	Resp. Party	Notes	LOD	Resp. Party	Notes	LOD	Resp. Party	Notes	LOD	Resp. Party	Notes	LOD	Resp. Party	Notes	LOD	Resp. Party	Notes
Proposed	Decks/Slabs	Deck/Slab																		
		Top Flange																		
		Fascia																		
		Sidewalk																		
		False Decking, Maintenance Sheeting, Stay-in-Place Forms																		
		Joints																		
	Approach Slab																			
	Bridge Railing																			
	Superstructure	Girders/Floor Beams/Stringers																		
		Other Support Types (Trusses, Arches, Cables)																		
		Diaphragms/Cross frames																		
		Miscellaneous Superstructure Elements																		
	Bearings																			
	Substructure	Abutments and Wingwalls																		
		Piers																		
		Foundations																		
	Appurtenances	Sign structures																		
		Lighting																		
		On-structure drainage																		
		Conduits																		
	Roadways	Horizontal control geometry (alignment)																		
		Vertical control geometry (profile)																		
		Final grade																		
	Earthwork	Structural embankment																		
		Earthwork																		
	Reference points and lines																			
	Utilities																			
Temporary Works	Earthwork	Excavation																		
		Stockpiles																		
		Erosion Prevention & Sediment Control																		
	Falsework																			
	Equipment																			
	Detours																			
Existing	Decks/Slabs																			
	Approach Slab																			
	Bridge Railing																			
	Superstructure	Girders/Floor Beams/Stringers																		
		Other Support Types (Trusses, Arches, Cables)																		
		Diaphragms/Cross frames																		
		Miscellaneous Superstructure Elements																		
	Bearings																			
	Substructure	Abutments and Wingwalls																		
		Piers																		
		Foundations																		
	Appurtenances	Sign structures																		
		Lighting																		
		On-structure drainage																		
		Conduits																		
	Reference points and lines																			
	Roadways	Horizontal control geometry (alignment)																		
		Vertical control geometry (profile)																		
	Terrain																			
	Utilities																			
	Context	Terrain																		
		Roadways																		
		Buildings																		
		Landmarks																		

Figure 31: Model Progression Specification with project delivery milestones.

Key milestones for the MPS are the four phases of project development in Figure 32, as well as Scope Verification, RID, Construction, and As-built. The latter two milestones describe to the contractor their requirements for submittals under the Standard Specifications section 104.02 “Plans and Working Drawings” (Michigan Department of Transportation, 2012).

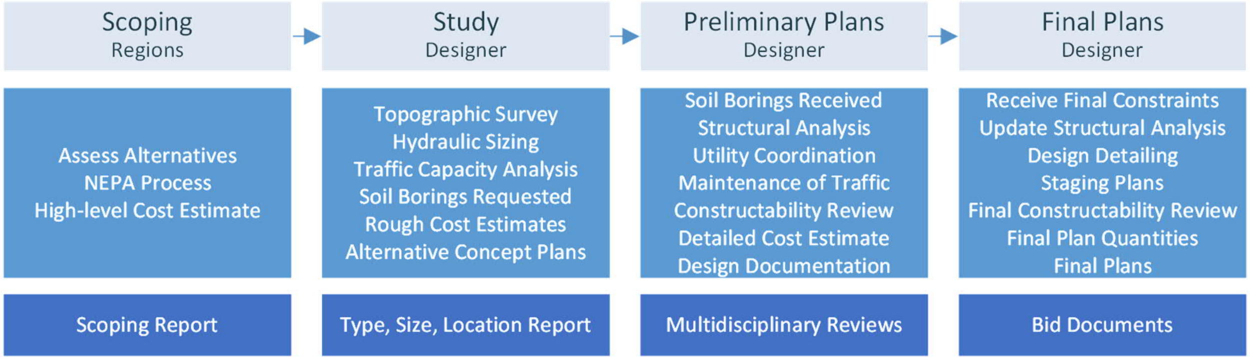


Figure 32: Bridge project development (Michigan Department of Transportation, 2009).

A MPS with multiple milestones may not be necessary except on complex or large bridge projects that support a wide range of 3D model uses. It is a useful tool when there are visualization or simulation uses, which can be open-ended. If the only intended uses are model-based plans production, or just parametric modeling for detailing, the LOD does not vary greatly by milestone and the milestones are largely design review milestones. The majority of bridge projects probably only need an inventory of the final model to provide with the RID. An example Model Inventory is provided in Figure 33. It is helpful to add the file name and the intended uses as well.

The MPS or Model Inventory is a tool to articulate the requirements for each milestone and thus document the assumptions behind the model content. It is valuable metadata to preserve so that the model can be reused in future for maintaining or operating the bridge. Without an MPS or Model Inventory, it is hard to interpret how the model may be used reliably. This is a problem for 3D roadway models as well, which is part of why it is difficult for the industry to move beyond disclaimers for those models. (Note: MDOT is working on LOD for roadway models, focusing on major project development milestones.)

The MPS or Model Inventory needs to:

- List all elements included in the model
- Assign a LOD to each model element
- Identify the responsible party behind each element

If the model also will support visualization or simulation uses, it is helpful to assign a measure of visual quality for each model element. This does not materially affect how the information may be used reliably, but the MPS or Model Inventory is a convenient place to document the requirements. The MPS or Model Inventory is also a convenient place to document the file name that includes the authoritative data for that element.

Category	Element	Sub-Element	LOD	LOV	Resp. Party	File Name	File Type	Primary Use	Secondary Uses	Notes
Proposed	Decks/Slabs	Deck/Slab								
		Top Flange								
		Fascia								
		Sidewalk								
		False Decking, Maintenance Sheeting and Stay-in-Place Forms								
		Joints								
	Approach Slab									
	Bridge Railing									
	Superstructure	Girders/Floor Beams/Stringers								
		Other Support Types (Trusses, Arches, Cables)								
		Diaphragms/Cross frames								
		Miscellaneous Superstructure Elements								
	Bearings									
	Substructure	Abutments and Wingwalls								
		Piers								
		Foundations								
	Appurtenances	Sign structures								
		Lighting								
		On-structure drainage								
		Conduits								
	Roadways	Horizontal control geometry (alignment)								
		Vertical control geometry (profile)								
		Final grade								
	Earthwork	Structural embankment								
		Earthwork								
	Reference points and lines									
	Utilities									
Temporary Works	Earthwork	Excavation								
		Stockpiles								
		Erosion Prevention & Sediment Control								
	Falsework									
	Equipment									
	Detours									
Existing	Decks/Slabs									
	Approach Slab									
	Bridge Railing									
	Superstructure	Girders/Floor Beams/Stringers								
		Other Support Types (Trusses, Arches, Cables)								
		Diaphragms/Cross frames								
		Miscellaneous Superstructure Elements								
	Bearings									
	Substructure	Abutments and Wingwalls								
		Piers								
		Foundations								
	Appurtenances	Sign structures								
		Lighting								
		On-structure drainage								
		Conduits								
	Reference points and lines									
	Roadways	Horizontal control geometry (alignment)								
		Vertical control geometry (profile)								
	Terrain									
	Utilities									
	Context	Terrain								
		Roadways								
		Buildings								
		Landmarks								

Figure 33: Model Inventory describing final PS&E deliverables.

4.2 Model Element Organization

The foundation of the MPS is the list of elements included in the model. The organization of bridge elements in the model should be logical to support design, construction, and asset management functions. Element-level organization that is consistent with the Bridge Inspection element-level organization will help ensure that the 3D models can be used for inspection purposes in the future. The *Michigan Bridge Element Inspection Manual* defines 10 major categories of bridge elements, some of which are broken down into subcategories, as shown in Table 8 (Michigan Department of Transportation, 2015). The model organization should support design, construction, and bridge management. The elements may need to be more disaggregate to support different traditional groupings, for instance for quantity estimates, construction specification and acceptance requirements, evolving element-level inspection standards, and the MiB$^{\text{RIDG}}$E data model.

Table 8: Bridge element organization (Michigan Department of Transportation, 2015).

Element	Sub-Element
Decks/Slabs	Deck Slab Top Flange Deck Top Surface Deck Bottom Surface Fascia Sidewalk Pedestrian Approach Wearing Surfaces False Decking, Maintenance Sheeting, Stay-in-Place Forms Joints
Approach Slab	
Bridge Railing	
Superstructure	Girders Floor Beams Stringers Trusses Arches Cables Miscellaneous Superstructure Elements
Protective Coating	
Bearings	
Substructure	Abutment Wingwall Column Pier Wall Pier Cap Pile Pile Cap/Footing Tower Trestle
Culvert	Culvert
Scour Protection	Scour Monitoring
Appurtenances	

The starting point for developing the bridge element organization was the *Michigan Bridge Element Inspection Manual.* Since the goal is to continue to use the models in operation and asset management, the model content needs to be at the same or a higher resolution as MiB^{RIDG}E. This enables the model data to be mapped to MiB^{RIDG}E data. For example, during design or construction it may be desirable to distinguish between a deck and a slab, but the two are represented as a single sub-element category for inspection. The sub-elements in Table 8 that are not applicable to a project may be deleted to simplify the project-specific model inventory or MPS. Additional, non-structural elements can be added to include earthwork, utilities, temporary works, construction equipment, and surrounding context, which may be needed to visualize the construction staging. The model elements should be organized by proposed elements (Table 9), existing elements (Table 10), and temporary works (Table 11). This provides a good basis for a 3D model element inventory to define the elements to include in the bridge model.

Table 9: Model element organization: proposed features.

Category	Element	Sub-Element
Proposed	Decks/Slabs	Deck/Slab Top Flange Fascia Sidewalk False Decking, Maintenance Sheeting and Stay-in-Place Forms Joints
	Approach Slab	
	Bridge Railing	
	Superstructure	Girders/Floor Beams/Stringers Other Support Types (Trusses, Arches, Cables) Diaphragms/Cross Frames Miscellaneous Superstructure Elements
	Bearings	
	Substructure	Abutments and Wingwalls MSE Walls Piers Foundations
	Appurtenances	Sign Structures Lighting On-structure Drainage Conduits
	Earthwork	Structural Excavation Structural Embankment Structural Backfill Earthwork
	Reference Geometry	Reference Points and Work Points Reference Lines
	Utilities and Drainage	Differentiate by utility type
	Roadway	Final Surface Roadway Prism Components Retaining Walls Guardrail

In almost all cases, proposed features need to be included. In many cases, existing features also are needed. These may need to be displayed on plans, used to compute quantities, or they may be important to fully communicate staging or demolition sequences. Often, existing features are not needed at the same LOD as proposed features. It may not always be worth modeling an existing structure. For example, if the model will only be used for plans production, it may be easier to use traditional means to represent the existing structure.

The model element organization for the bridge features should follow the same organization as Table 9, but may be consolidated to show only Elements or even systems if only a low LOD is needed. Table 10 shows only the non-bridge features. The main differences to the organization of elements included in Table 9 reflect the need to differentiate SUE designations for existing subsurface utilities and the different model content type for depicting existing roadway features compared to proposed roadway features. That is, proposed roadway features would comprise 3D corridor components, whereas existing roadway features would be depicted as the top of roadway terrain. Context elements would be included when the model is used to examine or visualize impacts outside of the project limits (such as traffic impacts), especially when the model is used to produce images or videos for engaging with the non-technical stakeholders.

Table 10: Model element organization: existing features.

Category	Element	Sub-Element
Existing	Roadways	Wearing Surface Retaining Walls Guardrail
	Terrain	
	Utilities and Drainage	Differentiate by utility type and SUE designation
	Context	Terrain Roadways Buildings Landmarks

When the model will be used for staging, simulation, or visualization, it may be necessary to include temporary works, interim conditions, and construction equipment (e.g. cranes).

Table 11: Model element organization: temporary works.

Category	Element	Sub-Element
Temporary Works	Earthwork	Excavation Stockpiles Erosion Prevention and Sediment Control Ponds
	Roadways	Interim Surfaces
	Shoring	Bracing Sheeting and Lagging
	Falsework	
	Equipment	
	Detours	Temporary Roads Temporary Bridges (Shoofly Bridges)

There are hierarchies of model organization. A bridge model may be split into separate files for each major system (e.g., superstructure.dgn, substructure.dgn). Elements may be placed on different levels (e.g., abutment, pier, footing), and elements may be placed as parametric components, which function like smart MicroStation cells. MicroStation Element Templates store pre-defined graphical properties (such as level, color, line style, line weight, fill, and transparency). Element Templates can also be used to assign materials for rendering and visualization. It is possible to select MicroStation elements by the Element Template, which aids in grouping bridge elements in the model into named groups or for saved views. MDOT uses the MDOT_02 workspace, which establishes standard cells, levels, level filters, colors, line styles, line weights, etc. The MDOT_02 workspace includes a level library for bridge design. The workspace could be extended to include the element templates, templates, and parametric templates for 3D bridge models, and the level library can be updated to accommodate 3D model needs.

Responsibilities for modeling and data entry can then be assigned to individuals who are part of the discipline advancing the design of the relevant elements. Each model element is assigned a designated LOD that is minimally sufficient to support the intended uses. By defining the LOD by model element, the bridge engineer does not need to progress the design of all model elements equally. Authorized use of the 3D model information can then be assigned by model element.

4.3 Level of Development (LOD)

LOD indicates how reliable the model geometry and information is at the different phases of project development (American Institute of Architects, 2016). It is expressly not a measure of the modeled object's detail, but rather how closely it reflects design intent and constructability. However, as seen in Figure 34, increasing development often requires increasing detail.

Figure 34: Three levels of development for a prestressed beam.

The LOD concept communicates authorized uses of the model and data, ensuring that, for instance, models created for visualization (which may be detailed, but not founded upon robust analysis or engineering intent) are not used for detailing, construction, or fabrication. Table *3*Table 12 contains the American Institute of Architects' (AIA) LOD definitions LOD 100 through LOD 500, which have become standard for describing

Building Information Modeling (BIM) models. While LOD is an important concept, carefully managing element-level LOD by design milestone (in a MPS) may not be necessary for most bridge applications.

Table 12: AIA definitions of LOD as applicable to bridges.

LOD	Model Element Requirements	Authorized Uses
LOD 100	Overall massing indicative of height, volume, location, and orientation. May be modeled in three dimensions or represented by other data.	Limited analysis Aggregate cost estimating High-level staging
LOD 200	Elements are modeled as generalized systems or assemblies with approximate quantities, size, shape, location, and orientation. Attributes may be attached to model elements.	Preliminary analysis High-level cost estimating High-level scheduling
LOD 300	Elements are modeled as specific assemblies and are accurate in quantity, size, shape, location, and orientation. Attributes may be attached to model elements.	Construction documents Detailed analysis Project controls
LOD 400	As per LOD 300, plus complete fabrication, assembly, and detailing information	Model-based fabrication Actual cost tracking Look-aheads Virtual mock-ups
LOD 500	Elements are as-constructed assemblies accurate in quantity, size, shape, location, and orientation. Attributes may be attached to model elements.	Maintenance and planning of future construction

The LOD and milestones are already clearly defined in the Bridge Design Manual, which defines the requirements for each milestone (Study, Plan Review Meeting, Plan Completion, Turn-in) (Michigan Department of Transportation, 2009) and through the Guidelines for Bridge Plan Preparation. (Michigan Department of Transportation, 2016) These requirements for the level of development of the various design elements at each milestone are relatively clearly understood. Prior to construction, bridge design is affected by other disciplines, but other disciplines are not affected by bridge design to the extent that milestone-based LOD descriptions are necessary in addition to the current guidance. Thus, for bridges, LOD is most important at the construction hand-over when the model passes from the original creator to others who need to be able to use it reliably.

The AIA LOD definitions are generic; industry is embracing the BIMForum element-level LOD definitions (BIMForum, 2016) in preference to the AIA definitions. Unfortunately, the BIMForum definitions do not sufficiently cover bridges and highway-related structures, and they do not include any roadway, terrain, or drainage features.

Another consideration when defining LOD for bridge models is that different features may be modeled in different software with vastly different data structures. For BIM, most software that is used produces models that are IFC compliant. That is not the case for bridges (yet), nor for the roadway, utilities, and terrain features. When attempting to assign LOD to each element in a MPS or Model Inventory, it is important to use definitions that reference a standard. In the case of infrastructure models, though, there is no clear standard. Instead, a variety of standards or references may be adapted and used. These are included in Table 13.

Table 13: LOD standards and references.

Element Type	LOD Definition Basis
Bridge	AIA LOD definitions (American Institute of Architects, 2016) BIMForum element-level LOD definitions (BIMForum, 2016) Create new element-level LOD definitions
Roadway/Site Grading	Confidence Level/Model Density LOD (Maier, et al., 2016)
Subsurface Utilities	ASCE 38-02 Quality Levels (American Society of Civil Engineers, 2002)
Temporary Works/Equipment	Purchase a standard library of components

In Phase III the suitability of these various standards and references will be assessed. It is possible that a modified generic LOD schedule more suited to the needs of bridge model data exchanges could be developed. For example, a four-tiered scale defined in accordance with the intended use of the model, such as in Table 14 could be sufficient. Otherwise, a bespoke collection of element-specific LOD descriptions may be needed for some elements, with general LOD descriptions for the rest.

Table 14: A possible generic LOD schedule for bridge-related features.

LOD	Description
LOD-V	Sufficiently developed for **visualization**. Geometric accuracy suitable to look correct, may depict the entire deck as a single object, exterior features only. There may not be any structural analysis behind the component sizes.
LOD-A	Sufficiently developed for **analysis**. Geometrically accurate for major systems, but there may be simplifications where the detail does not affect the analysis. Sufficient engineering intent to estimate costs for the superstructure and substructure units. Lacks the detail to create plans or details.
LOD-P	Sufficiently developed for **plans**. Geometrically accurate to the measurement precision with sufficient detail to create plans and take-off quantities. Geometry is based on robust analysis.
LOD-F	Sufficiently developed for **fabrication**. This would essentially be guidance to contractors on what to deliver for shop model review and to keep for post-construction applications.

4.4 Visual Quality

Creating visualizations can be very open-ended. An opportunity exists to create standard libraries and element templates that have the visual textures pre-applied, but creating visualization outputs still requires setting lighting, placing cameras in the view, and rendering. Most technical uses of 3D models do not require this level of sophisticated visualization (Federal Highway Administration, 2016). Coloring a surface green, as opposed to applying a “grass” material texture, makes a difference to the file size, render time, and visual quality.

Incorrect assumptions about the level of visual quality can quickly increase costs for models and their video and image outputs. When visualization uses are indicated, it is helpful to provide guidance as to what the needs are to suit the target audience. Table 15 describes different grades of visual quality and associated target audiences.

Table 15: Grades of visual quality and applicable uses.

Visual Quality	Visualization Elements	Target Audience
Photorealistic	3D elements are *textured* with *materials* *Perspective* view style Defined *camera* locations Defined *lighting* (locations, colors, intensities) *Rendering* required to produce images and videos	General public
Representative	3D elements are *colored* in solid colors *Perspective* or *orthometric* view style Defined *camera* locations, *lighting,* and *rendering* optional (can use *shaded* view styles and screen grabs to create images)	General public Non-technical stakeholders Technical stakeholders
Illustrative	3D elements may be any color No cameras, lighting, or rendering needed Can use *shaded* or *wireframe* view styles Can create images with screen grabs	Technical stakeholders Project team

Figure 35 contrasts a wireframe model and a rendered model of the same scene. The rendered model appears to use a mix of material textures and representative colors (e.g., light gray for asphalt in preference to an asphalt material).

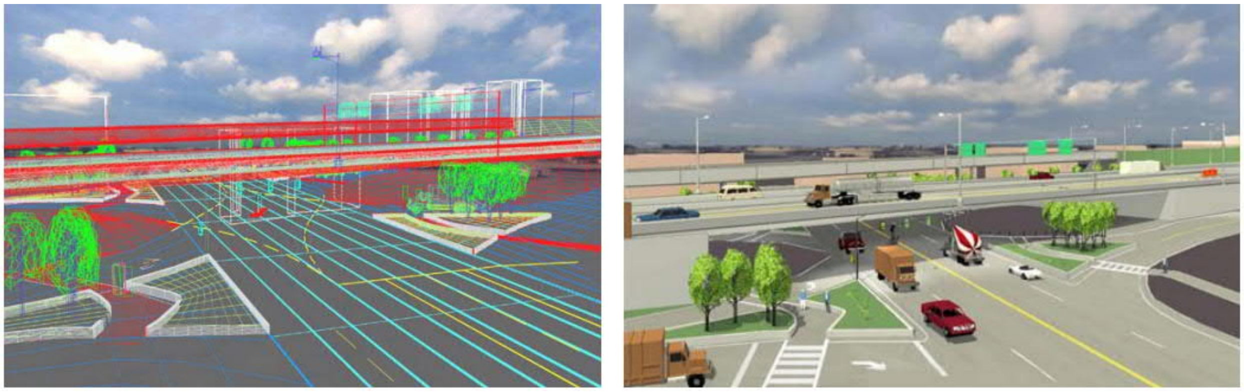


Figure 35: A wireframe model (left) and a rendered model (right) (AASHTO, 2003).

4.5 Managing Distance Distortions

Michigan uses the Michigan Coordinate System 1983 (MCS 83); a Lambert Conformal Conic projection with three zones (north, central, and south) (State of Michigan, 1988). This means that design coordinates in International Feet are distorted relative to the true distances on the ground. The amount of distance distortion varies depending on the distance from the project location to the standard parallels that define the MCS 83 zones.

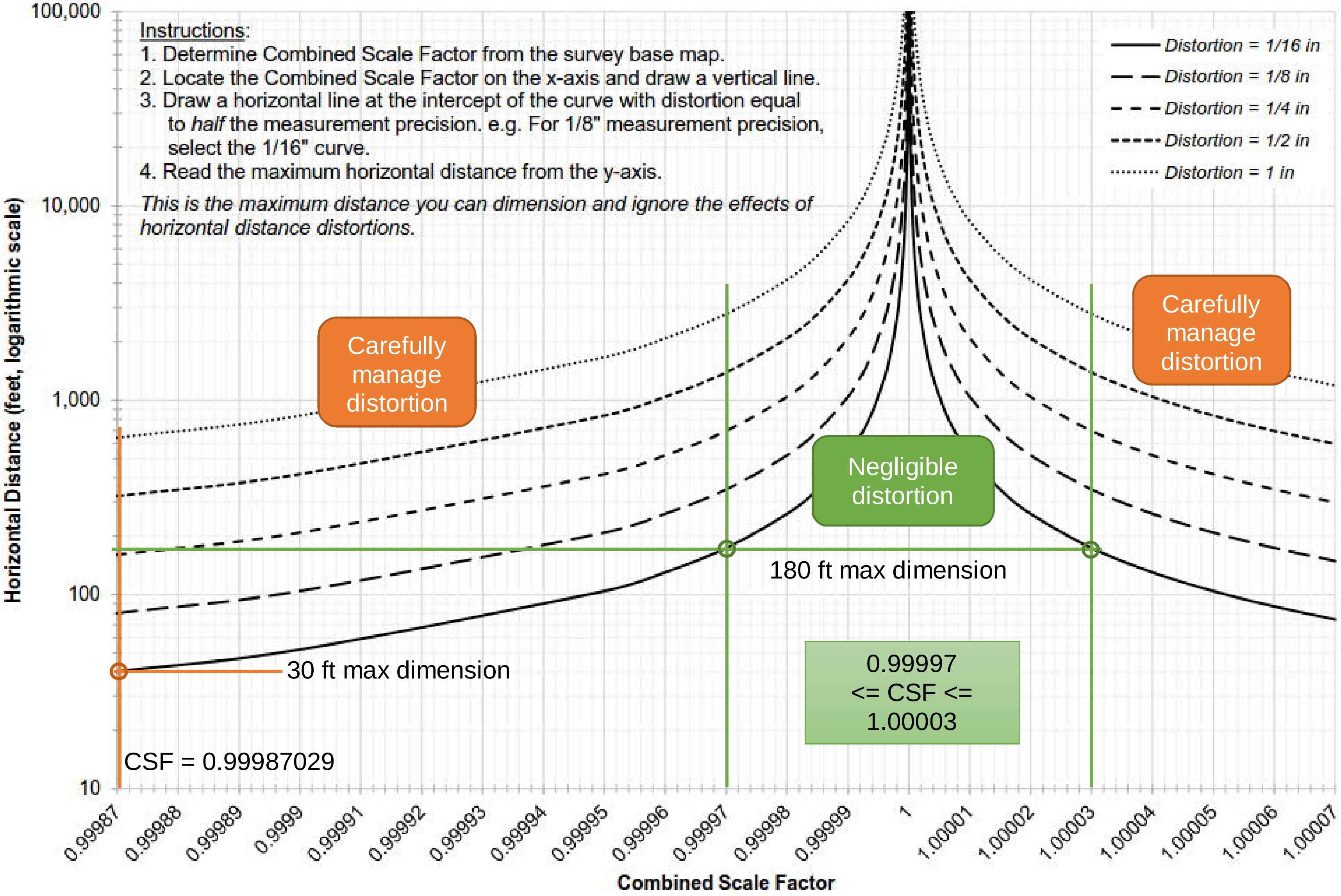
The horizontal distance distortions are computed by a licensed surveyor and expressed as a Combined Factor, sometimes called a Combined Scale Factor (CSF). The Combined Factor describes the ratio of grid distances measured in MCS 83 coordinates to true ground distances. In reality, the Combined Factor varies at every point in the state, but for a small project, usually a single Combined Factor will be reported. For widely dispersed projects, sometimes a Combined Factor is computed for every bridge location.

Many areas in Michigan have significant distortion. The midpoint of each of the three State Plane zones has similar levels of distortion; the worst case distortion depends on elevation as well as location. In Goodrich, which is southeast of Flint, the CSF is 0.99987029. This is close to the maximum distortion in the southern zone. Here, a distance measured as 500 feet using coordinates on the MCS 83 grid is actually 500 feet and 3/4 of an inch on the ground. Construction surveyors manage this distortion to stake out the bridge. Traditionally, survey and coordinate data is provided in MCS 83 grid, but bridge engineers draft in ground units in a custom coordinate system that has no distortion. In construction, once the reference points and lines are set using the MCS 83 grid coordinates, all the work is relative to those points in the ground-based distances. This workflow is effective. Using 3D models disrupts this practice; the intent is for a single model to serve both purposes. The distance distortion in a 3D model created on MCS 83 grid coordinates may be so significant that the model is not accurate within normal measurement precision.

In order for the 3D bridge models to line up with the 3D roadway models and other design information (such as utilities), the bridge models need to be created in the same MCS 83 grid coordinates. This ensures that they can be used in visualization, simulation, design coordination, and constructability review. However, depending on the longest dimension in the bridge, and the CSF, this means that the bridge model may not be dimensionally accurate to the normal 1/8 inch measurement precision reflected in standard plans for bridge elements when the MCS 83 grid distances are scaled to ground distances. This creates a problem that must be managed.

Figure 36 is a nomograph to help bridge engineers determine whether distance distortion will be significant for their project, based on the CSF. To be accurate with a 1/8 inch measurement precision, the maximum acceptable distance distortion is 1/16 inch. For places with CSF on the order of Goodrich, ¾ of an inch over 500 feet works out to 1/16 of an inch over 30 feet. That most likely is not an issue for dimensioning the substructure units, but it would be a problem for beam lengths.

Bridge models also need to be dimensionally accurate so that they can be used for fabrication. When dealing with a large CSF, it takes advanced and sophisticated Computer Aided Drafting and Design (CADD) management to have a single dimensionally accurate 3D bridge model (measured in ground distances) that lines up with the roadway and other models on MCS 83 grid coordinates. OpenBridge Modeler uses the horizontal geometry to lay out the bridge. This workflow enables roadway geometry changes to propagate dynamically through the bridge geometry.



Instructions:
1. Determine Combined Scale Factor from the survey base map.
2. Locate the Combined Scale Factor on the x-axis and draw a vertical line.
3. Draw a horizontal line at the intercept of the curve with distortion equal to *half* the measurement precision. e.g. For 1/8" measurement precision, select the 1/16" curve.
4. Read the maximum horizontal distance from the y-axis.

This is the maximum distance you can dimension and ignore the effects of horizontal distance distortions.

Figure 36: Nomograph to determine maximum undistorted distance.

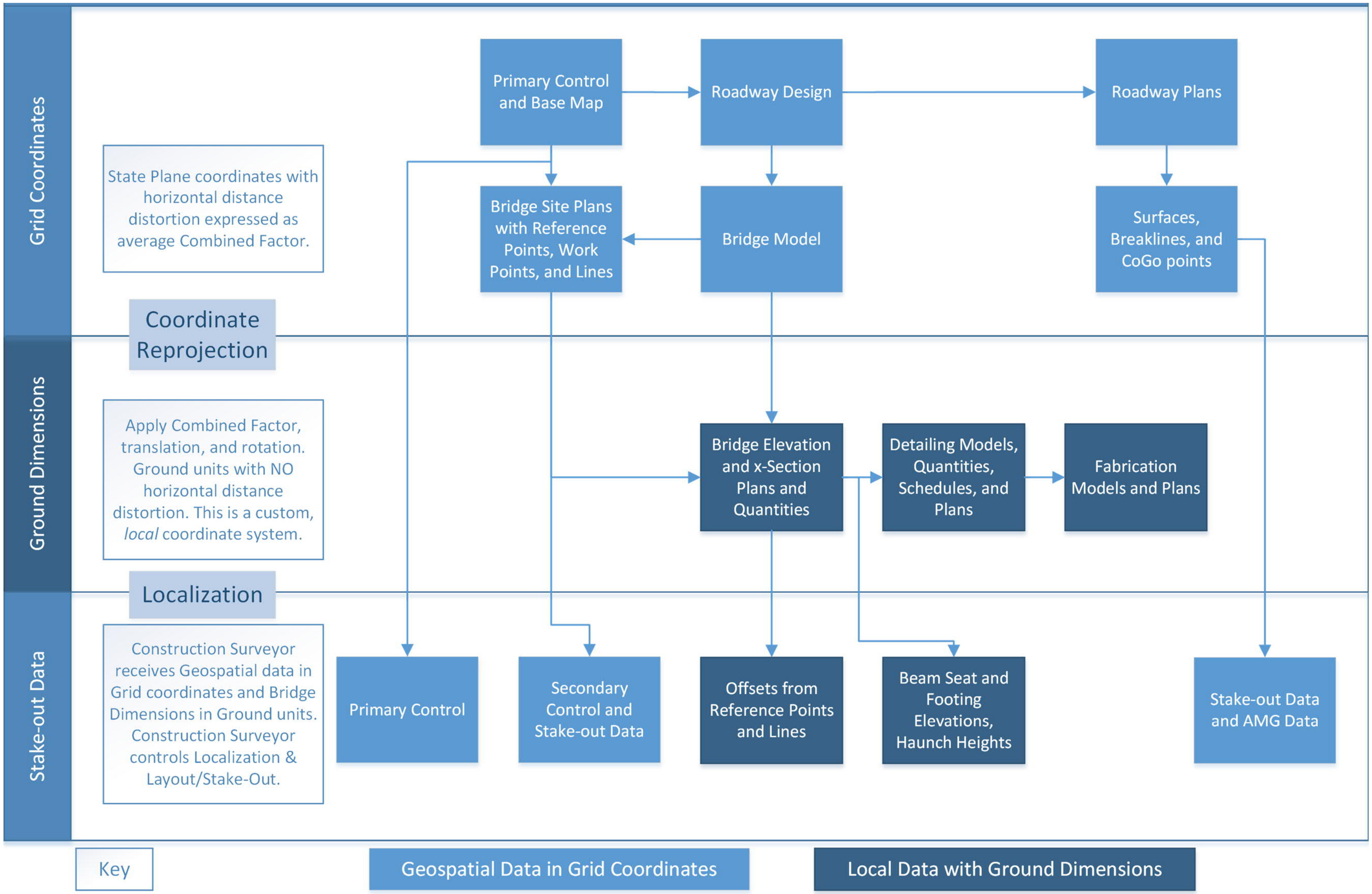


Figure 37: Data flow to construction managing local and MCS 83 coordinates.

In other words, OpenBridge Modeler models the bridge in MCS 83 grid coordinates. This model could be projected into ground coordinates for dimensioning, but the workflow to do so relies on creating a custom coordinate system and using the geospatial references function in MicroStation. It also introduces the risk that custom coordinates that appear on the surface to get MCS 83 coordinates may inadvertently be sent to construction.

Another approach that avoids this risk and does not rely on advanced MicroStation skills would be to have two models; a grid scale model for location plans, design coordination, and visualization, and a ground scale model for structure plan dimensioning and detailing. This largely mimics the current workflow. However, the dynamic change propagation between OpenBridge Modeler and ProStructures is disrupted. The MPS or Model Inventory would need to clearly identify the authoritative source for the information to be used in construction.

Bridge construction is set from a baseline related to the design alignment and a reference point for each substructure unit. Vertical benchmarks are set along the construction baseline. Geospatial measurements stop once the reference points and reference lines are established in the ground. Subsequent set out uses dimensional measurements, essentially ground-based distances in local coordinates.

Figure 37 shows how data is exchanged and managed from the MCS 83 grid coordinates for survey base map, roadway, and other design information through local, ground coordinates for structure plans that are dimensionally accurate. The third row shows how the data is used in construction. Data that is used in geospatial (MCS 83) grid coordinates is shown in the light blue boxes. Data that is used in local ground coordinates is shown in the dark blue boxes.

With parametric model-based plan production it is important to review the standard plans to ensure that MCS 83 geospatial (distorted grid) information and local (undistorted ground) information is not conflated. All *geospatial coordinates* and *station-offset* data is MCS 83 geospatial information. The authoritative source of information for sheets conveying this information would be the grid scale model. All sheets with local *dimensions* would be derived from the ground scale model. Reference points and lines, work points, soil boring locations, and features that have a coordinate reference or station and offset reference are information in MCS 83 grid coordinates.

Table 16 summarizes the different types of information shown on standard plan sheets (Michigan Department of Transportation, 2016) and the associated measurement precision. The recommendations in **Error! Reference source not found.** are items MDOT can consider internally or discuss with MITA and other construction partners to determine whether there are risks of confusion or opportunities to clarify the standard plans guidance.

Table 16: Measurement precision and information on plans.

Plan Type	Measurement Precision	Recommendations
General Plan of Site	Dimension: 1/8”	• Consider removing general structure dimensions from these plans. Primary information is geospatial coordinates and station references. These need to stay in MCS 83 grid for layout. Structure dimensions are provided on other plans. • If dimensions are needed, recommend providing clarification on the measurement precision and basis of the measurement.
Construction Staging Details	Dimension:1/8”	• No site information is included. These are ground distances.
Soil Boring Data	Station & offset: 1 ft N/E coordinates: 0.1 ft Lat/Long: 6 decimals	• Clarify the measurement precision for northing and easting to be consistent with station and offset tolerances. These are MCS 83 grid references to come from the site plan. No bridge information shown.
General Plan of Structure	Station: 0.01 ft Elevation: 0.01 ft Dimension: 1/8” Slope: 0.5	• Clarify the measurement precisions for structure units. • Clarify that station references must be placed in the base map (MCS 83 grid) and are read as plain text in the General Plan of Structure.
Details	Elevation: 0.01 ft Dimension:1/8” Angle: 1 second Slope: 0.5	• No site information is included. These are ground distances relative to reference points and lines. • Guidance already notes that steel piles are constructible to a 6” tolerance on placement, and spacing dimensions should reflect this.
Steel Reinforcement Details	Dimension:1”	• Clarify the measurement precision; the example sheet has most to a precision of 1”, but some dimensions to the ¼”.

4.6 File Formats and Metadata

In Phase III, the sample models will initially be created in proprietary Bentley formats, which are compatible with MDOT’s currently available software. The extent to which IFC and other formats can preserve data integrity and accessibility with MDOT’s current software also will be explored. The models themselves are important deliverables; they are useful as part of the Reference Information Documents (RID) and provide useful information for operating and maintaining the structure. It is important to preserve key metadata to ensure that the model can be used reliably. The necessary metadata is listed in Table 17, along with the purpose for the metadata.

Table 17: Important 3D model metadata.

Metadata	Purpose
MPS or Model Inventory	• Defines authoritative source of information for each element • Identifies responsible party for each element • Identifies the authorized uses for which the model can be applied reliably
Geospatial Metadata	• Provides information to construction surveyor for accurate layout • Provides CSF to determine reliable measurement precision
LOD Standard or Reference	• Defines the LODs used in the MPS or Model Inventory

4.7 Derivative Products

Many derivative products can be created as outputs from the models. The number and type of derivative products will affect the cost. The level of effort to prepare these outputs depends on the required visual quality and how the outputs will be used. Some derivative products, especially those related to visualization and simulation, can be expensive to produce. Consequently, it’s important to clearly identify how they will be used, how many are needed, and the requirements for visual quality. Table 18 lists derivative products from 3D models. Some are standard design deliverables (contract plans, schedules, estimated quantities), while others are value-added products.

Table 18: Derivative products from 3D models.

Output	Description	Guidance
Contract Plans	Created from parametric models that are geometrically accurate within the measurement precision. Uses core MicroStation tools and production workflows.	Current policy (Bridge Design Manual, Guidelines for Bridge Plan Preparation) addresses the guidance for creating and using contract plans.
Rebar Schedules	Created from parametric models that are geometrically accurate within the measurement precision. Uses core ProStructures tools and production workflows.	Current policy (Bridge Design Manual, Sample Bridge Plans) addresses requirements for schedules.
Estimated Quantities	Created from parametric models that are geometrically accurate within the measurement precision. Uses core MicroStation, Geopak, OpenBridge Modeler, and ProStructures tools and production workflows.	Current policy (Bridge Design Manual, Standard Specifications and Special Provisions) addresses the guidance for estimating quantities.
3D PDFs	Created in MicroStation. 3D PDFs preserve saved views and level view functionality. The 3D models can also be navigated and sectioned within the PDF. Normal PDF mark-up functions are also preserved.	3D PDFs could be a useful addition to plan review processes, as they do not require special software and thus are more accessible than 3D models in proprietary formats.
Images	MicroStation has powerful visualization tools. As described above, images can be created in a variety of ways, some with little effort, others requiring expertise with the visualization tools.	Images can be included as RIDs, included in plan sheets to convey the design intent or staging, used in

Output	Description	Guidance
		presentations at public meetings, added to permit applications, etc.
Fly-through Videos	MicroStation has powerful visualization tools. Creating fly-through videos requires expertise with the visualization tools. Visual quality needs will affect the cost to produce.	Fly-through videos can be useful for design review and stakeholder engagement.
Simulations	MicroStation has simulation (4D modeling) tools. Creating a simulation requires a critical path method schedule with uniquely named tasks, and organizing the 3D model into item sets that correlate with the schedule tasks.	The simulation is a MicroStation file that can be updated by editing either the schedule or the model. The simulation can be played within the MicroStation file.
Simulation Videos	The simulation videos are created from a simulation. An image is produced for each time step (e.g., one per week) and composited together in post-production.	Simulation videos represent one scenario and cannot be edited. They are more easily shared and played for the public or other stakeholders.

5. Implementation

Consistency and standardization are important to ensure that models can be easily and reliably used by individuals who did not create them. This section explores how the framework can be incorporated into MDOT's guidance and standards for creating and using the models, how to incorporate flexibility for atypical projects, the priorities for creating sample models in Phase III, and the strategy for coordinating with MITA, contractors, surveyors, and fabricators on construction needs for models and derivative products provided as part of the RID.

5.1 Incorporation into MDOT Standards

To be effective, the framework needs to be incorporated into the relevant sections of MDOT's policy that guides how bridge information is created and used. The screening process led to a focus on policy for bridge design, where the models would typically be created. However, as the industry progresses toward data standards for bridges, it will be important to keep in mind the future data needs for construction, inspection, operation, and asset management and update the standard for creating models as these evolve.

5.1.1 Bridge Design Manual

There is a current research project that is looking into best practices for modernizing MDOT Bridge Design Manual, guides, and policy documentation. While the policy to guide the development and quality control of 3D bridge models would reside in the Development Guide, full value capture requires using 3D models and their derivative products in the standard processes and decision-making milestones of project development, which are guided by the Bridge Design Manual.

The Bridge Design Manual should include any pertinent information for understanding the 3D model derivative products (such as 3D PDFs, images, videos, and simulations) that are used in decision-making. This includes the following:

- LOD definitions
- Guidelines or definitions for visual quality
- Identification of derivative products that support decision-making

The Bridge Design Manual can also include information about how 3D models and their derivative products can be used at each decision-making milestone. For example, adding 3D PDFs to the information shared in advance of The Plan Review Meeting or including images of staging alternatives to the Preliminary Constructability Review.

5.1.2 Guidelines for Bridge Plan Development

The Guidelines for Bridge Plan Development provide guidance regarding what information to include on each sheet. Changing the way that bridge plans are developed creates an opportunity to engage with MITA to discuss how bridge plans are used and may be streamlined. For example, MDOT is already working on implementing rebar schedules as stand-alone spreadsheets instead of as plan graphics because the data is more accessible in that format. This could reduce the level of effort to create plans and improve the accuracy of the contract documents by avoiding manual steps in the process.

Implementing model-based plans production necessitates an evaluation of the processes of creating the plans from the models. The authoritative information source needs to be identified for each sheet. Sheets that conflate local dimensions and MCS 83 grid-based information should be reconsidered because of the challenges of aligning the two coordinate systems. Significant gains to production efficiency can be achieved if a standard library of parametric models with dynamic standard plans and schedules can be created.

5.1.3 Development Guide

The Development Guide provides guidance for managing the design production and CADD resources. It is currently most mature in how it addresses road design. This guidance would need to be further developed to provide guidance in the sections reserved for bridge models to incorporate information regarding the following:

- Determining if a model will be required
- Determining the LOD and LOV for any models
- Standards for MPS or Model Inventory
- Standard file naming conventions and folder structures
- Standard object naming conventions
- Acceptable file formats for models and derivative products
- Guidance for creating models and derivative products
- RID requirements and RID review checklists

5.1.4 Bridge Design Workspace

The MDOT_02 workspace provides the automation tools and resources that MDOT’s designers and technicians use to develop 3D models and plans. The workspace would need to be further developed to include the resources that bridge designers and technicians would use to develop 3D bridge models and plans. This includes the following:

- Libraries of standard models (e.g., ProStructures files with models, sheets, and schedules)
- Libraries of standard parametric components (e.g., piers, abutments, foundations) for OpenBridge Modeler
- Libraries of standard templates (e.g. beams, decks, barriers) for OpenBridge Modeler
- Libraries of Feature Definitions and Element Templates to incorporate standard level symbology, and standard views with level presets
- Seed files for OpenBridge Modeler
- Seed files ProStructures that are preset with levels, dimension styles, and rebar label codes and types

5.2 Flexibility for Atypical Projects

A great deal of variety in bridge types, work categories, site constraints, and other factors lead to the suitability of various uses of 3D models. Project execution planning is a flexible process by which additional uses can be identified and planned for. A Project Execution Plan (PxP):

- Identifies favorable BIM uses
- Identifies the process flow for developing and using information
- Defines the modeling requirements by element and LOD to support the uses
- Identifies the responsible parties for model authoring
- Addresses interdisciplinary information exchange proactively
- Describes the resources needed for support

In most cases, the uses of the 3D model will be narrowly defined and a project manager will be able to create a MPS or Model Inventory in isolation. However, some projects may benefit from developing a PxP in a multidisciplinary, collaborative process. Projects with many disciplines converging at the bridge, where uncertainty or complexity may lead to a more iterative design phase, as well as projects with significant project risks or impacts, are likely candidates to benefit from a PxP.

The foundation for project execution planning is to set project goals, which define the priority 3D model uses. For instance, a project with significant impacts on the public may have goals related to stakeholder engagement that justify an investment in visualization. Anyone with a stake in data exchange, or who will rely on multidisciplinary data, should be involved in creating the PxP. The group should also include people who understand the data and software functionality. The Scoping phase should be used to assess the need for project execution planning. The PxP could be developed during the Scope Verification Meeting.

Figure 38 shows how the project execution planning process works. The process is used to populate standard metadata, such as the MPS or Model Inventory, and references the LOD standard.

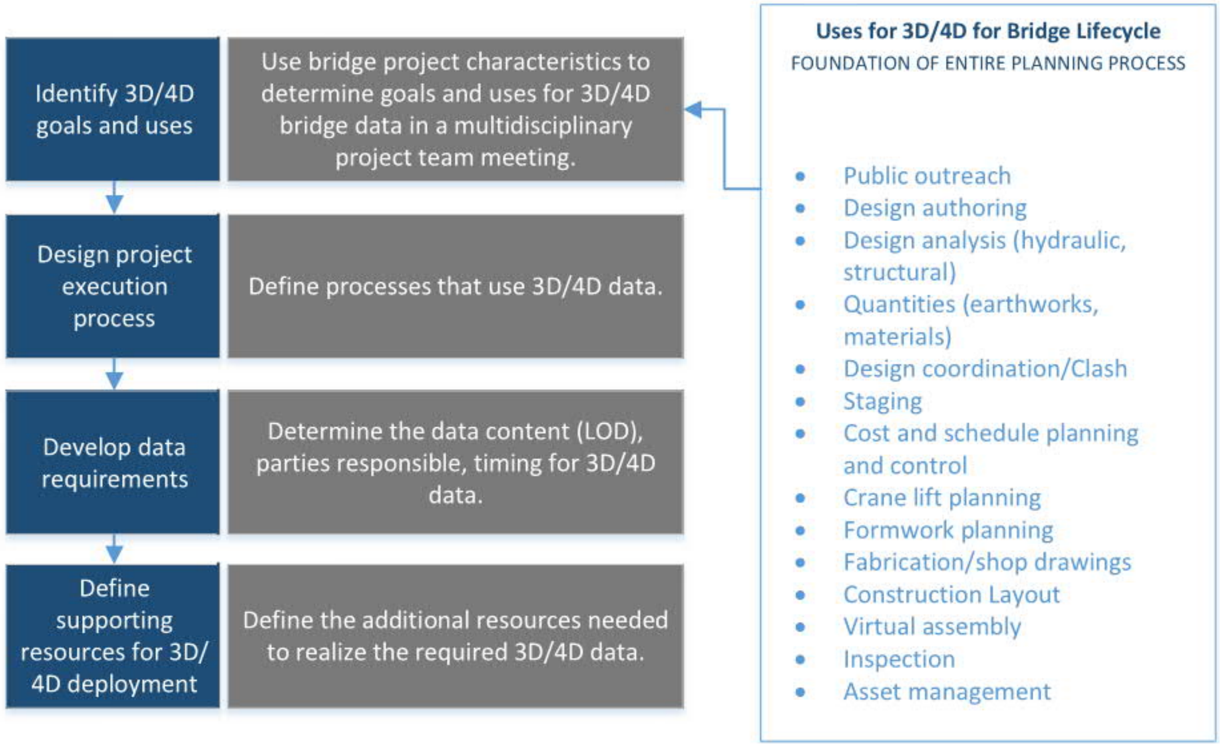


Figure 38: Project Execution Planning process as it relates to bridges.

5.3 Model Selection Criteria for Phase III

MDOT provided three potential projects and WSP added a fourth candidate. The projects provide a dataset from which to develop the 3-6 sample models in Phase III. These models need to meet the criteria for testing the framework and evaluating both the value and costs of the priority uses, and the suitability of the available modeling tools.

5.3.1 Priority Uses to Evaluate

The Phase II report identified the following priority uses for the pre-construction phase:

- Site Plan and Excavation Design
- Model-based Plans Production
- Parametric Models for Detailing
- Visualization of Congested Details
- Structural Analysis and Design
- Visual Design, Sizing, and Placing Components

Model-based Plans Production and Structural Analysis and Design are primary uses. The rest are secondary uses that can be derived from the primary models. That is, parametric models for detailing is a subset of model-based plans production, and visualizations of the congested details can be produced from the detailing model. Site Plan and Excavation Design, using, for instance, PowerGeopak for earthwork and OpenBridge Modeler for the substructure, is another subset of model-based plans production. Visual Design, Sizing, and Placing Components can use a structural analysis model from, for example, LEAP Bridge, if it's created by importing the terrain and roadway geometry.

Primary Use	Secondary Uses	Tertiary Uses
Structural Analysis	Visual Design, Sizing, and Placing Components	Design coordination, staging, visualization outputs
Model-based Plans Production	Site Plan and Excavation Design Parametric Models for Detailing	Visualization of Congested Details

There are some circumstances where only visualization is warranted, rather than in combination with structural analysis or model-based plans production. In this case, the visualization objectives can often be achieved with a relatively simple model.

5.3.2 Framework Components to Test

The Framework developed in Phase II incorporates the following components:

- A MPS or Model Inventory as a tool to document the model
- A strategy for developing the standard Model Element Organization
- A strategy for developing standard Levels of Development
- A strategy for developing standard Levels of Visualization
- Two approaches to managing distance distortion
- The requirements for file formats and metadata
- A range of 3D model derivative products

5.3.3 Sample Model Objectives

The Phase II report identified several areas to be explored in Phase III. These are listed in Table 19 along with the evaluation approach.

5.3.4 Workflow Evaluation Priorities

The Phase II report identified several areas to be explored in Phase III. These are listed in Table 20 along with the evaluation approach and assessment criteria.

Table 19: Evaluation of Sample Model Objectives.

Objective	Framework Component	Evaluation Approach
Effective plans production workflows for geometrically accurate models	3D model derivative products File formats and metadata	Produce a set of plans from a model or models (e.g. a mix of Geopak, OpenBridge Modeler, and ProStructures models to produce a full plan set.)
Seamless workflows for managing geospatial distance distortions	Managing distance distortion	Evaluate various workflows to produce models that are dimensionally accurate in ground distances, but report the correct grid coordinates, where CSF < 0.99997 or CSF > 1.00003.
Effective LOD definitions and evaluating the need for element-level definitions	Levels of Development and Levels of Visualization	LOD definitions are meaningful to communicate the limitations of model development at various milestones. Create a set of example deliverables (e.g. Study, Plan Review Meeting, Plan Completion, Turn In) to illustrate the different LOD.
Effective 3D model organization	Model Element Organization	Workspace model organization must be aligned to the MPS/Model Inventory organization.
Effectiveness of the MPS and Model Inventory as 3D model metadata	Model Documentation File formats and metadata Model Element Organization	Capture feedback from MDOT's bridge community on the effectiveness of the MPS/Model Inventory at communicating the authorized/intended uses of the models, as well as at estimating the level of effort to produce models.
Value of 3D PDFs for design review	3D model derivative products	Capture feedback from MDOT's bridge community on the effectiveness of the 3D PDF for design review and communicating the design intent for construction.
Whether IFC and other neutral formats preserve data integrity and accessibility	File formats and metadata	Export model to IFC and reimport, then compare. Also compare models that have been read/written via IFC in different software.
Extent to which the models are useful to MDOT's construction partners	Model Documentation Levels of Development and Levels of Visualization File formats and metadata 3D model derivative products	Capture feedback from MITA and other construction partners, including surveyors and fabricators.
Whether extensible models (i.e., that can be progressed for fabrication) is a priority for MDOT's construction partners	File formats and metadata	Capture feedback from MITA and other construction partners, especially fabricators. Is one format better than another? E.g. IFC vs. DGN.
Necessary refinements to the framework for Phase IV	All	Capture any updates and feedback on the Framework throughout Phase III.

Table 20: Workflow Evaluation Approach and Assessment.

Objective	Evaluation Approach	Assessment Criteria
Leverage existing workflows and institutional knowledge.	Map the existing workflow, tools, and skill level necessary and compare to the proposed workflow, tools, and skill level.	Timing of design decisions. Number of software tools engineers and technicians would need to master. Skill level required in software tools. Applicability of current software tools and skill levels/core competencies.
Improve the efficiency of production workflows.	Create one set of models using the integrated LEAP Bridge, OpenBridge Modeler and ProStructures workflow. Propagate typical design changes between the different tools at typical points in the production process. Evaluate the workflow of Tekla BIM Structures for bridges.	Amount of rework required when propagating a design change through software tools and plan sheets. Number of manual processes replaced with automated processes.
Minimize need for training and skill maintenance.	Assess how intuitive the process and software interface is. How many software tools are required and does it require advanced expertise?	Number of software tools engineers and technicians would need to master. Skill level required in software tools. Applicability of current software tools and skill levels/core competencies.
Customizable to MDOT standards for components and documentation.	Port the MDOT_02 workspace to OpenBridge Modeler and ProStructures. Create the resource files needed to develop the sample models. Add the levels, element templates, feature definitions, etc. necessary to support the model organization.	Amount of new content required in the workspace to support OpenBridge Modeler and ProStructures. Standard-compliant plan graphics and annotation can be automated using dynamic sections and views.
Does the process enable a defined, appropriate LOD for the intended uses?	Create a set of example deliverables (e.g. Study, Plan Review Meeting, Plan Completion, Turn In) using the model-based plans production process.	Number of manual processes replaced with automated processes. Compare level of effort to incorporate required LOD in the model to level of effort using traditional process, e.g. for camber, haunches, slab & screed tables, rebar schedules, details, etc.
Is the process consistent with current and evolving data governance standards?	Post the models on MDOT's ProjectWise server and receive feedback from MDOT on the ability to access the data. Map MDOT_02 workspace to model organization and model organization to MiB^{RIDG}E organization.	Data is compatible with MDOT's ProjectWise and software tools. Model organization is consistent with MiB^{RIDG}E to enable future data mapping from design to inventory.
Is the model consumable in construction by MDOT's inspectors and contractors?	Provide sample models to Inspectors in formats that are compatible with their normal inspection tools (e.g. iPad, ProjectWise, Bentley Navigator, Adobe Acrobat).	Inspectors find models accessible and navigable. Inspectors find models helpful.

5.3.5 Summary of Phase III Priorities

The objectives and workflow evaluations for Phase III set ambitious parameters for conducting the work in Phase III. In order to make most effective use of the time and resources available for the third phase, they must be prioritized. The minimally-sufficient model deliverables for Phase III are:

- A set of models (including Geopak, LEAP Bridge, OpenBridge Modeler, and ProStructures) sufficient to deliver a complete set of plans
- Staged models and plan deliverables for Study, Plan Review Meeting, Plan Completion, and Turn-in
- 3D PDF output at Plan Review Meeting, Plan Completion, and Turn-in
- One steel bridge model and one concrete bridge model
- MDOT_02 workspace extensions sufficient to develop the models in OpenBridge Modeler and ProStructures
- Model Inventory or MPS for each milestone
- Set of LOD and LOV definitions
- i-Model format model for evaluation in Bentley Navigator (mobile application)
- IFC format model
- Evaluation of the Tekla BIM Structures workflow for bridges

At this time, the Bentley bridge software does not support the IFC file format, but ProStructures does. It is anticipated that the AASHTO SCOBS T-19 committee will make a decision regarding bridge data standards at the Summer 2017 meeting. Developments arising from that meeting will determine the viability and urgency for evaluating the IFC format. Opportunities to create staged construction graphics related to substructure construction are an ancillary priority.

5.3.6 Project Datasets for Sample Models

MDOT provided three potential projects and WSP added a fourth candidate. These are:

- M-28 over Jackson Creek
- I-94 over Jackson & Lansing Railroad
- M-57 over Shiawassee River
- I-75 over Coolidge Highway

The projects and their characteristics are included in Table 21, along with a recommendation for creating sample models using these datasets.

Table 21: Example project characteristics.

Project	**M-28 over Jackson Creek**	**I-94 over Jackson & Lansing Railroad**	**M-57 over Shiawassee River**	**I-75 over Coolidge Highway**
Summary	Full replacement with full closure and traffic detour	Full replacement with partial-width construction	Full replacement with full closure and traffic detour	Two full replacements with staging TBD
Designer	MDOT	MDOT	n/a (project complete)	WSP
Status	Plan Review complete	Structure Study complete	Construction complete	Structure Study in progress
Superstructure	60-ft single span 45" PCI beams	724-ft 6-span Michigan 1800 PC beams	142.5-ft single span Michigan 1800 PC beams	Steel and Concrete options assessed in Study, single span PCI beams preferred.
Substructure	Cantilever abutment with pile supported footing	Cantilever abutments with pile supported footings and cap and column piers on micropiles or H-piles	Cantilever abutment with micropiles	Cantilever abutment with pile supported footing
CSF	**TBD**	**TBD**	0.99989040	**TBD**
Other factors	Skewed	Horizontal curve Sensitive environment	Skewed	
Survey Data	CADD files available	CADD files available	CADD files available	CADD files available
Roadway Data	CADD files available	CADD files available	CADD files available	CADD files available
Design	In progress	In progress	Final plans available	In progress
Notes		This is the only bridge with piers. It has a variety of pile types.	This is the only bridge with a complete design.	LEAP Bridge models available from analysis
Recommendation	Use to determine the level of effort to repurpose the M-57 abutment models and plans.	Use to create a multi-span bridge example in OpenBridge Modeler.	Use to test workflows to manage distance distortion. Use to create a set of models, plans, and 3D PDFs representing staged design deliverables (Study, Plan Review Meeting, Plan Completion, and Turn-in). Create selected detail visualizations.	Use to test the process of exchanging data between LEAP Bridge, OpenBridge Modeler and ProStructures. Use to create a steel bridge example in OpenBridge Modeler. Use to test the usefulness of 3D PDF in Plan Review Meeting.
Priority	Fourth	Third	First	Second

5.4 Outreach to Construction Partners

The objective of reaching out to MITA and other construction partners is to examine how the model organization, presentation, and file format meets the needs of contractors for bidding and construction. This will provide useful feedback for how to manage the horizontal distance distortions, as well as how to deliver the bridge models as part of the RID. Construction partners may need to be shown how the models may benefit them before meaningful feedback can be captured.

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Appendix 6. Recommendations for OBM Improvements

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Questions and Requests Submitted to Bentley for OBM Improvement

Submitted on June 30, 2017

1. Pull-down menu of Variable names for efficiency in deck template creation.
    a. **Response**: Already available in release SS3
2. Using equations for deck constraints, i.e. thickened overhang width = overhang width to center of beam – (beam width / 2).
3. Also related to equations above… Indicator constraints, i.e. waterstop = 1 if present, 0 if not.
4. Make substructure templates more like deck/barrier templates as far as constraints and variables.

Submitted on July 19, 2017

1. Add approach slabs to list of OBM elements.
    a. **RESPONSE:** Indeed, we will add this enhancement in a future release.
2. Allow top of wingwalls to follow roadway geometry (u-wings with vertical curves).
    a. **RESPONSE:** Good point, do you have additional information on this behavior so that we can put together the requirements for our development team?

Submitted on September 28, 2017

1. Pull-down menu of Variable names for efficiency in deck template creation.
2. Using equations for deck constraints, i.e. thickened overhang width = overhang width to center of beam – (beam width / 2).
3. Also, related to equations above… Indicator constraints, i.e. waterstop = 1 if present, 0 if not.
4. Make substructure templates more like deck/barrier templates as far as constraints and variables.

Submitted on April 22, 2018

1. Direct export to IFC from OBM.
2. Sleeper slabs added as OBM elements (or included with approach slab when they are added).
3. Ability to create combined footings for abutment and wingwalls (U-type or flared wingwalls).
4. Improved functionality with the models and the reinforcement tools within ProStructures (i.e. a bridge abutment/wingwall combined footing reinforcement tool) or the addition of reinforcement tools within OBM.
5. Ability to define excavation surfaces in relationship to the bridge models and imported/referenced surfaces and obtain earthwork quantities within OBM or

tutorials (on the Bentley Bridge Analysis YouTube page?) on how to do this with existing civil tools.

Questions and comments compiled by MDOT staff during training phase (May 11, 2018)

General:

1. Is there a location under help that describes what the input variables are for the different templates? Some are easily identified and others like the offsets require trial and error without the variable description.
2. Users should be able to enter a level for each component of the bridge (abutment/wingwall- stem, footing, piles, etc).
3. It would be nice if the template libraries defaulted to the workspace, but allowed a user to load a local template library.
4. The dialog boxes for parametric constraints and the pile definitions have a significant lag. I am not sure if this is something that is a machine dependency or if it is the program.
5. Substructure templates do not have the same folder structure that the superstructure has.

Beams

6. When defining the beam layout it would be beneficial if there was a toggle that would make the beam end value match the beam start values. For example, if the toggle is selected when the beam start offset is adjusted it would also adjust the beam end to match.
7. When defining a beam it would be beneficial if there was toggle that would have the start and end value match when they are change. For example, if the toggle is selected when the start value for the top flange is change it would also adjust the end value for the top flange to match.
8. When defining beams you should be able to define all the parts of a built up beam, but in order to save your work you need to hit ok in-between defining each element.

Deck

9. When defining your parametric constraints it would be nice if there is a way to export/import those values. It can enhance remaking the model if needed and it would allow us to generate the models faster.

10. Users are having issues with saving changes to the parametric constraints when placing the deck. It appears that constraints must be added after the deck is placed or changes are lost.

Substructure

11. Users should be able to rename Pierlines through the Properties after placement.
12. For the Elevation Constraints on the substructure it seems the fixed elevation is for the top of footing. Most DOT's will define a footing based on the bottom of footing. It would be nice if we could define the bottom of footing in the elevation constraints rather than the top. Or the elevation should be called out in the dialog window as the "top of footing elevation" to assist users.
13. When modifying the pile layout in the abutment template, the piles show incorrectly in the template graphic. The piles appear to be embedded in the stem partially up the wall. This can be confusing as you're trying to modify the template. It's not until you close the template and reopen that the graphics display properly.

Auxiliary Units

14. It would be nice if you would be able to reselect the point the barrier follows. Currently you need to delete and redefine the unit to select a new point for the unit to follow. This could be problematic if there are multiple parametric constraints.
15. Currently we combined sidewalks and barriers together due to the limitations in the software. It would be nice if we could have these templates be separate.

Piles

16. It would be nice if the pile layout would be dynamically adjusted when the substructure template is adjusted.
17. It would be nice to define independent spacing and angles for each pile row or have the ability to group select piles to make changes to angles.
18. It'd be helpful if the piles were numbered in the graphic to correspond to the pile numbering in the table below.
19. It would be helpful if the pile angle could be placed using the ratio rather than the angle.
20. Help available in templates to identify template offset locations.
21. Combined abutment and wingwall footing.

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