PART 1

General Structures

Integration of Information and Automation Technologies in Bridge Engineering and Management

Extending the State of the Art

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The current U.S. practice of information transfer during the bridge design, fabrication, construction, and operation processes is fragmented. These processes involve repeated manual transcription of data, which is error prone; approvals (e.g., of shop drawings) that are time-consuming; and formats that beg for standardization to facilitate electronic information transfer. Without such standards, electronic information exchange is impossible. This paper surveys the shortcomings of current piecemeal applications of information and automation technologies. It then explores the promise of parametric three-dimensional bridge information modeling as an enabling technology for accelerating the design and delivery of bridges and articulates aspects of the envisioned accelerated bridge delivery process for two purposes: to provide a glimpse of current technologies available to streamline the process of bridge delivery and to articulate anticipated advances that can be expected to facilitate accelerated bridge delivery. In lieu of a complete industrywide modeling of bridge information in a standardized format, savvy bridge design–build teams can be expected to obtain a competitive advantage by integration of computer-aided design, computer-aided engineering, and computer-integrated manufacturing, which will result in rapid and better-quality project delivery and subsequent cost-effective life-cycle management. As a result, all three fundamental objectives of bridge delivery would be expected to be attained: higher quality, faster delivery, and greater economy.

The end of an era is approaching. Bridge engineering and construction have relied on drawings on paper as the primary representation of construction documentation for centuries. But this is essentially the only industry making three-dimensional (3-D) products without having at its core a digital product model representation and the streamlined product delivery that comes from the electronic data exchange capabilities thereby facilitated. Other closely related industries have documented and projected reduced costs, faster delivery, and improved quality as a result of implementing 3-D integrated design and manufacturing processes based on computer-aided design (CAD), along with accompanying interoperability standards (e.g., *1–4*). The bridge enterprise is overdue to do the same (*5*). Failure to do so has been documented as a significant additional cost in the closely related capital facilities industry (*6*).

Other recent and current efforts to represent or use electronic or 3-D bridge data for various purposes omit major aspects of the overall design-through-construction process and thereby fail to leverage those data to anywhere near the extent possible. For example,

- Recent parametric design tools and transXML (*7*) omit such aspects as detailing for fabrication, construction management, erection procedures, and the like.
- Recent software specifications and tools for the precast concrete industry (*8*, *9*) are developing significant pieces of the 3-D parametric modeling infrastructure needed for streamlined precast concrete components but to date are not oriented to the bridge industry.
- In the bridge-specific data modeling area, only limited aspects of the overall picture are addressed in any given research or deployment application, and therefore possible data management leverage is not attained. For example, when inspection is modeled (*10*, *11*) manual entry of data is required specifically for inspection; similarly, when design and rating are modeled (*12*), the data for inspection or other aspects of asset management that these data could support, such as life-cycle costing, are not leveraged (*13*).
- Although 3-D modeling has been and is being used for visualization purposes as noted in Wallsgrove and Barlow (*14*), Hughes (*15*), and the various case studies assembled by the Transportation Research Board's Visualization Task Force (*16*), the same geometry painstakingly created merely for visualization is not leveraged for use in fabrication and construction.
- Such 3-D modeling has also been used for structural analysis of bridges too complex for their behavior to be predicted well enough by the traditional line-girder analyses (e.g., *17*), and for documenting as-built 3-D geometries (e.g., *18*, *19*). But such models are each typically standalone. Once again 3-D geometric bridge data are not leveraged for the multiple purposes that they could serve because of the absence of electronic data exchange and interoperability standards for those data.
- Even when electronic data exchange is pursued (e.g., *20*), only relatively small pieces of the overall workflow involved in bridge delivery are addressed. Inefficiencies in the overall workflow process that could be eliminated by a full comprehensive reengineering of the business processes to take full advantage of 3-D bridge information modeling (BIM) are, consequently, therefore not addressed.

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Thus, the current U.S. practice of information transfer during the bridge planning, design, fabrication, construction, and operation processes is fragmented. These processes involve repeated manual transcription of data, which is error prone; approvals (e.g., of shop drawings) that are time-consuming; and formats that beg for standardization to facilitate electronic information transfer. Without such standards, electronic information exchange is impossible.

The purpose of this paper is to explore the promise of parametric 3-D BIM as an enabling technology for accelerating the design and delivery of bridges and to articulate aspects of the envisioned accelerated bridge delivery process for two purposes: to provide a glimpse of current technologies that are available to streamline the process of bridge delivery and to articulate anticipated advances in the future that can be expected to facilitate accelerated bridge delivery. There are two distinct but related aspects of a streamlined approach:

- A single, centralized 3-D bridge data model or repository of the evolving bridge design and
- Electronic data exchange standards that enable bridge design, detailing, fabrication, erection, and management software applications to talk to each other, so that tedious, time-consuming, error-prone manual data reentry can be avoided.

The present paper focuses primarily on the first of these. As for the future, a complete modeling of bridge information in a standardized format (which does not yet exist) can be anticipated to facilitate integration of CAD, computer-aided engineering (CAE), and computer-integrated manufacturing (CIM), which will result in rapid and better-quality project delivery and subsequent cost-effective life-cycle management. Consequently, all three fundamental objectives of bridge delivery would be expected to be attained: higher quality, faster delivery, and greater economy.

CENTRALIZED MODEL CONCEPT

Figure 1 shows the 3-D modelcentric vision for the integrated design and construction process (*8*). Similar diagrams appear for steel bridges in Chen et al. (*21*) and for capital construction projects in Vanegas et al. (*22*). From the single, central 3-D model, a given project stakeholder (e.g., owner, designer, contractor, fabricator, precaster, or erector) can extract current project information relevant to that stakeholder at any given time. There is no more need to chase down information from 2-D drawings only to wonder whether it is current.

3-D BIM processes for integrated design and construction have previously not been deployed for real bridge projects in the United States. CAD software packages used in the bridge industry routinely produce only traditional 2-D drawings. Documentation processes based on 3-D modeling, however, are radically different from traditional processes based on 2-D modeling, as summarized in Table 1.

While it is true that processes centered on 3-D modeling have been deployed in other industries (e.g., aerospace and automotive), the CAD software packages available for those other industries do not currently provide a number of the features and amenities that bridge industry stakeholders would desire. These include, for example, different loads and load combinations and analysis methods, complex roadway geometries that use the terminology of highway and bridge engineers, and the multiple deflected geometries to be anticipated during the erection process for steel superstructures. These kinds of concerns do not outright prevent their application to bridges, but they make such application nontrivial. Figure 2 illustrates the aspects of bridge-specific workflow centered on a 3-D model explored in the current research. The ideals of single data entry and of “model it, don’t draft it” are followed as closely as possible throughout. Selected snapshots from this workflow are provided in the remainder of this paper.

An example of a partially constructed 3-D model produced from available software is shown in Figure 3 (*23*). From this model can be extracted not only geometric data but also, for example,

- Up-to-date shop drawings:
- Quantity takeoffs and bills of materials;
- Computer numerically controlled (CNC) input files to drive automated shop equipment such as rebar benders or beam line hole-punching machines for steel members;
- Piece marking for coordination with shipping schedules, bills of lading, and erector progress onsite;

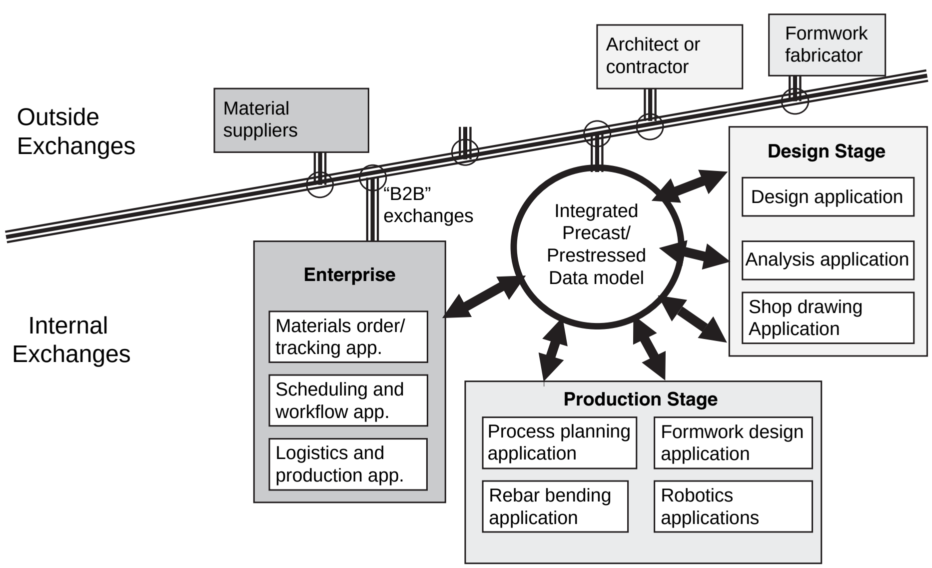

FIGURE 1 Centralized model supporting integrated process (*8*).

TABLE 1 Comparison of 2-D and 3-D Documentation Processes

2-D	3-D
2-D CAD provides an electronic "drawing board."	3-D CAD enables a parametric model.
2-D drawings contain the information.	3-D model contains the information; drawings are only reports.
2-D drawings are intended to be human-readable; separate manual data entry is required for analysis.	3-D model is computer-readable so that direct analyses are possible.
Coordination is difficult; information is scattered among different drawings and specifications clauses.	Coordination is automatic: 3-D model is single source for all product information.
Manual checking.	Automated checking.
No support for production.	Potentially full support for production (via CNC code, etc.).

NOTE: Adapted from Sacks (*8*).

- Fabrication labor and material estimating, material procurement, and material management in the shop during fabrication;
- Erection procedures; and
- Bridge data used subsequently in rating calculations and various bridge management (asset management) functions.

A number of additional sources describe background for this work (*22*, *24–26*).

ASPECTS OF INTEGRATED DESIGN-THROUGH-CONSTRUCTION WORKFLOW

This section presents a glimpse of what the implemented vision might look like to a user of integrated software that could be developed. This scenario makes use of existing technologies from distinct industries and adapts them for the bridge industry. Figure 2 provides a frame of reference in which to place the individual aspects of those technologies that will be discussed in the remainder of the paper.

In this scenario, the designer uses appropriate 3-D modeling software to document the bridge design in three dimensions. Figures 4 and 5 illustrate the bridge definition on the highway alignment and the resulting 3-D model of the steel framing, respectively (*27*).

Once the designer creates the model, he or she exports it in a suitably exchangeable form (e.g., XML). This XML could be some blend of emerging dialects like transXML (*7*) and future XML developments that will support robust data transfer for the bridge. The project website would be enabled with effective XML visualization tools that will read the XML file uploaded by the designer and display it in 3-D form. Once the designer uploads the drawings, the fabricator would log into his or her section of the project website and there be able to review the drawings. The fabricator would be able to

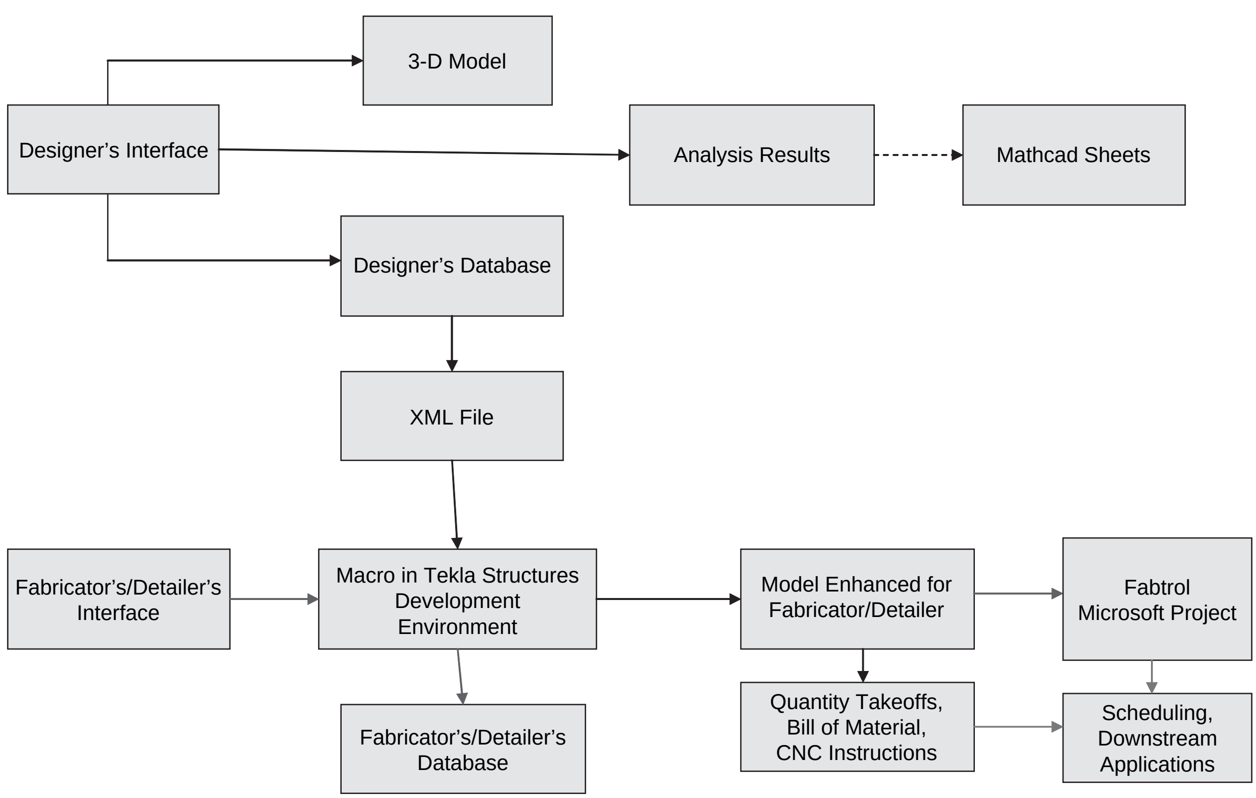

FIGURE 2 Workflow explored by means of 3-D BIM.

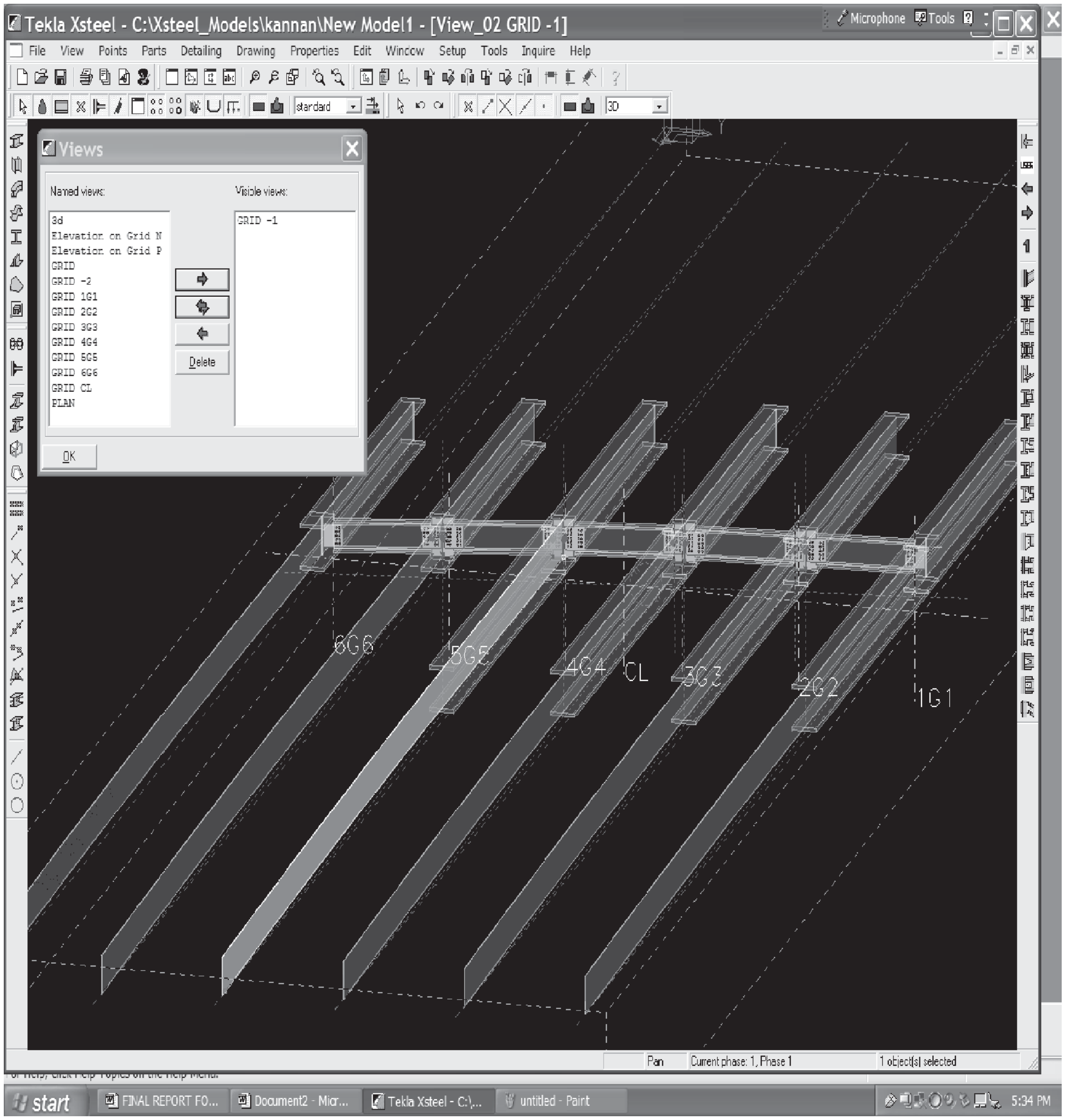

FIGURE 3 Partial 3-D steel bridge model [girder portions and diaphragms through use of Tekla software (*23*)].

inspect the 3-D model the designer uploaded. In addition, he or she would have the option to view the XML and append fabrication attributes to it. The model could then be transferred via XML to detailing software (as indicated in the workflow, Figure 2) to add information needed for full support of fabrication operations and shop drawing generation (if any stakeholders still think they need traditional 2-D drawings). An example of such a model being detailed is shown in Figure 6, which encompasses detail down to the bolts and welds.

Thus, the central model would get updated while its complete integrity would always be maintained as the project progresses. Information in it would thereby be reliably leveraged to drive downstream processes rather than there being reliance on tedious, time-consuming, error-prone manual data reentry to feed those processes. This is not to say that independent checkpoints are removed—quite the contrary. The checkpoints must obviously be kept in the new workflow while the possibility of infusing new errors through manual transcription is removed.

The fabricator's CAM system, which would be connected to the Internet, would have software translators to read the bridgeXML file and generate the G codes for the CNC machines. Shop drawings could also be generated from the same central bridgeXML file (although it is questionable whether there would be any need for human-viewable 2-D shop drawings because the fabricators would have the 3-D central model and would be driving the CNC fabrication machines directly from it).

The 3-D centralized model, updated to as-fabricated geometry, could then be used to conduct virtual assembly. Being able to do this would shorten delivery schedules dramatically and reduce costs because physical preassembly (to ensure fit-up) would no longer be necessary. The model also would help the erector to visualize the assembly well before erection starts. He or she could then anticipate the on-site problems and plan the erection process accordingly. Figure 7 shows a portion of the 3-D model with diaphragm-to-girder connections of interest to the erector.

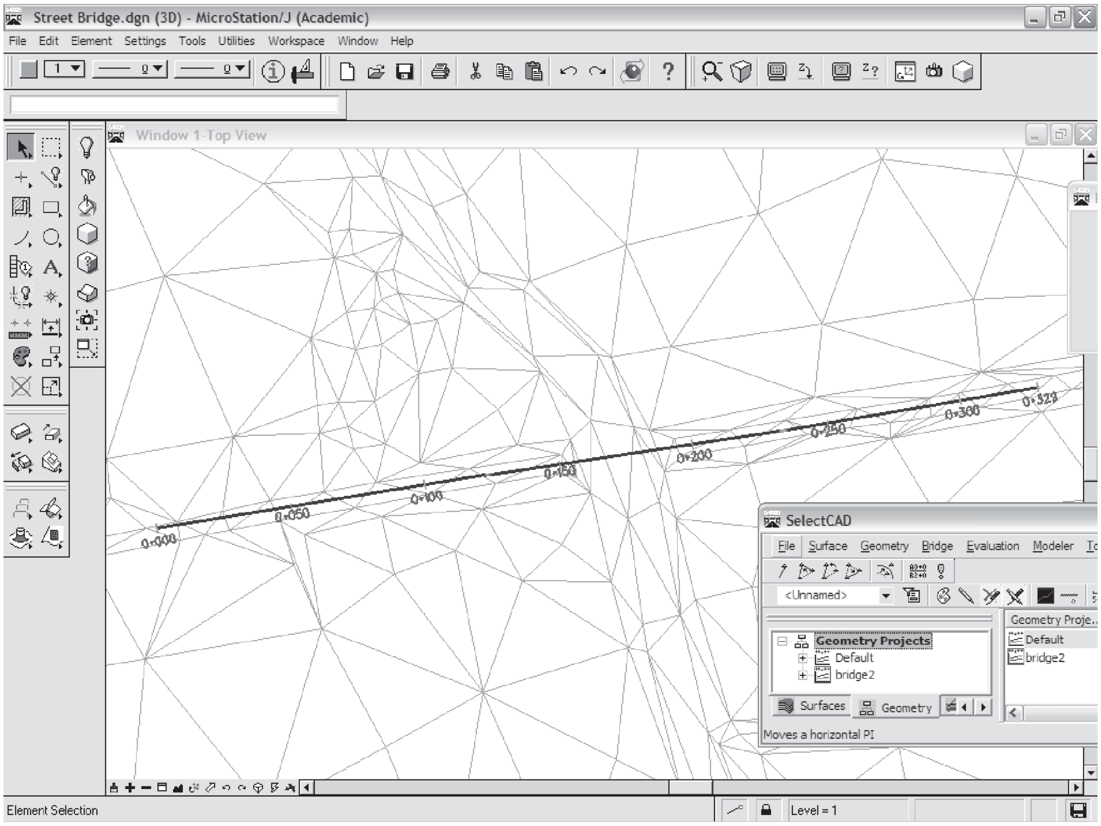

FIGURE 4 Bridge location on roadway alignment through use of Bentley software (*27*).

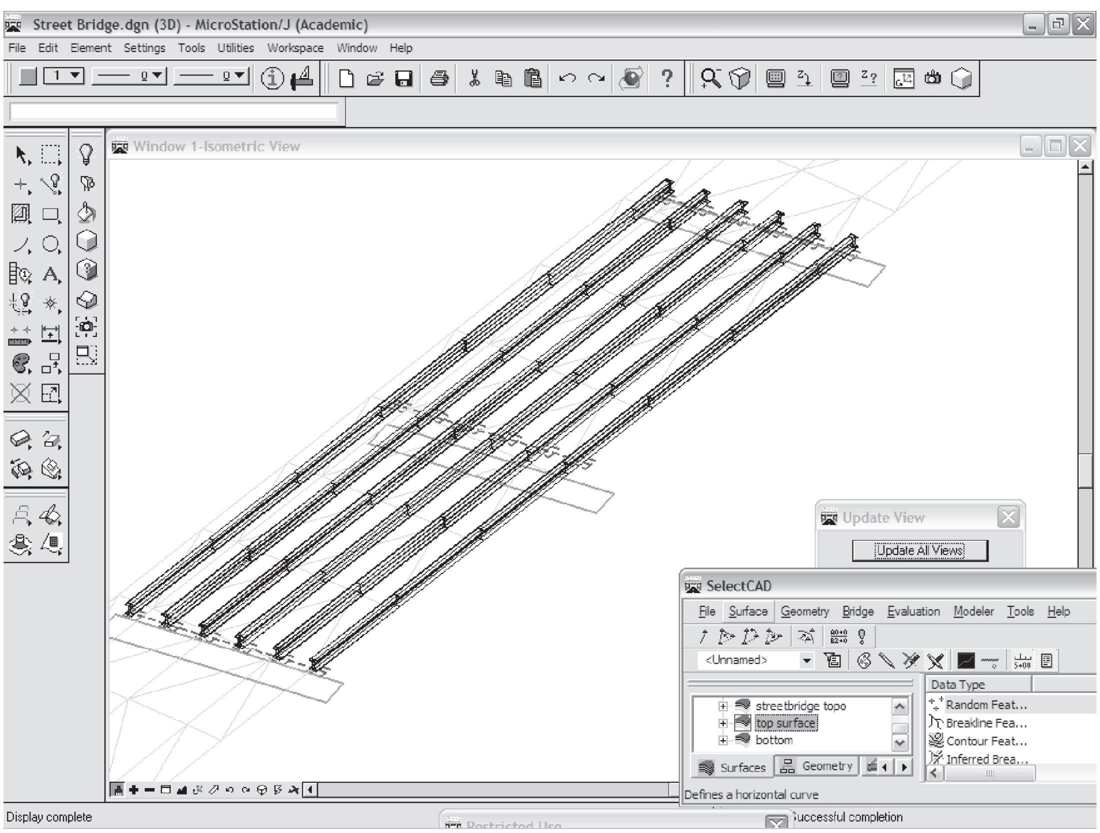

FIGURE 5 A 3-D model of steel bridge framing by means of Bentley software (*27*).

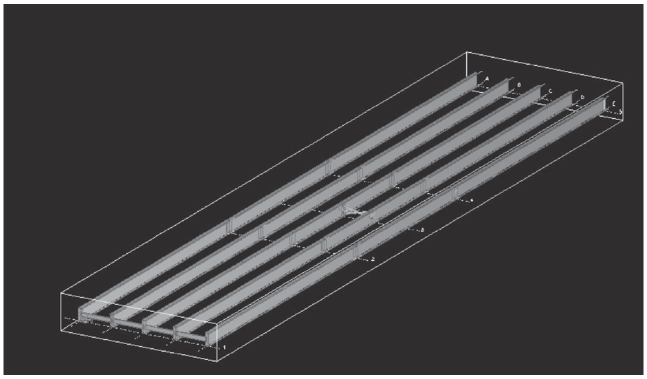

FIGURE 6 A 3-D model under construction in detailing software (*23*).

Features of such 3-D modeling and detailing software typically include the following:

- Useful modeling tools, such as 3-D grids, adjustable work area, and interference checking;
- A catalog of available material grades, profiles, and connection-detailing utilities down to individual stirrup bends and bolts;
- Macros to assemble complex connections, subassemblies, and entire structures, such as trusses;
- Intelligent connections, such as end plates and clip angles, to automatically connect main members;
- Rebar detailing and material report generation;
- Links to transfer data to and from other software used for analysis, design, shop material management, and project scheduling and deliveries; and
- Drawing wizards to create drawings quickly and export data needed to drive CNC fabricating machines.

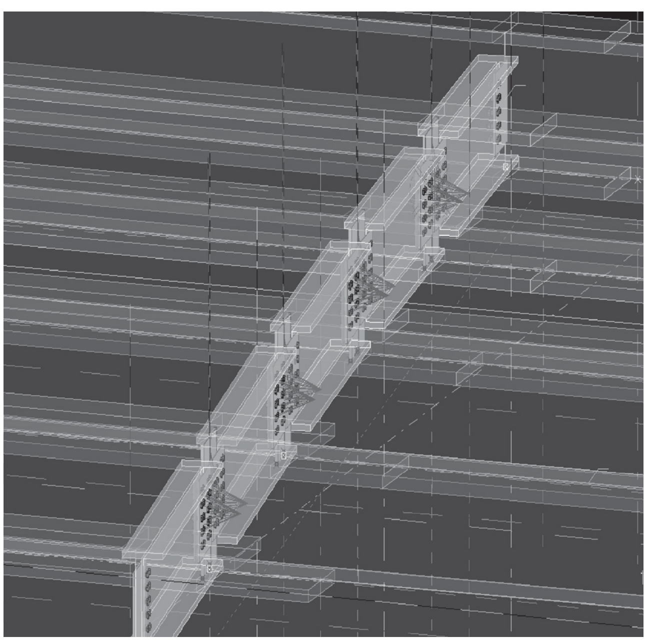

FIGURE 7 Diaphragm placement in 3-D model through use of Tekla software (*23*).

Steel detailing is not the only kind of detailing supported; reinforced concrete detailing can be supported as well. For example, Figures 8 and 9 illustrate pier and deck rebar detailing, respectively. Table 2 tallies a detailed estimate based on unit cost in which the quantities are all extracted automatically from the 3-D model. Thus, the principal advantage of using a 3-D modeling approach stems from the reusability of the design data during tasks (e.g., material procurement, fabrication, etc.) that occur downstream from the initial design.

Manufacturing support software already provides the following kinds of capabilities to support streamlined operations:

- Centralized project details;
- Basic task management, such as estimating, preparing advanced bills of material, purchase ordering, checking out materials, and stock keeping;
- Change order tracking (for example, date change order arrived, date price was quoted, and date price was approved by general contractor);
- Communications log (for example, record of phone conversations with owner on a diaphragm clash issue);
- Two-way links to project scheduling software for generation or update of project schedules automatically;
- Integrated drawing viewer allowing e-redlining;
- CAD imports with revision control;
- Efficient material nestings, from both rolled steel and plate stock;
- Automated purchasing integrated with self-maintaining inventory;
- Production tracking (for example, complete shop floor time control for each process—drilling, handling, welding, blasting, and the like—to provide more refined estimation and cost control for future use); and
- Automated shipping (for example, autogenerated shipping labels for site receipt and verification).

ENVISIONED PAYOFFS

Engineers in related industries have reported the following kinds of productivity gains:

- Effective visualization of design alternatives that permit a broader exploration of design alternatives early on;

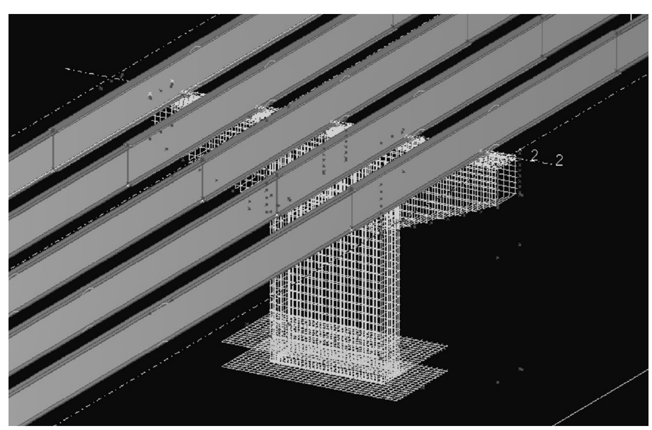

FIGURE 8 Pier detailing in 3-D model through use of Tekla Structures software (*23*).

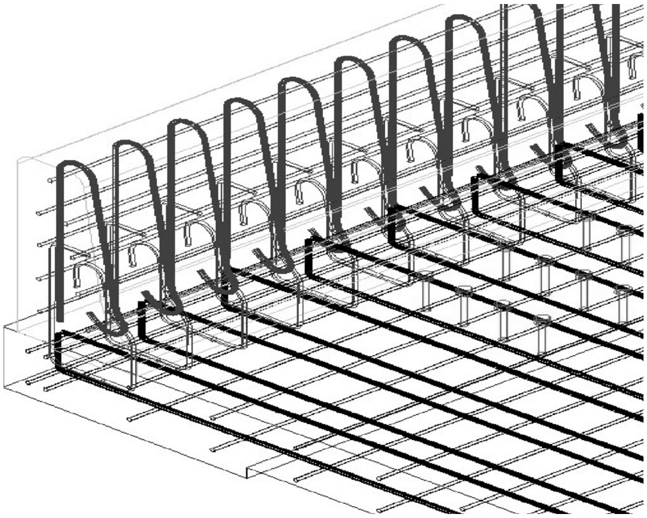

FIGURE 9 Deck detailing in 3-D model by means of Bentley MicroStation TriForma software (*27*).

- Automatic drawing production—drawings are simply reports extracted from the model [for example, 50 drawings at 2 days per drawing versus one model at 12 days (100 days versus 12 days) with drawings automatically extracted from the model (*28*)];
- Automatic quantity (bills of material) generation, which leads to quicker estimates;
- Automatically updated design changes (into other drawing sheets, sections, elevations, and details);
- Bridging of gaps between analysis, design, and production of construction documentation;
- Reduced need for fabrication drawings;
- 2.5% to 15% reduction in construction costs and 10% to 15% reduction in project schedule, a significant portion of which comes from reduction in field rework (*1–4*).

GLIMPSE OF THE FUTURE

Although many individual pieces of the envisioned workflow described above are possible today with available software, there are still several key missing links. The principal one is an industry standard bridge data modeling language that is sufficiently robust to support interoperability of bridge information for the entire bridge life cycle. The authors believe that to leverage maximum benefit from 3-D parametric BIM as it evolves throughout the bridge's life cycle, starting from design, the following steps will be needed:

- The industry must endorse the extension of transXML (or development of bridgeXML) to support more comprehensive bridge data modeling in all aspects of the bridge life cycle; development of such a language will likely require forceful leadership by an agency strong enough to ensure broad stakeholder participation in a cause that is not guaranteed ahead of time to be win–win situation for all.
- Bridge owners need to conceive of themselves as owners–stewards of the bridge data as they evolve, not just as owners–stewards of the constructed bridge itself.
- A suite of projects should be run modelcentrically in parallel with conventional 2-D approaches for producing design documentation and construction documents, through use of an incremental phased approach to build a track record by which to document practices needed to attain better, faster, more economical bridge delivery on the basis of BIM methodologies.
- Model management quality control–quality assurance from the earliest stages is needed to support the information needs of downstream stakeholders (i.e., a genuine teamwork-based culture). Thus, model information must be sufficiently accurate not only to bid from but also to build from.

XML has recently emerged as a new standard for data representation and exchange on the Internet. Leading software developers are committed to XML and are quickly moving toward using XML internally as well as creating XML-oriented tools and products. Because XML provides a standard syntax for representing data, it is perceived to be a key enabling technology for the digital exchange of information on the World Wide Web. Design, construction, operation, and maintenance of steel and concrete bridges have unique data transfer needs; thus, there is a need for initiating XML schema development efforts to support integrated design and construction of these bridges. With such schemas, independent stakeholders agree to use a common language (vocabulary) for interchanging data.

Even before XML schemas are implemented, however, it is desirable to develop an implementation-independent description of the domain. The unified modeling language (UML) is emerging as the most popular representation scheme in standards development projects. Thus, before XML implementation, a series of UML diagrams would need to be developed to define the syntax (terminology), semantics (meaning), and constraints of a stylized bridge design, construction, operation, and maintenance vocabulary.

It is therefore desirable to develop bridgeUML diagrams and corresponding bridgeXML schemas along with demonstration examples to support web-friendly electronic data exchange for interoperability throughout the processes of designing, constructing, erecting, and operating a steel or concrete bridge structure. This effort would be an attempt to integrate the entire bridge life cycle around the notion of a single, central 3-D bridge data "warehouse" that is accessible (with suitable permission levels) to each of the stakeholders involved in the processes of designing, constructing, and operating a bridge. The stages involved would need to include not only design and fabrication but also change tracking, inspection tracking, virtual assembly, construction, as-built documentation, and records management (*29*).

IMPLICATIONS FOR PRACTICE

To bring about the advancements needed to move the bridge industry to accelerated delivery without increasing cost or sacrificing quality, it would appear that at least the following developments must take place:

- A complete modeling of bridge information in a standardized 3-D digital format with accompanying commercial-strength bridge-friendly parametric software that is 3-D capable;
- Increasing use and acceptance of the design–build (D-B) mode of project delivery or at least the removal of disincentives to electronic information exchange that are inherent in conventional design–bid–build (D-B-B) project delivery; and
- A rethinking and resulting redefinition of the roles of the respective stakeholders involved in bridge delivery in accordance with the above two developments.

TABLE 2 Material Takeoff (Extracted Entirely from Model) and Estimate

Family	Component	Description	Weight Unit	Weight (mass)	Quantity	Unit	Unit Price	Total
Deck	28 MPa deck concrete N	28 MPa concrete for NB bridge deck	kg	499.4	207.75	m^3	$260.00	$54,015.00
Deck	28 MPa deck concrete S	28 MPa concrete for SB bridge deck	kg	499.4	207.75	m^3	$260.00	$54,015.00
Deck	Lat rebar N	Transverse rebar for NB bridge deck	kg	8,330.4	8,330.4	kg	$1.50	$12,495.60
Deck	Lat rebar S	Transverse rebar for SB bridge deck	kg	8,247.4	8,247.4	kg	$1.50	$12,371.10
Deck	Lon rebar N	Longitudinal rebar for NB bridge deck	kg	8,249	8,249	kg	$1.50	$12,373.50
Deck	Lon rebar S	Longitudinal rebar for SB bridge deck	kg	8,234.4	8,234.4	kg	$1.50	$12,351.60
Deck	Shear studs N	Shear studs for NB composite deck	kg	4,608	5,760	pc	$2.50	$14,400.00
Deck	Shear studs S	Shear studs for SB composite deck	kg	4,608	5,760	pc	$2.50	$14,400.00
Foundation	Concrete N	28 MPa concrete for north abutments	kg	411.5	171.16	m^3	$260.00	$44,501.60
Foundation	Concrete S	28 MPa concrete for south abutments	kg	406.8	169.2	m^3	$260.00	$43,992.00
Foundation	HP 250 × 85 N	HP piles for north abutments	kg	31,905	350	m	$130.00	$45,500.00
Foundation	HP 250 × 85 S	HP piles for south abutments	kg	31,905	350	m	$130.00	$45,500.00
Parapet	Lat rebar N	Transverse parapet rebar NB	kg	1,795.4	1,795.4	kg	$1.50	$2,693.10
Parapet	Lat rebar S	Transverse parapet rebar SB	kg	1,795.4	1,795.4	kg	$1.50	$2,693.10
Parapet	Lon rebar N	Longitudinal parapet rebar NB	kg	1,002.6	1,002.6	kg	$1.50	$1,503.90
Parapet	Lon rebar S	Longitudinal parapet rebar SB	kg	1,002.6	1,002.6	kg	$1.50	$1,503.90
Superstructure	HPS steel N	High-performance weathering steel for plate girders NB	kg	191,995.2	191,995.2	kg	$3.00	$575,985.60
Superstructure	HPS steel S	High-performance weathering steel for plate girders SB	kg	191,995.2	191,995.2	kg	$3.00	$575,985.60
						Total		$1,526,280.60

NB = northbound; SB = southbound.

• In addition, a collaborative, industrywide monitoring and shepherding of developments will be necessary, in line with the resolution recently passed at the 2005 annual meeting of the AASHTO Subcommittee on Bridges and Structures; the resolution concludes with these words:

> Be it Resolved: That the AASHTO Highway Subcommittee on Bridges and Structures acknowledges the importance of "Comprehensive Integrated Bridge Project Delivery through Automation" in achieving its goals. Further, Subcommittee affirms its leadership role by charging one of its existing Technical Committees or a separate Task Force to coordinate further development, refinement, and transfer of this technology in partnership with the FHWA. (*30*)

Each of these developments is discussed briefly (as are practitioner implications) in the following section.

Complete 3-D Parametric Modeling in Standardized Digital Format

Although the advantages of 3-D models versus 2-D drawings are clear (Table 1), for the industry to make full use of these models requires that issues involving methods of data presentation and exchange through the Internet or other electronic means be addressed. Such exchange requires development of major standards, for which common languages need to be used to be of ultimate benefit to all involved in using these technologies. The initial step in this direction will be to develop an implementation-independent description of the domain that defines the syntax, semantics, and constraints of a bridge design, construction, operation, and maintenance vocabulary. Design, construction, operation, and maintenance of steel and concrete bridges have unique data presentation and transfer needs; therefore, development efforts must be initiated to support integrated bridge design and construction. The emerging UML and the existing XML are now available to address expeditiously the needs of data presentation and digital exchange of information.

While all that may appear daunting, a smoothly running team can preemptively develop its own "bridge language" standard without having to wait for an entire industry to develop an industrywide standard. Competitive advantage is to be gained by the conversion of workflows to 3-D BIM approaches sooner rather than later.

D-B Mindset Versus D-B-B Adversarial Fragmentation

Who owns the model? is a question that often arises among individual stakeholders who hear for the first time about 3-D BIM concepts but are themselves still steeped in the current adversarial, fragmented way of doing business in the construction industry in general and the bridge industry in particular. This question is presumably asked partly from concern for liability (e.g., if errors in electronic data are carried forward into construction) and partly from the conventional understanding of drawings as instruments of service. The recently issued Appendix A, Digital Product Models, of the American Institute of Steel Construction's code of standard practice (31) addresses the second aspect of the issue in a common-sense way [i.e., that in the absence of ownership clauses to the contrary in the contract documents, information added to the model by the fabricator belongs to the fabricator (while information in the model provided by the designer is owned by the designer)]. Perhaps more to the point, however, is how D-B projects can remove some of the business process fragmentation. Here increased incentives for the streamlined process would result from sharing of electronic information among project stakeholders. It can be anticipated that savvy D-B teams will increasingly exploit these possibilities before D-B-B projects will.

Reshaping of Stakeholder Roles

In the envisioned 3-D BIM approach, the integrity of the model is paramount. As such, "it is imperative that an individual entity on the team be responsible for maintaining" the model so as (*a*) to ensure data integrity and security and to coordinate flow of information to all team members when information is added to the model and (*b*) to assure proper tracking and control of revisions (*31*). Whether this entity is the design engineer, the detailer, or a new "model manager" stakeholder, other stakeholders will likely have their own workflow affected. For example, dimensions cannot be fudged on drawings because the drawings, no longer work products in their own right, are now reports extracted directly from the central model, a model that will be employed, for example, to generate CNC data for use in fabrication operations. Thus, the dimension needs to be sufficiently accurate not only to bid from but also to build from. The implications of this brave new world for each stakeholder are still to be understood fully. Business model and best practices implications will need to be hammered out in relation to both steel (e.g., *32*) and concrete (e.g., *33*).

SUMMARY

This paper envisions a future for the accelerated delivery of bridges on the basis of the following notions:

- A comprehensive informationcentric approach to the planning, design, construction, operation, and maintenance of bridges through a single, coordinated shepherding of bridge information that serves multiple purposes as it evolves and
- A coordinated leveraging of design information into downstream operations: 3-D visualization; detailing; "shop drawing" production and review; "erection drawing" production and review; CNC-driven fabrication, construction, operation, and maintenance; asset management; health monitoring, condition assessment, and the like.

The need is articulated for further bridge industry effort to generate a uniform language for electronic communication of bridge lifecycle information so as to shepherd such a vision into reality. To transfer the results fully to highway practice, the following elements are needed: commercial-strength bridge-friendly parametric software that is 3-D capable, bridge owners friendly to and supportive of streamlined business practices, and stakeholders migrating toward 3-D BIM-based collaborative ways of doing business.

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