USE OF DESIGN DRIVERS, PROCESS MAPPING, & DSM TO IMPROVE INTEGRATION WITHIN AN INTRODUCTORY BIM COURSE

Lei Xu[1] and Cynthia C.Y. Tsao[2]

ABSTRACT

The Architecture-Engineering-Construction (AEC) industry recognizes Building Information Modeling (BIM) as an efficient means to develop and disseminate design information. However, if a project requires (1) tight coupling between systems and components because doing so generates value for the project and (2) interdependent engineering disciplines to work in parallel due to schedule requirements, the team may face difficulties when they re-integrate any work completed independently back into the main model. To address this problem, we propose combining the use of design drivers, process mapping, and Design Structure Matrices (DSM) to improve a project's ability to de-couple building components, enable concurrency in component development, and achieve seamless BIM integration within a parametric BIM environment. Specifically, these tools combined may help projects reveal and then reduce the number of design interdependencies between building components.

We developed and tested the proposed methodology using a civil engineering course that introduced undergraduate and graduate students to parametric BIM. We taught this course once a year for three years, and we refined the proposed methodology during the third year. Although the methodology is rudimentary and requires further study, we hope this paper will inspire other researchers to test this methodology within learning labs in academia and practice.

KEYWORDS

Parametric BIM, BIM Integration, Design Handoffs, Teaching BIM

INTRODUCTION

Due to increasing building performance demands, AEC projects have become increasingly complex as evidenced by the Construction Specifications Institute's (CSI) expansion of the MasterFormat from 16 to 50 divisions (Johnson 2004). In response, the AEC industry has become heavily fragmented (Ahmad et al. 1995). Researchers have been advocating integration as a means to manage project complexity (e.g., Baccarini 1996) and reduce AEC industry fragmentation (e.g., Howard et al. 1989). Thus, advancements in information technology, online collaboration tools, and social media have allowed AEC project teams to work better as virtual teams (Chinowsky and Goodman 1996) while being geographically dispersed (El-Tayeh and Gil 2007).

[1] Former Graduate Research & Teaching Assistant, Univ. of Cincinnati, CEE Dept., Phoenixville, PA, 19460, Phone +1 513/305-7168, xulei25@gmail.com

[2] Research Affiliate, Lean Construction Institute, Brookline, MA, 02445, Phone +1 510/593-4884, dr.tsao@leanconstruction.org

In this paper, we will describe a methodology for component integration within an introductory parametric BIM course. The methodology uses design drivers, process mapping (e.g., Tuholski et al. 2009), and DSM (Steward 1981) to help instructors determine if they have minimized the interdependencies between components. Then, students will be able to develop their components more easily in parallel, that is, concurrently. To improve upon the proposed methodology, we propose that AEC researchers in academia and practice consider testing the methodology to identify existing or create new opportunities for: (1) interdependent engineering disciplines to execute their work in parallel and (2) restructuring work (Tsao et al. 2004).

TEACHING BIM IN UNIVERSITIES

The increasing demand for graduates with a BIM background has led to a greater incorporation of BIM into curricula (Setareh et al. 2005, Sacks and Barak 2010, and Hyatt 2011). However, of the 45 respondents to a survey of members of the Associated Schools of Construction (ASC) that offered undergraduate construction programs, 86.7% of respondents identified "faculty time and resources required to develop a new course" as barriers to providing BIM education at the undergraduate level (Sabongi 2009). Becerik et al. (2011) found that of the 101 AEC programs throughout the U.S. that responded to a survey on recent trends in technology integration, the top two reasons for not incorporating BIM into curriculum are (1) there is no one to teach it (55%) and (2) schools have inadequate resources to make the curriculum change (45%). This paper's proposed methodology may help reduce some of these constraints by improving the manageability of teaching an introductory BIM course for instructors. Then, as some instructors form student groups to develop BIM models (Salazar et al. 2003 and Nielsen et al. 2009), the proposed methodology may also allow instructors to move beyond just emphasizing collaboration as a vague principle and objective to making the collaboration effort much more transparent (Kymmel 2008 and Barison and Santos 2010) by making design handoffs between students explicit through the use process maps and DSMs.

CASE STUDY OVERVIEW

To expose the University of Cincinnati's Civil & Environmental Engineering (CEE) students to cutting-edge AEC practice, we developed the elective course "CEE 686: Introduction to Digital Prototyping for AEC Projects" using Gehry Technologies' Digital Project (DP). DP is a CATIA-based parametric BIM software program that allows building component information to be transmitted directly to fabricators' computer numerically controlled machines. We offered CEE 686 in the spring quarters of 2006, 2007, and 2008, and 6, 8, and 6 undergraduate and graduate students took the course respectively. We adapted chapters 1-4, 7-10, and 13 of Cozzens (2005) to provide DP-specific training for students during the first five weeks of the 10-week academic quarter.

HALF HOUSE MODELS I, II, AND III

Prior to course development, the authors embarked on DP training with Professor Anton Harfmann from the University of Cincinnati's College of Design, Architecture, Art, and Planning (DAAP). Professor Harfmann's course, "Construction II and

Computer Skills," teaches DAAP students how to use two-dimensional formats to communicate building assemblies and relationships using a 3-D model of a simple house. Designed by architect John Hejduk, "The Half House" consists of rectangular, semi-circular, and triangular rooms connected by a circulation spine.

After initial DP training, author Lei Xu took Professor Harfmann's course to practice using DP by developing Half House components. Due to this initial experimentation, Professor Harfmann allowed the authors to use the Half House as the basis for CEE 686 and provided resource materials for Half House components to CEE 686 students. Subsequently, we developed unique Half House models each year, and we will refer to each model as "Half House Model I", "Half House Model II", and "Half House Model III" to make a distinction between the different models.

We adapted the rectangular room of the Half House into a two-story office building and basement for each Half House model. The models' components consisted of geometric shape, parametric, quantity take-off, and scheduling data. Students developed the components either individually or paired up with partners.

INTEGRATION MANAGEMENT

An objective of CEE 686 was to have all components readjust correctly due to a changing Half House footprint, height, and number of bays. However, as Kaner et al. (2008) noted, "… productive use of BIM requires careful planning of how a building is to be modeled." In particular, DP "require[s] you to program the parametrics as you model… [so] an operator… would have to anticipate all project directions beforehand in order to program the geometries and their relationships to each other as you build them. So you must foresee the programming concept before you begin to model the geometry (VBT 2007)." Accordingly, as well as due to the steep learning curve, we relied on James Kotronis, Managing Director of the US-Eastern Region at Gehry Technologies, to assist us in integrating components into Half House Model I.

Eventually, we learned how it was often both easier and faster to develop completely new components with correct parameters and links to other components as opposed to trying to debug old components that were developed incorrectly and/or contained broken links to other components (ibid). Subsequently, by the third year, we achieved CEE 686's primary objective in Half House Model III by overcoming DP's learning curve and implementing our proposed methodology. Thus, we guided 4 undergraduate and 2 graduate students to develop a working parametric model consisting of 14 building components within a 10-week academic quarter.

PROPOSED METHODOLOGY

Our proposed methodology includes the use of three main elements: (1) a Design Driver, (2) Process Mapping, and (3) a Design Structure Matrix (DSM). The following sections explain each of these elements in greater detail.

DESIGN DRIVER

To improve component integration within a parametric BIM environment, we used a Design Driver every year to help clarify a drawing protocol by establishing project reference points, lines, and planes (Staub-French and Khanzode 2007). We managed the Design Driver as a separate component in the main model, and we created it before any other component. In the Half House models, the Design Driver consisted of reference points, lines, and planes that drove the entire project by defining the building footprint, height, and number of bays. The Design Driver does not contain any actual building components, and we strived to keep it as simple as possible.

When building components are based solely on the Design Driver, they can be developed in parallel once the operator defined the Design Driver in the main model (Figure 1). However, due to complex project requirements, project teams may not have the flexibility to define every component based solely on the Design Driver. Rather, projects will encounter the need to define components based on other components, as was the case with our Half House models (Figures 2 and 3). Furthermore, as we nested more components (that is, components were defined by preceding generations of components) (Figure 3), it became increasingly difficult to integrate and manage components in the main model because it was difficult to debug and find the source of any errors in design logic if the component (e.g., C-3 in Figure 3) did not behave properly as a result of changing project parameters.

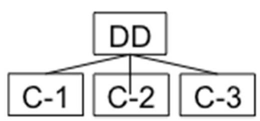

Figure 1: Ideal Condition for Component Integration

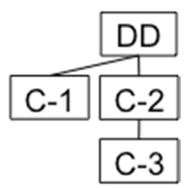

Figure 2: Component 3 is defined by Component 2

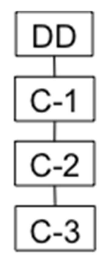

Figure 3: Nesting Increases Integration Challenge

Thus, we spent considerable effort to make all Half House components defined by the Design Driver whenever possible and allowed for nesting only when it was appropriate due to design logic. For example, once we defined the Z-axis location of a structural steel beam (C-2 in Figure 2) using a reference plane in the Design Driver (DD), we defined the bottom of metal decking (C-3 in Figure 2) by the top plane of the structural steel beam. Our efforts in connecting building components directly to the Design Driver in effect helped decouple some components and allowed for greater concurrency amongst the students as they were able to develop more building components in parallel once we established the Design Driver.

The Cynefin framework identifies one strategy for shifting from a “complex” work environment to a “knowable” work environment is to make stronger connections between a central director and its constituents (Kurtz and Snowden 2003). Thus, using a Design Driver introduces a “central director” into the BIM development process, and this can help project teams transform what may have been originally perceived as “complex” design challenges into “knowable” design challenges.

PROCESS MAPPING

Process mapping (aka swim-lane diagrams) is an effective technique for making transparent the handoffs of work between individuals and/or companies (e.g., Tuholski et al. 2009). After completing Half House II, we developed a process map that illustrated the relationships between all building components. From this general process map, we developed individual process maps for each component to provide students better guidance on how to develop their components. Specifically, we identified (1) every activity involved in the development of each component, (2) the incoming, pre-requisite handoffs of work that allowed these activities to proceed, (3) outgoing handoffs of work that occurred after an activity which enables a future activity for the same component to proceed (we labeled these handoffs as "Outgoing Internal Handoffs"), and (4) outgoing handoffs of work that occurred after an activity which enables a future activity for a different component to proceed (we labeled these handoffs as "Outgoing External Handoffs") (Figure 4).

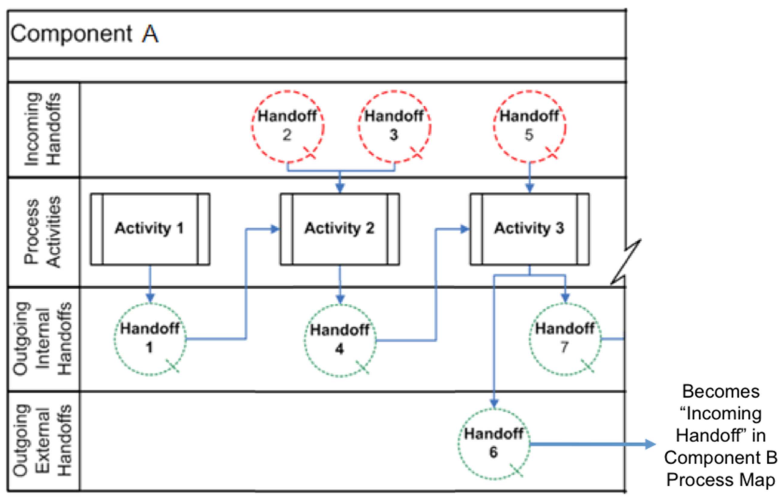

Figure 4: Sample Process Map

Incoming handoffs can come from the Design Driver or other components. For example, Handoff 6 on Figure 4 may become an Incoming Handoff for Component B. Thus, identifying Outgoing External Handoffs helps students understand how their component development will impact the component development efforts of others.

Based on our experiences from Half House Models I and II, the individual process maps made information flows transparent and illustrated how components were related to other components as well as the main model via the Design Driver. In particular, we used the individual process maps to address many of the questions that students asked in previous years as they attempted to develop their components. Once we developed the individual process maps, we were able to identify ways in which we needed to update the Design Driver from Half House Model II to better support component development. As a result, we created a revised Design Driver for Half House Model III. Then, we distributed the individual process maps to students, and they were able to proceed with developing components for Half House Model III very smoothly in comparison to the previous two years.

DESIGN STRUCTURE MATRICES (DSM)

Austin et al. (1999) developed the Analytical Design Planning Tool (ADePT) that uses Design Structure Matrices (DSM) (Steward 1981) to clarify and manage the interdependency between building design activities. Hammond et al. (2000) then developed DePlan that combines ADePT with a production management tool called ProPlan. Similar to the manufacturing industry, AEC projects have found DSM to be an effective tool for decomposition and integration (Senthilkumar and Varghese 2009). However, unlike the manufacturing industry that may be able to mass-produce multiple products following a single DSM effort, AEC teams may be hard-pressed to re-use a DSM from a previous project without spending considerable effort to update it for new project conditions. Furthermore, Maheswari et al. (2006) notes, "significant effort is required from the experts to estimate information dependency attributes." These factors may partially explain why there is limited application of DSM in the AEC industry. However, since ADePT and DePlan have been successfully implemented on AEC projects (Hammond et al. 2000), we decided to test if DSM can assist us in managing the component development process for Half House Model III.

Once we developed the individual process maps and updated the Design Driver for Half House Model III, we generated a DSM to check the relationships between the revised Design Driver and the 14 planned components. Since "Outgoing Internal Handoffs" only helped students understand how to develop their own components, the DSM that we developed only tracked the "Outgoing External Handoffs" for the Design Driver and 14 components. The subsequent DSM's 40 rows and columns consisted of 15 Design Driver elements and 25 elements from the 14 components.

Within the DSM, we identified 79 handoffs managed between the Design Driver and 14 components, 78 of which were positioned below the diagonal. This showed us that our use of a Design Driver in combination with process mapping was extremely effective in helping us remove all but one interdependent relationship between the Design Driver and 14 components. As a result, the DSM was an early indicator to us that component development would proceed smoothly on Half House Model III.

The DSM further revealed that: (1) Seven "1^{st} generation" components relied only on the Design Driver, (2) Four "2^{nd} generation" components relied on the Design Driver and only one other "1^{st} generation" component, (3) One "3^{rd} generation" component relied on "1^{st} and 2^{nd} generation" components, and (4) Two interdependent components relied on a "1^{st} generation" component. Thus, these insights helped us improve the sequencing and assignment of component development to the 6 students taking the course during the third year.

While our use of DSM was limited in this case study, we anticipate that future research could explore using DSM to restructure work amongst BIM components. Future research could also explore whether other elements of DePlan can be used to improve and enhance not only BIM instruction but other AEC courses as well.

IMPLEMENTATION GUIDELINES FOR PROPOSED METHODOLOGY

To help instructors that plan on teaching parametric BIM within a university setting, we outline the following implementation guidelines based on our experiences and lessons learned from developing the proposed methodology:

1. Identify primary **project components** and how they are related to each other.
2. Develop **initial Design Driver**. Make components defined by the Design Driver whenever possible and allowed for nesting only when it is necessary (e.g., it is appropriate due to physics and/or design logic).
3. Develop **general process map** that illustrates how component are related.

4. Develop **individual process maps** for each component (including Incoming Handoffs, Activities, Outgoing Internal Handoffs, & Outgoing External Handoffs).
5. **Revise Design Driver** based on insight from individual process maps.
6. Develop **initial DSM** based on Outgoing External Handoffs.
7. **Restructure work** to reduce nesting and interdependencies between components.
8. **Update Design Driver and process maps** if necessary due to restructuring work.
9. **Revise DSM** based on updated process maps to check for any more inefficient dependencies or interdependencies between components. If so, return to Step 7.

Once students experience this proposed methodology within an "Introduction to Parametric BIM" course, we believe they will be ready to become intimately involved in developing the Design Driver, general and individual process maps, and the DSM for a new project within a follow-up course in parametric BIM.

ANALYZING THE METHODOLOGY'S IMPACT ON THE COURSE

The following sections discuss the differences in processes and results before and after implementing the proposed methodology.

BEFORE IMPLEMENTING THE PROPOSED METHODOLOGY

Half House Models I and II were developed in the following fashion:

Phase 1 (Training): Students completed DP training individually using the adapted Cozzens (2005) chapters. They privately struggled to fix training mistakes that may have already been resolved by others and seemed to ask for help from the instructors only as a last resort.

Phase 2 (Development): We paired up students and assigned each pair the development of several components. Despite having a partner in place, they split the assignments with their partners and developed components individually.

Phase 3 (Assembly): Students worked with instructors to integrate their components back into the main model. During the first year, we relied on Gehry Technologies to assist with resolving integration problems. Some integration problems remain unresolved by the course's end, so some components did not behave correctly when changing certain parameters. As a result, we did not achieve the primary course objective of having all components readjust correctly based on a changing Half House footprint, height, and number of bays.

AFTER IMPLEMENTING THE PROPOSED METHODOLOGY

Half House Model III was developed in the following fashion:

Phase 1 (Training): Students completed DP training individually using the adapted Cozzens (2005) chapters. We encouraged students to help each other in their training. As a result, students spent less time and performed better on their training assignments compared to previous years.

Phase 2 (Development and Assembly I): We paired up students and assigned each pair the development of their first batch of components. They were also responsible for integrating their components into the main model. Working closely with their partners, they developed their components without knowledge of how their components interacted with components developed by other students. Once the students completed the development of their components, we distributed the individual process maps to provide optional instruction on how to integrate their components into the main model. Student pairs that were not able to integrate their components into the main model on their first try then used the individual process maps to assist with resolving integration problems. As a result, the instructors spent less time resolving integration problems and students experienced a sense of accomplishment earlier in the course compared to previous years.

Phase 3 (Development and Assembly II): We assigned students pairs the development of their second batch of components. They were still responsible for integrating their components into the main model, and now they were also equipped with individual process maps before they began component development. The individual process maps provided instruction on naming convention for related parameters as well as selection of reference points, line, and/or planes. The maps also helped student pairs understand how their components interacted with the components developed by others. Although we developed the maps before the course began, we decided to postpone release of the maps until the assembly portion of Phase 2 so both instructors and students can experience the impact of introducing the maps. Compared to Phase 2, the quality of the developed components increased since we spent less time resolving integration problems for most of the components. Instead, as predicted by the DSM, we spent some time assisting the integration of the two interdependent components. Despite this additional challenge, we achieved the primary course objective of having all components readjust correctly based on a changing Half House footprint, height, and number of bays. We were also able to conduct simulations of project sequencing (i.e., 4D CAD) and quantity takeoffs for certain components, although we did not have time to fully explore these subjects.

ANALYZING THE METHODOLOGY'S IMPACT ON INSTRUCTION

For Half House Model II, we spent time developing some components in advance of assigning them to students so that we could sort out better strategies for developing the components. We also identified potential problems that the students may encounter so that we could become better prepared to handle them should they emerge during the course. Once we assigned the students their components for development, we then helped them with component development whenever they asked for assistance. When we attempted to integrate the components into the main model, we spent time debugging some components because they did not behave properly in response to changing related parameters. As noted earlier, sometimes it was easier for us to instruct students on how to create new components properly as opposed to identify where their old components went wrong in design logic.

For Half House Model III, we established rules (e.g., distinguishing between Outgoing Internal Handoffs vs. Outgoing External Handoffs, Outgoing External Handoffs from one component → an Incoming Handoff for another) for process maps and generating maps. Then, once we distributed the maps, we found a dramatic reduction in the amount of time that we spent developing and assembling components.

Now that we have developed the individual process maps and students have tested them for guidance in component development, future offerings of this course can leverage the instruction effort made for Half House Model III. As a result, by maintaining the same component assignments and distributing the same process maps, the potential instruction effort required for a subsequent course offering may amount to about 13 hours or so of developing and assembling components. Table 1 compares the instruction effort that we spent while working on Half House Models II and III.

Table 1: Comparison of Instruction Effort for Half House Models II and III

INSTRUCTION ACTIVITY	Half House Model II	Half House Model III
Establishing rules for process maps		10 Hours
Generating process maps		25 Hours
Developing components	29 Hours	10 Hours
Assembling components	12 Hours	3 Hours
TOTAL	41 Hours	48 Hours

LIMITATIONS AND CHALLENGES OF PROPOSED PROCESS

Due to the high learning curve, students spent the first five weeks of the 10-week quarter on BIM training and the next four weeks developing and integrating components into the main model. During the last week, we discussed BIM tools such as clash detection, quantity takeoffs, and 4D-scheduling. As a result, we did not have time to discuss the relationship between BIM and integrated project delivery, design management, concurrent engineering, set-based design, target value design, etc. However, without hands-on parametric BIM experience, student discussion of these broader design issues would be superficial at best. It was valuable for students to understand (1) how components related to each other through reference points, lines, and planes in the design driver and (2) the process for making changes to the main model and individual components. Thus, a 15-week semester may allow enough time for students to learn parametric BIM and discuss its implications in AEC practice.

CONCLUSIONS

This case study demonstrated that we improved introductory BIM instruction by using a Design Driver, process mapping, and DSM. Specifically, a Design Driver and process mapping improved our ability to (1) train students in how to model within a parametric BIM environment and (2) coach students in how to develop their components so that they can integrate seamlessly into the main model. DSM helped us (1) predict that component integration would proceed smoothly, (2) identify components that would require additional integration management, and (3) determine how to sequence component assignments so that more students could work concurrently. Our proposed methodology may help overcome some of the barriers to teaching BIM in universities. Thus, we hope this paper will inspire other researchers to test our proposed methodology within learning labs in academia and practice.

ACKNOWLEDGEMENTS

Thanks to Anton Harfmann of the Univ. of Cincinnati (UC) and James Kotronis of Gehry Tech for their help with this course. We would also like to thank UC’s CEE Department for providing financial support for course development and refinement.

REFERENCES

Ahmad, I.U., Russell, J.S., and Abou-Zeid, A. (1995). “IT and integration in the construction industry.” Taylor & Francis, *Constr. Mgmt. & Econ.*, 13(2), 163-171.

Austin, S., Baldwin, A., Li, B., and Waskett, P. (1999). “Analytical Design Planning Technique.” *Design Studies*, 20(3), 279-296.
Baccarini, D. (1996). “The concept of project complexity—a review.” Elsevier Ltd., *Int’l. J. of Project Mgmt.*, 14(4), 201-204.
Barison, M.B., and Santos, E.T. (2010). “Review and Analysis of Current Strategies for Planning a BIM Curriculum.” CIB W78, *Proc. 27th. Int’l. Conf.,* Cairo, Egypt.
Becerik, B. G., Gerber, D.J. and Ku, K. (2011). “The Pace of Technological Innovation in AEC Education.” *J. of Info. Tech. in Constr.*, 16, 411-431.
Chinowsky, P.S., and Goodman, R.E. (1996). “Managing Interdisciplinary Project Teams Through the Web.” Springer Pub. Co., *J. of Universal CS*, 2(9), 597-609.
Cozzens, R. (2005). *CATIA V5 Workbook,* Schroff Development Corp., pp 528
El-Tayeh, A., and Gil, N. (2007). “Using Digital Socialization to Support Geographically Dispersed AEC Project Teams.” ASCE, *JCEM*, 133(6), 462-473.
Hammond, J., Choo, H.J., Tommelien, I., Austin, S.A. and Ballard, G. (2000). “Integrating Design Planning, Schedule and Control with DePlan.” *Proc. IGLC-8,* Brighton, UK.
Howard, H.C., Levitt, R.E., Paulson, B.C., Pohl, J.G., and Tatum, C.B. (1989). “Computer Integration: Reducing Fragmentation in AEC Industry.” ASCE, *J. Comput. Civ. Eng,* 3(1).
Hyatt, B.A. (2011). “A Case Study in Integrating Lean, Green, BIM into an Undergraduate CM Scheduling Course.” *Proc. 47th ASC Int’l. Conf.*, Omaha, NE.
Johnson, R.W. (2004). *MasterFormat 2004 Edition.* The Construction Specifications Institute, Alexandria, VA, ISBN 0-9762399-0-6.
Kaner, I., Sacks, R., Kassian, W., and Quitt, T. (2008). “Case Studies of BIM Adoption for Precast Concrete Design by Mid-sized Structural Engineering Firms.” *ITcon*, 13, 303-323.
Kurtz, C.F., and Snowden, D.J. (2003). “The New Dynamics of Strategy: Sense-making in a Complex and Complicated World.” *IBM Systems J.,* 42(3), 462-483.
Kymmell, W. (2008). BIM: Planning and Managing Construction Projects with 4D CAD and Simulations, McGraw-Hill Professional, New York, 270 pages.
Maheswari, J.U., Varghese, K., and Sridharan, T. (2006). “Application of DSM for Activity Sequencing in Concurrent Engineering Projects.” ASCE, *JCEM*, 132(5), 482-490.
Nielsen, D., Fleming, M., and Kumarasuriyar, A. (2009), “An Innovative Learning Model for Teaching Arch. Technology...” *Proc. Int’l. Conf. Educ. & New Learning Tech.,* Barcelona.
Sabongi F.J. (2009). “The Integration of BIM in the Undergraduate Curriculum.” *Proc. 45th ASC Ann. Int’l. Conf.,* Gainesville, FL.
Sacks, R. and Barak, R. (2010). “Teaching Building Information Modeling as an Integral Part of Freshman Year CE Education.” ASCE, *J. Prof. Iss. Eng. Educ. Pract.,* 136(1), 30-38.
Salazar, G.F., Polat, I.H., and Almeida, J.C. (2003). “The Role of the 3D Parametric Building Model in the Future Education…” *Proc. 4th Int’l. Sym. IT CE.*, Nov 15-16, Nashville, TN.
Senthilkumar, V. and Varghese, K. (2009). “Structured Methodology to Formulate Drawing DSM for Construction Design.” *Architectural Engrg. and Design Mgmt.*, 5 (4), 225-248.
Setareh, M., Bowman, D.A., Kalita, A., Gracey, M., and Lucas, J. (2005). “Application of A Virtual Environment System in Building Sciences Education.” *J. of Arch. Engrg.,* 11(4).
Staub-French, S., and Khanzode, A. (2007). “3D and 4D Modeling for Design and Construction Coordination: Issues and Lessons Learned.” *ITcon*, 12, 381-407.
Steward, D.V. (1981). “The Design Structure System: A Method for Managing the Design of Complex Systems.” *IEEE Trans. Engrg. Mgmt.,* 28(3), Aug, 71-74.
Tsao, C.C.Y., Tommelein, I.D., Swanlund, E., and Howell, G.A. (2004). “Work Structuring to Achieve Integrated Product-Process Design.” ASCE, *JCEM*, 130(6), 780-789.
Tuholski, S.J., Gursel, A.P., Tommelein, I.D., Bomba, G. (2009). “Lean Comparison Using Process Charts of Complex Seismic Retrofit Projects.” ASCE, *JCEM*, 135(4), 330-339.
VBT (2007). “Technical Notes from Experiences and Studies in Using Parametric and BIM Architectural Software.” Virtual Build Tech., Park City, UT.