Building Information Modeling for Constructing the Past and Its Future

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This article shares findings on the projected use of software tools such as BIM as they apply to planning and construction for preservation practice.

This article originated as a paper at the "Capturing the Past for Future Use" symposium held in Los Angeles on Nov. 2-3, 2009, as part of the APT annual conference.

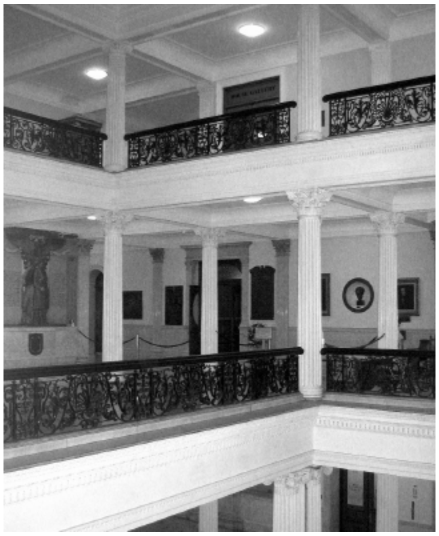

Fig. 1. Photograph of typical circulation space in the Massachusetts State House (Brigham addition, completed c. 1895), 2009.

While we observe and perceive the world and its structures with our senses, documenting such observations in words, images, and other forms of data requires the presence of a recording medium or technology. Whether the technology used is a computer, a laser, or a cloth tape,[1] such tools mediate and measure the physical world into a representation. Since the Enlightenment, there has been an acknowledgment that any single representation of the built environment is inherently partial, since "there is always a residuum of reality left out" of each description.[2] This partiality is the foundation of conventional practice both in drawn depictions and also in written reports documenting historic structures; the descriptive analyses are carefully chosen to be representative encapsulations of the actual reality in a way that communicates to future generations.[3] Yet, the power of systems of measure for recording is their ability to be generalized and universal: to enable new deductions to be made from recorded data.[4] Since the task of architectural documentation is not simply to make unchangeably static pronouncements but rather to create new representations that can be used authoritatively along with past and future scholarship, it is a logical extension of our technologies to use them to encapsulate and unify an ever-widening scope of partial representations. This paper examines a particular architectural technology — building information modeling (BIM) — and how its use in practice engages with these issues of representation and completeness.

Introduction and Overview of Projects

At EYP/Architecture and Engineering in Boston, the majority of the technical staff in architecture has worked on projects incorporating BIM for four or more years; BIM is currently used for seven engineering disciplines within the firm,[5] in coordination with architectural modeling. In this paper two recent projects in New England will be used primarily to discuss the use of BIM in architectural applications for preservation work. One example is an existing-conditions model of the Massachusetts State House in Boston created while completing the master plan for all interior spaces within the 600,000-square-foot building. The complexity of the building — it has five major eras of construction starting with Charles Bulfinch (1795-1798), plus subsequent additions (c. 1842, 1895, 1917, and 1986), and more than 40 interior levels inside an eight-story envelope — motivated the state agencies involved, led by the Massachusetts Division of Capital Asset Management, to request a BIM tool for managing ongoing interior changes, both for offices and major spaces of historic significance. The master plan was developed between 2006 to 2008, and a more detailed BIM file was completed in early 2009 (Figs. 1 and 2).

The second major project is the rehabilitation and expansion of James Hall at the University of New Hampshire. Constructed in 1929 and sited on the main historic quad of the campus, this 55,000-square-foot building was designed by campus architect Eric Huddleston and has housed the Earth Science and Natural Resources programs since 1970. The scope of work included a full renovation of laboratory and classroom areas, rehabilitation of the ornamental public stair and associated interior masonry, complete exterior-envelope improvements, window replacement throughout, and two additions totaling 18,000 gross square feet.

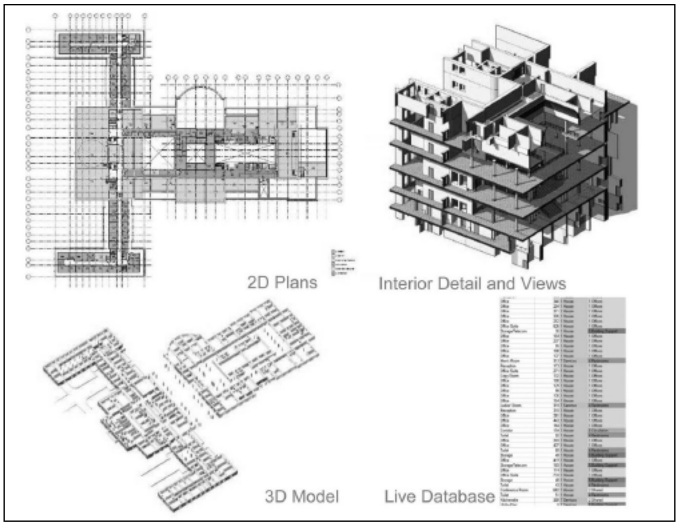

Fig. 2. Interrelated aspects of BIM, Massachusetts State House documentation, 2009.

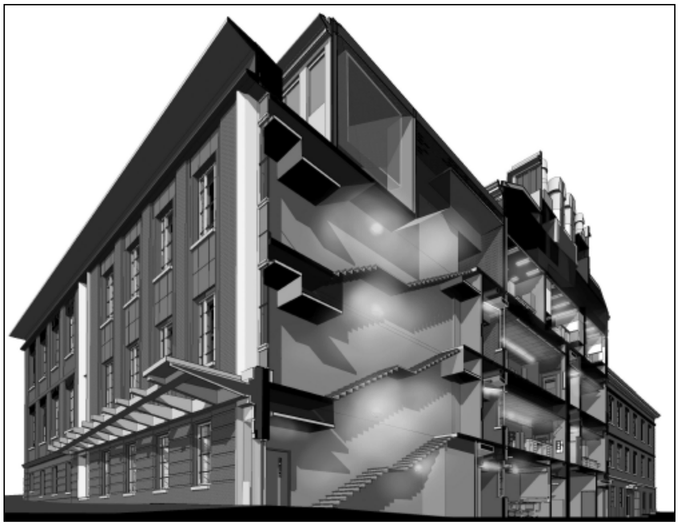

Fig. 3. James Hall, University of New Hampshire, BIM file, 2008. Overall section perspective developed for presentation, showing new addition at left, existing building rehabilitated and modified at right and beyond.

This project used BIM from conceptual design in 2006 through laboratory planning and construction documents in 2008; construction was substantially completed by December 2009 (Figs. 3 through 5).

BIM Primer

Building information modeling, or BIM, is a process in which software is used to create a single virtual model of the geometry of a building that is a visual representation of an intrinsic database containing information about construction materials and assemblies, as well as spaces and areas within the building. This single central file, generally referred to as "the model," can be worked on simultaneously by multiple users, and the geometry of the model is constantly updated within all plans, sections, elevations, and 3-D vignettes. Moving a wall in plan, for example, ripples through other orthogonal and perspectival views, and the effects of the alteration on the area and other properties of the room will automatically be updated within the schedules and data contained within the model (Fig. 2).

BIM tools (including Revit and other software packages[6]) are a subset of parametric software in that they use dimensional and/or mathematical variables called "parameters" for a variety of purposes and properties, from the numbering of rooms to the spacing of mullions. There are many other types of parametric software used for deriving forms of complex curved surfaces or patterns, but the key differentiation of BIM is the "I"; in BIM each wall, door, window, and even each fixture carries with it latent information about its properties, location, extent, and identification.

Therefore, the processes of documenting existing conditions and creating a new design in BIM consists of placing walls, floors, and other constructed elements on spatial "levels." These levels not only mark floor heights but also contain, or "host," the spatial data about rooms, furnishings, and any other user-defined aspects within the building. Each of these levels has plans showing building elements as 2-D "slices" of the model, and the final details of the construction that has been modeled are often drawn as 2-D "drafting" overlays and notes within enlarged details. In practice, the layer of brick thickness is modeled in a new wall, but the individual ties and joints are drafted only at a scale to see that level of detail. This is an important bifurcation that illuminates how BIM is more than 3-D drafting: it must have a consistent level of detail that is aligned with the purposes and intents of how the model is to be used. A BIM file created for visualization and planning or even for construction will not need every typical detail (such as a brick tie) modeled; however, for a BIM file to be used for material estimating and construction planning, it will need substantially more internal content added than would typically be drawn in conventional drafting.

This differentiation connects to how BIM has the potential to be powerful specifically for interventions on historic buildings. The model can communicate not just the form of the historic fabric being documented; it can also include data relating to identification and inventory. BIM can also use its tools of phasing to represent multiple points in the history and transformation of the building over time. Rehabilitation and other complex tasks require that the model reflect not only existing conditions that will remain in place but also reflect the physical implications of demolition, repair, and other activities. BIM uses phasing to describe the sequence of work and at what stage elements are to be removed, added, or changed. However, this feature also presents methodological challenges:

- To what extent shall the existing conditions be investigated and modeled to enable this visualization and documentation?
- To what extent should existing conditions be modeled in order to communicate how they should be preserved or modified during the project?

Tools and Applications

Data. All architectural documentation is communicative in that its content serves not as an end product — a creative work of digital or printed art — but rather a means by which to record observed conditions and to communicate intentions for the built environment. But the instructional qualities of documentation are magnified in preservation work, given the information contained in reports and embodied in the building itself. The management of data for historic fabric can be a paramount task, whether for individual projects or for large institutional clients with protocols guiding accounting of spaces and elements across multiple buildings.[7]

One primary application of BIM to preservation practice is to manage and manipulate data. The model can associate data with elements, rooms, and so forth in a way that remains continuously updated as modifications are made for new design or to record as-built conditions. Furthermore, the user can query the model for the embedded data, thus deriving schedules and customized views of the data. These views can be, for example, tables of information or plans colored according to certain data parameters, all automatically updating as changes are made in plans, schedules, or other views.

This functionality was a primary motivation for the use of BIM on the Massachusetts State House, since BIM enables the unification of the textual and numerical documentation with graphical representation. For example, it served as a tool for generating plans for each space and also housed all the data of areas and totals within each type of space, use, or element documented. The model completed during the master-planning process can be enriched by this data and archived as a snapshot in time, but its use does not end there. Once the model is defined as a contractual deliverable and the client has a commitment to comprehending, using, and updating the model, it can serve not as a passive record for consultant reference but as an active tool for client use. The client is already using the data in this model to understand which spaces have which historic features, to document office changes, and to communicate data about preservation assessments for new projects, such as fire-alarm replacement.

This data function is useful at a more architectural scale in the tracking of typical elements, such as windows. Windows are of particular interest due to the range of actions associated with them. On the University of New Hampshire project, some steel windows had been replaced with new units; others had been refinished and repainted in place (Figs. 3 through 5) or replaced with enlarged openings to enable mechanical systems and hallways to cross between the existing building and the primary addition. The simple result of such documentation is obviously a window schedule, but BIM enables users to assign information such that there is a direct correspondence between the data tags for windows shown on drawings, such as demolition and construction elevations, and the data for windows as scheduled. In order for that range of tasks to be captured in the model clearly (demolition, replacement, refinishing), each window "object" must be imbued with the data needed throughout the process. The modeling team should ask: Who will use this? What do consultants need to extract live information from specific assemblies, and in what format? In the cases discussed here, BIM data was used for drawing production and for 3-D visualization based on mullion extrusion profiles to evaluate the compatibility of new aluminum frames and mullion types with existing steel window frames, but BIM was not used for fabrication. Had this same granularity of data been incorporated for existing, demolished, and new construction elements, the data could have informed cost estimating and even some fabrication, as is becoming possible with structural steel for new construction. Although BIM will not become the tool used to fabricate directly, improvements in interoperability will enable its data to be used within fabrication tools and technologies being used by subcontractors. More contractors are now using BIM data to check takeoff areas and extract views for estimating in early phases.

Fig. 4. Detail of Figure 3, showing (left to right) section through new corridor, laboratories, original corridor with yellow glazed brick, other spaces within, and original red brick exterior wall with steel windows, 2008.

Geometry. There is a second major component of the BIM process particular to preservation practice: the description of geometry and conditions is increasingly inseparable from assertions in that same model about future changes shown on the construction documents. 3-D geometry is nothing new to preservation documentation; historically, the documentation of existing conditions has been a task that is fundamentally separate from proposed work. This separation assumes that evaluations of significance should be based upon the extant historic material itself, rather than upon designs or motives that seek to alter or add to fabric. Furthermore, the composition of geometric views, as in an analytique or a multiview conditions survey or construction document, has been for decades free to have each view be independently articulated rather than interdependent upon electronic models. In BIM, however, the manner in which the existing conditions are constructed — how its constituent elements are demarcated and interrelated — determines the types of actions or changes that can be modeled for design and construction phases. For example, if only one wythe of a thick brick wall needs to be removed or demolished, it will need to be modeled and identified separately from adjacent wythes.

Using BIM for preservation documentation thus requires a level of judgment beyond its use for other construction tasks. In BIM files for freestanding new construction, the task of geometric

Fig. 5. James Hall, University of New Hampshire, 2009. The steel windows from the original exterior envelope were refinished within the newly enclosed circulation area in the addition, offering views from the corridor to the laboratories in the existing building.

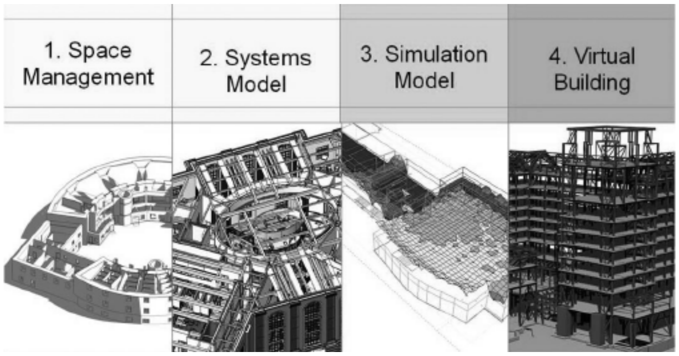

Fig. 6. Levels of BIM in practice at EYP, 2009. The Massachusetts State House BIM file would be a level 1 in this categorization, while the James Hall BIM file would include additional detail found in level 2. Levels 3 and 4 require the input and collaboration of product manufacturers, contractors, and subcontractors to provide integrated simulations for energy and other criteria (3) and to be used comprehensively in construction (4).

definition consists of forming a model of the intended result when construction is completed. Using BIM for renovation or fit-out projects requires an accurate model of the shell and structure distinct from new work but rarely requires full modeling of existing and/or historic features. BIM for preservation, however, is not nearly as silent about proposed alterations; how the team defines geometries within the model is evidence of deliberate choice and intentions for future change. In modeling the State House interior, the initial BIM tracked the overall shape of the exterior but not its details, since the exterior restoration was already completed and documented in 2-D formats at a high level of detail. The client intends to develop the initial BIM model with additional detail as investigation and preservation work proceeds in the future, and they have begun initial laser scanning on some rooms for that purpose. Furthermore, those historic spaces envisioned to be changed the least, such as public spaces with highly complex ceilings that needed more schematic modeling, can have scanning deferred. In contrast, the vast office spaces, which are constantly being modified and repaired, required relatively intense model documentation of the old and new walls which were deduced from hand measurements,[8] since even a laser scan would not be well-suited to capture the network of small rooms divided irregularly through multiple changes over the past century.[9]

At EYP, modeling complex buildings has been a firm-wide learning process throughout which continual dialogue with clients regarding the intended uses of the model has been key. Verbal and/or written frameworks for documentation, known as BIM Execution Plans,[10] exist in several formats which clients and consultants can use to discuss the scope of modeling and documentation. These plans can serve as vehicles for user input and feedback, refined throughout the process. The plans, however, generally require visual examples shared between clients and consultants to show how a category to be modeled — doors, for example — relates to the needs and expectations of a given project. For instance, at some phases the geometry of a door surround may be of high importance (e.g., for verifying existing clearances related to accessibility), but the geometry of the door leaf may not need detailed modeling for visualizing its panels, knobs, and so forth for the client. BIM can enable users to insert textual information, such as notes about features within data fields for the door or other objects, so that features can be inventoried and shown in the model file or exported to a spreadsheet for future use outside of BIM. In a building like the State House, where the model contained more than 1,400 doors, the dovetailing of geometry and data is powerful and valuable, once it is clear which data is represented in the physical geometry of the model (height, width, type of swing) and which data is represented in note fields attached to the doors (materials, notable stylistic features). Since there will always be more detail that could be modeled, it is crucial to develop the model to the extent that it is a useful record of what should be modeled.

Typical sources of geometric excess — those that are slow to compute in visualizations and can require a disproportionately significant amount of time to model — include stair railings and other repeated elements. If a railing is only to be documented and shown in a typical enlarged detail, it may not be realistic to replicate this around all levels of a model when interior renderings are not a major output. While stairs in BIM for new construction offer great potential for parametric invention and ways of modeling intelligent design strategies that adapt their constraints (code parameters of risers) to variable conditions (floor-to-floor heights), historic stairs and railings are difficult to fully model due to their variation from the current norms that underlie the logic in “smart” BIM stairs. EYP has found in preservation projects such as James Hall, where the historic stair remains for convenience rather than egress, that if the geometry of risers are well modeled — with their height and extent shown accurately in plan and section — then their ornamental railings can be a hybrid of drafting overlaid upon the stairs. The railing at James Hall was being partially dismantled, cleaned, and re-welded with in-kind stock to increase its height for safety and being reinstalled; such actions for an irregularly twisting rail would require advanced computational detail, yet could be accommodated in a few simple 2-D details and a relatively conventional shop-drawing process. A fully modeled railing in a BIM file would not have been of use to the fabricator in the shop and field. If the hybrid of drafting and modeling communicated the intent well and if further detail were required for visualization of a portion of the stair, it would have been possible with the BIM file as well.

Moreover, the questions of geometric definition at finer-grained scales become ones of parametric geometry. Does one model a continuous, solid cast-stone balustrade as a railing (an element that is extruded in space linearly) or as a portion of a wall (an element based upon vertical planes of construction), if both tools can produce similar results in a 2-D view? More generally, if one is no longer simply drawing typical profiles but extruding each cornice along a wall, there is a question of how to select the geometric tool (and its accompanying neologism) within the software to represent a conventional construction element: cornice mouldings become "wall-hosted swept profiles," while quoins that protrude from the face of a wall at a consistent distance may be examples of "face-based parametric repeating families." Given enough effort early on in modeling, the geometric tools that have been developed largely to describe the complex geometries of new construction are nonetheless sufficiently malleable to serve well in the modeling of historic architectural details.

Layers. This leads to the issue of layers. Beyond the data of a wall (its alphanumeric type) or the geometry of its shape, each wall can be defined not only as a wall type of a typical thickness but also as a 3-D assembly of layers with various properties assigned. The team should consider the following questions: Which walls are structural and nonstructural? Which layers are insulating? How many wythes of brick are present? Do exterior layers return at openings? These are questions distinct from the computer-aided drawing programs that use layers to organize drawing files (as groups of lines, shapes, and filled regions) and are often also subtly distinct from building envelope layers (as in WUFI thermal analyses[11]), since BIM uses layers in walls and floors to describe their complex intersections. But in preservation work the composition of layers has two added wrinkles. First, the geometry of existing historic buildings is often more complex than layered assemblies indicate: corbelling, coursing, and quoining with cut brick that are relatively easy to build physically on a construction site are often highly specific and time-consuming to model in a manner where every sectional slice conveys the coursing or internal construction. Second, the geometry of how those walls join each other three-dimensionally requires extensive modeling and survey work not only in the pre-design stages but also throughout the design and construction-document process. If a wythe is to be removed or altered as part of the proposed work, the modeling of the existing wall needs to reflect this.

The certainty and precision of the model are only as powerful as the knowledge and accuracy that went into creating it. The model is a tool for documenting and visualizing observed and inferred information, but the model is not a source from which to extract field conditions. Uncovering existing conditions and other past modifications to the envelope and structure require nimbleness, as always. The modeling process helps to make all views and drawings of geometry internally consistent and precise but not always accurate to what is extant once demolition and construction begin. The level of accuracy and consistency in the actual building generally serves as a metric for the appropriate level of detail in its BIM description, and aligning the two is a task of professional judgment rather than of software proficiency. It is not accidental that it is termed a building information model, not an architectural knowledge model.

Form. Beyond the primary usefulness of information-rich modeling techniques, there are a few extended applications. First, many of the computational advances of contemporary forms in the complex geometries and mathematical patterning of new architecture can be translated into BIM applications relating to preservation and rehabilitation. These tools within software packages, including BIM applications, are fundamental to describing complex geometries, as well as the logic that governs how a practitioner models shapes that are more complex than a simple solid of extrusion or of revolution. These same tools and processes can be used within the design process for projects where new construction is a component of rehabilitation; the same geometric processes or relationships used to create the model of existing forms can be used with different profiles to design and fabricate forms that dovetail in some ways with complex existing geometry, complementing the existing fabric, particularly where a complex curvature occurs in vaulting or other systems.[12] The parametric tools of BIM can be used to document existing structures and understand the relationships of materials that guide their design geometry and can enable the same tools and relationships to inform choices about new construction that is sympathetic yet differentiated from existing material. At a very simple level in a planar example, window-mullion proportions can be represented parametrically. Since BIM utilizes relationships between elements, one would model window mullions in a collection of historic windows using the logic of spacing — what dimensions are constant and which mullion extents vary or are repeated for different opening sizes — and these data can offer ways to create variations on new mullion patterns for new windows.

Regardless of which forms can be achieved visually or technically in BIM — from the scale of a mullion to the scale of a vault — the essence of BIM is that it is not merely a collection of forms. Laser scans[13] can reproduce only the visible geometric boundaries of a room, facade, or surface and require labor-intensive conversion into individual walls, cornices, windows, and so forth, often by first interpreting the 3-D scan into 2-D views.[14] Furthermore, those computational surveys do not mean that the model will automatically include the depths or construction information contained within the solid mass of the building. Point-cloud surveys, 2-D interpretation, or 3-D surface forms can be highly detailed, but if they are just forms that do not contain data about how their geometry is determined, they are thus mute, unable to offer users information (numerical data or relative dimensional relationships) within the model. BIM does not know intrinsically how a wall becomes a vaulted ceiling or how the latter becomes applied ornamentation. BIM cannot represent an infinitely thin surface; it requires the model to have elements with thickness and therefore volume and thus requires users to represent their knowledge of a building's substance rather than merely report the appearance of its exterior. As more young practitioners and students fluent with modeling software navigate the practical connections between parametrically defined forms and realities of construction, their skills in geometry and modeling can be readily adapted to the geometric and computational fluency for preservation efforts using BIM and other tools. They may find that some of the most challenging geometric situations are those to be found in existing buildings, where robust parametric definitions can aid the documentation process.

Sequencing. As clients' abilities to finance projects in a single phase has diminished in recent years, there is increasing potential of using BIM's capacity of phasing data to enable the visualization and tracking of changes over multiple complex phases. Past EYP preservation projects such as Harvard's Widener Library involved more than a dozen phases to maintain continuous operation, and BIM software includes capacities for the model to be a prototype for the ongoing transformation of each phase. In this regard BIM is what John Tobin of EYP has termed a proto-building,[15] whereby the representation of the architecture is only one of many roles: the file must also document the building process virtually. Yet this use requires careful creation of phases of rehabilitation. For example, a typical BIM window or door at the UNH project must be in a wall to exist, but if the door is demolished or removed, the wall tends to fill in with identical brick veneer, which is precisely the opposite of physical reality and contradicts the preservation intention about differentiating old and new work where openings are filled, as well as the documentation of changes; the sequencing and modeling must not only look correct but be carefully crafted so as to present both the technical and visual results accurately at each phase. One must therefore model the existing conditions — the opening and its surrounding structure as separate from the frame and glass — in order to enable detailed phasing and sequencing. The sequencing of construction activities, however, generally requires a far finer level of separation to represent the work separated by material or by trade, and the use of the BIM for these tasks is best determined on a project-specific basis where models are exchanged with (or transferred to) BIM-enabled construction professionals.

Collaboration. It is a mantra of BIM software users and industry advocates alike that BIM software enables (and/or requires) collaboration. Much of its power as a tool is that it enables the entire team to work simultaneously in the same file, including the engineering, when systems are modeled. This power extends only as far as the model is "complete," which is both its benefit to preservation projects requiring close coordination and also its challenge for preservation projects where the model is inevitably somewhat abstracted from field conditions in some way. The commitment to a single platform from design-team members and consultants and collaboration potentially from the client and/or contractor, along with file-version management and file-size issues, complicate this.[16] Hence, the appearance of completeness of a model belies an iterative process. It is worth noting that while various modeling protocols are in discussion within the industry, notably by the General Services Administration and other public-sector entities that advocate BIM, there is no single national or international BIM standard, so at this time there do not yet exist well-established guidelines for when a model is complete or ready for collaboration.[17]

Conclusions

This situation leads to two conclusions. First, it is important to show what is meant, and for what purpose. Simply modeling the location of elements does not embody the full intent of an assertion about what a condition, location, or material should be or should not be changed to. The ability to "slice" a model to understand more conditions three-dimensionally than an existing-drawing set would allow is a powerful result of any detailed recording,[18] yet doing so within the framework of BIM also enables the model potentially to imply rather than to state, to be misread or misconstrued. There is nothing like a clear description: a word is worth a thousand screenshots to state purpose. Consultants and collaborators must recognize that the model inherently embodies implied purposes of use that may or may not be congruent with their purposes. At UNH, modeling existing and new steel for spatial coordination versus modeling steel for connections, for grounding continuity, or for other analytical purposes are very distinct.

Over the years BIM software has trended toward "Swiss Army knife" status, being used for multiple purposes, from surveying to specification coordination to rendering, but that approach has moved from that apogee toward some decentralization. The tendency towards centralization of building geometry and identification of rooms within BIM should never preclude the use of other, parallel software for more focused purposes, such as conceptual visualization (SketchUp) or energy modeling (EnergyPlus). The unification of documentation in a single electronic model links informational data with graphical representation, and it enables the model to be a resilient tool; BIM may become a powerful way to unify comprehensive historical documentation with design and rehabilitation work.

Since the amount of information or intelligence that could be added to a BIM file is unlimited and since one can always discover more information to add from documenting an existing building, design teams and clients need to recognize ways to categorize BIM work so that the intelligence embedded in them is suitable for their intended purposes. In realizing that we create many types of BIM work for markedly different purposes, EYP has developed four "levels," or degrees, of BIM (Fig. 6). These levels range from computationally simple models (such as at the State House), used for relatively simple space organization, up to those that have models of multiple building systems or even those executed to a level of detail such that they can be used for direct fabrication and construction simulation (virtual building) in partnership with contractors and subcontractors. The levels of information and modeling required for each level are quite different, rather than merely additive. Thus, it is crucial in any project (but especially a preservation project) to formalize the level of BIM and the extent of modeling; "doing BIM" on a project is not a singular task or umbrella term, and it might continue to evolve with the industry. For example, while many innovations aimed at transforming the construction industry over past years have focused on the oft-challenging task of incorporating standardized IFC (Industry Foundation Class) data within BIM, the present realities of practice for preservation and new construction have shown that the simple ability to model and draft in the same BIM software outweighs other needs and desires.[19]

This leads to a second and final point: models require the ongoing questioning and refining by the team of how complete is "complete." There will always be more detail that can be added. Once a ceiling plan communicates each soffit plane, does each concealed piece of gypsum or plaster need to be modeled? Each panel in the door? Each moulding, dentil, or light switch? Even common construction elements, such as masonry transitions in three dimensions, remain a difficult and time-consuming challenge for existing and rehabilitated work: unless one models almost down to each brick, the model remains to some extent a sketch. Hence, developing the techniques to show surface profiles in the model (while retaining some details of their construction in drafted overlays) is improving this efficiency. The most transformative aspect of BIM for preservation work is that it corrals a host of potentially separate forms of data and assembles all the design documents and sheets, schedules, spreadsheets, references to photos, and other data into a single file. The ability to unify envelope models with building detailing is just one incarnation of this potential, but it heightens the importance of practitioners who can discern and pare down information in order to make collaboration focused. When preservation work evolves over long periods of time, the guide for BIM is to always use the reality of the information needed to guide eventual construction, rather than the assumptions of any particular software, as the metric for quality in methodology. While its specific uses in preservation will evolve, BIM represents a valuable way in which building-simulation technology unifies geometry and data to be mutually supportive of the goals and products of preservation practice.

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Notes

1. Edward Allen, *Stone Shelters* (Cambridge, Mass.: MIT Press, 1969), 191–192.

2. Dalibor Vesely, *Architecture in the Age of Divided Representation* (Cambridge, Mass.: MIT Press, 2004), 177.

3. For example, see also John Burns, *Recording Historic Structures*, 2nd ed. (New York: John Wiley and Sons, 2004).

4. Notable in the scholarship of measurement in recent years is Robert Tavernor, *Smoot's Ear: The Measure of Humanity* (New Haven: Yale University Press, 2007).

5. Current disciplines using Revit at EYP include structural engineering, mechanical (HVAC) engineering, electrical engineering, plumbing engineering, fire-protection engineering, telecommunications, and energy analysis and engineering.

6. Revit, owned and expanded by Autodesk since 2002, is a software package that is used widely in the U.S. and increasingly abroad; other BIM software includes products by Bentley (Architecture) and Graphisoft (ArchiCAD). Lachmi Khemlani, "Top Criteria for BIM Solutions: AECbytes Survey Results," Oct. 10, 2007, www.aecbytes.com/feature/2007/BIMSurveyReport.html, accessed July 5, 2010. Patrick Suermann, "Evaluating the Impact of Building Information Modeling (BIM) on Construction" (PhD dissertation, Univ. of Florida, 2009), http://etd.fcla.edu/UF/UFE0024253/suermann_p.pdf. Suermann states on p. 36, referring to Khemlani 2007: "Until this [2007] survey, there were no unbiased, widely disseminated studies showing which software platforms were preferred by BIM operators. An overwhelming majority of respondents, more than all the others combined, answered that they were using Autodesk's Revit software. This was also corroborated in the McGraw-Hill 2008 BIM Smart Market Report, which showed that 67% of its respondents also used Revit, making it the highest used platform by nearly a 2:1 ration compared to non Autodesk software applications."

7. See the article by Caroline Alderson et al. on page 11 of this issue.

8. This is an extension of the need for hand measuring with respect to earlier CAD methods in David Woodcock, "Discovery through Documentation: The Investigation of Historic and Cultural Resources," *APT Bulletin* 37, no. 1 (2006): 37–44.

9. See the article by Catherine Lavoie on page 19 of this issue.

10. As of this writing (2009-2010), current BIM Execution Plan (BEP) templates are being refined by teams led by Indiana University and Pennsylvania State University, while other institutional and public-sector clients are developing project-specific templates, and the National Institute of Building Sciences is working toward national BIM standards; see "Building Smart Alliance National BIM Standard," www.buildingsmartalliance.org/index.php/nbims/, accessed July 5, 2010.

11. Software for calculating the combined heat and moisture transfer in building enclosure components; for example see www.wufi-pro.com/.

12. At the scale of the form of a building rather than just the form of a detail, the relationships between forms and data can be used in the design of new structural elements — vaults, trusses, shells — found in historic structures whose physical form relates to their performance. A new textbook includes software that accomplishes just this for the design and analysis of historic-masonry structures and additions; see Edward Allen, Waclaw Zalewski, David Foxe, Jeff Anderson, et al., *Form and Forces: Designing Efficient, Expressive Structures* (New York: John Wiley and Sons, 2009).

13. See the article by Caroline Alderson et al. on page 11 of this issue.

14. See the article by Catherine Lavoie on page 19 of this issue.

15. John Tobin, "Proto-Building: To BIM is to Build," AECBytes.com (2008), www.aecbytes.com/buildingthefuture/2008/ProtoBuilding.html, accessed July 5, 2010.

16. Since the State House model was begun in 2006, there have been five subsequent versions of the software, and while files can be opened in later versions, those opened or saved in later versions cannot at present be opened in earlier versions of the software. See the article by Catherine Lavoie on page 19 of this issue.

17. See the article by Caroline Alderson et al. on page 11 of this issue.

18. See also discussion of measurement benefits in Bernard M. Feilden, *Conservation of Historic Buildings* (Oxford: Elsevier, 2003), 221–223.

19. Lachmi Khemlani: "Top Criteria for BIM Solutions: AECbytes Survey Results," Oct. 10, 2007, www.aecbytes.com/feature/2007/BIMSurveyReport.html, accessed July 5, 2010. "Full support for producing construction documents" ranks first amongst priorities of respondents in the industry, while "IFC compatibility" ranks 15th of the 19 listed priorities.