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Toward deep impacts of BIM on education

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Abstract Building information models (BIM) provide a way to represent buildings and communicate about them. In teaching engineering, we also need representations of buildings and are communicating knowledge about them. While teaching engineering we refer to the very same real-world objects that have an explicit conceptualization in BIM. This explicit conceptualization did not exist in the age when design communication relied on drawings and documents. The question that this paper asks is this: due to BIM, communication in the industry has changed. Should communication of engineering knowledge – teaching – change as well and how? While much has been written about teaching BIM and incorporating BIM into the curricula, this paper is exploring the general impact of BIM on engineering education. It grounds earlier work (Turk, 2018) on insights from pedagogy. Five scenarios of the interplay between BIM-influenced engineering communication and teaching are presented. The paper argues that ignoring BIM may create a cognitive dissonance between academic learning and industrial work. We are finding that the impact of BIM is twofold: vertically there is a need to establish a reference between knowledge concepts (in teaching building) and information objects (in building information models). Horizontally BIM is an integration technology that allows for a more holistic design and planning. Both the language of individual courses as well as cross references and synergies among courses should change. A “T” style structure of the courses around BIM is proposed as a basis for integrated curriculum. Pedagogical

approaches based on deep learning, model based learning and project based learning are suggested.

Keywords engineering education, building information modelling, engineering communication, curriculum development

1 Introduction

BIM can stand for building information models, building information modeling or building information management. It has radically changed the communication in the construction industry, particularly the representation of buildings. Note: what we say about buildings is also true for any other product of the architecture-engineering-construction (AEC) industry such as roads, bridges, civil infrastructure, etc.

Radical is the change of communication language: the set of symbols and the way in which they can be combined to transfer ideas. In traditional communication, engineers used geometrical elements, formulae, numbers and natural language words as symbols. How they can be combined was defined by standards about engineering drawings, rules of mathematical notation, and grammars of natural languages. Intelligent human observer was able to interpret combinations of primitive symbols into complex engineering concepts. In a trivial example of Fig. 1 she was able to recognize, from a few lines on paper, a beam with a concentrated load.

In BIM, the symbols are not generic geometric, mathematical or natural language elements but objects that have properties. Objects belong to classes or families. For example, a timber beam belongs to a class of beams which belongs to a class of linear structural elements.

The advantage of such objects is that computer algorithms, not just humans, can parse them and automatically use the information associated with them. Objects are specified in a computer readable language. BIM standards strive to include all objects – all symbols – required to exchange information about buildings so that there is no need to resort to generic graphical or natural

Received August 13, 2018; accepted March 1, 2019

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The study was conducted as a part of the project P2-0210 funded by the Slovenian Research Agency (ARRS).

language elements. BIM defines a finite language to communicate about buildings that ideally would leave little to human interpretation. BIM equivalent of Fig. 1 is in Fig. 2.

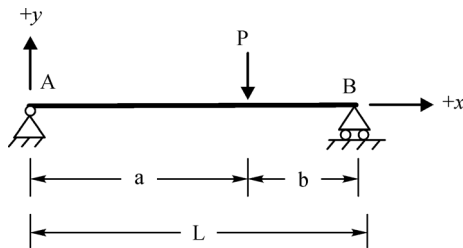


Fig. 1 Beam with a load – unstructured representation.

2 Related work

The research on the interplay between BIM and education took several directions: (a) how to teach BIM itself—mostly in the context of information technology courses and specialization (Ibrahim, 2007; Barison and Santos, 2010; Sacks and Pikas, 2013), (b) how BIM is changing the creative design process (Cheng, 2006; Brown, 2008), (c) how BIM is impacting construction management (Clevenger et al., 2010; Kim, 2011; Peterson et al., 2011; Migilinskas et al., 2013), and (d) how is BIM disrupting construction education in general (Becerik-Gerber et al., 2011; Macdonald, 2012). This paper is in the last category (d). It draws from pedagogy research that is concerned with the construction of language and its impact on transfer of knowledge (Howe and Berv, 2000; Christie and Martin, 2008).

Research on the BIM pedagogy is slowly emerging. Eadie et al. (2016) rightly claimed that BIM is more than just technological replacement for CAD and that it offers potentials for integrated curriculum which connects disciplines and connects learning to real-life problems. Technology-assisted learning facilitates learning complex systems and differentiates instruction to be tailored for students' individual needs.

Hjelseth (2017) explored three different pedagogical

frameworks to integrate BIM with higher education: (a) Integrated Design and Delivery Solutions (IDDS), (b) Technological Pedagogical Content Knowledge (TPACK), and (c) Trinity of BIM as building information model/modeling/management (BIM3P). He suggested not to teach BIM separately but to make it an integral part of core architecture and engineering subjects. In this scenario, BIM disappears as a separate subject and becomes a tool for learning architecture and engineering.

Turk (2018) asked if BIM should change the language of engineering. This paper answers that question with a Yes and extends the engineering argument with pedagogical theory.

3 Problem statement

To teach about architecture and engineering we use language. Books and lectures are in a natural language. Engineering concepts usually have precise natural language definitions. When represented mathematically they get an implicit information model consisting of the values that mathematics manipulates. However, each discipline, each message (lecture) invents symbols on “as needed” basis. Not only are symbolic representations of a beam different in, say, Structural Mechanics Course and in Wooden Structures Course, there exists no common set of symbols and no finite set of symbols.

But when these same students will start using BIM, such a shortlist of symbols (called objects or elements) with a shortlist of properties (called attributes) will emerge. In fact, these terms are being standardized in an effort complementary to BIM standardization – in BuildingSmart Data Dictionary (Buildingsmart, 2018).

The question is, should the teaching of just about any topic of engineering take into account that there exists a list of symbols (terms) that are routinely used to communicate about buildings. Should those that teach vertical engineering courses and are mentioning beams, columns, cantilevers, rebar etc. adapt their language and talk about ifc_beam, ifc_columns etc? Of course, without the ifc_ prefix but in the meaning implied in the data dictionary.

```

/* beam A-1 - beam axis along global x axis ----- */
/* cardinal point = 1 - bottom left */
/* enhanced definitions introduced in IFC2x4 - IfcBeamStandardCase ----- */
#1000= IFCBEAMSTANDARDCASE ('0juf4qyggSI8rxA20Qwnsj', $, 'A-1', 'IPE220', 'Beam', #1001, #1010, 'A-1', $);
#1001= IFCLOCALPLACEMENT (#100025, #1002);
/* set local placement so that the z-axis is co-linear to the beam axis ---- */
/* the y-axis (cross product of x & z axis) is up direction of profile ----- */
#1002= IFCAXIS2PLACEMENT3D (#1003, #1004, #1005);
#1003= IFCARTESIANPOINT ((0., 0., 0.));
#1004= IFCDIRECTION ((1., 0., 0.)); /* local z-axis co-linear to beam axis */
#1005= IFCDIRECTION ((0., 1., 0.)); /* local x-axis */
#1010= IFCPRODUCTDEFINITIONSHAPE ($, $, (#1050, #1020));
#1020= IFCSHAPE REPRESENTATION (#100011, 'Body', 'SweptSolid', (#1021));
#1021= IFCEXTRUDEDAREA SOLID (#1022, #1023, #1024, 2000 \.

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Fig. 2 Beam represented as an IFC object.

Should they, in their mathematical models, use variables that map to attributes of BIM objects? Should the textbooks of just about any engineering course be rewritten so that the languages – of (a) BIM based industrial processes and (b) natural or mathematical language of education – would merge?

4 Communication models in industry and education

This Section presents semi-formal models of communication in engineering work and in engineering education. The models show that in engineering work the parties communicating are not just humans but software, and robots as well. However, in the education process, the communication is between teacher and student which both are human. They exchange information and knowledge using symbols. Humans can easily bridge different symbolic representations. But software has problems with that. For this reason, BIM ensures the consistency of symbolic representations within itself and standardized BIM, such as IFC, does so across the industry.

4.1 Knowledge communication

Knowledge has been defined as the ability to respond properly to a problem (Winograd, 1991). The response is a result of processes in the mind. In some cases, the response is information (i.e., spoken, written word); in others, a material activity (i.e., doing something). A well-established model that relates the real world to our understanding of it and to the words and symbols we use to communicate about it, is the semiotic (or meaning) triangle (Ogden and Richards, 1994) (Fig. 3). Things or objects (we shall call these “O”) are items from the real world. Experiences in the psyche or thoughts or concepts (“C”) are ideas we hold about things in our minds. Words, drawings and other symbols (“S”) are used so that we can communicate about our thoughts about real world objects.

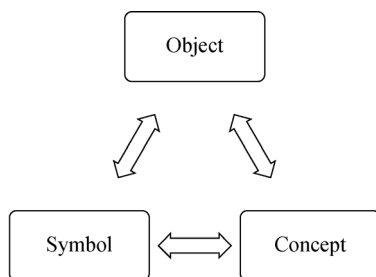


Fig. 3 The semiotic (meaning) triangle.

In this context, learning is equipping the student with useful C(oncepts) so that she can deal with real-world O(bjects) appropriately. Learning can happen in two ways.

First, on the C-O edge of the triangle by gaining experiences in the real world. Experiential learning utilizes learning by engagement, interaction and reflection in real-world. In higher education, workplace learning and some methods of collaborative learning provide experiential learning but are an exception to the rule.

A second kind of learning takes place when we listen, view or read about real world Objects. Symbols such as words, drawings, mathematical equations etc. are used in the communication. This learning is happening on the C-S edge of the triangle. Most of the higher education learning programs are taking place along this C-S edge. Students do not deal with real world objects but with their symbolic representations – like the ones shown in Fig. 1.

Building Information Models are a very advanced form of a symbolic representation of buildings but are not the only available symbolic representation of buildings. Symbolic representations (models) are created to study real world phenomena scientifically or to teach about them. Several such models are created, specifically, for a problem that is studied or taught.

4.2 Islands of education and conceptualization

One could argue that a phenomenon of “islands of conceptualization” exists throughout the construction profession, much like the “islands of automation” (VTT, 2002). The latter idea was used to explain the problems of information exchange in the construction industry. The point was that there exists computer software supporting specific tasks in the construction industry, however, each of these software programs is an island and can hardly talk to other software. BIM is the technology to fix this.

Similarly, islands of conceptualization would mean that for different problems to be addressed scientifically and for different engineering subjects we teach, we choose to conceptualize the real world differently – we have many instances of Symbols and Concepts about the same real world Object (Fig. 4). Another way of saying this is that there exist silos of knowledge and silos of learning – each topic in its own course, with its own textbooks, and own representations.

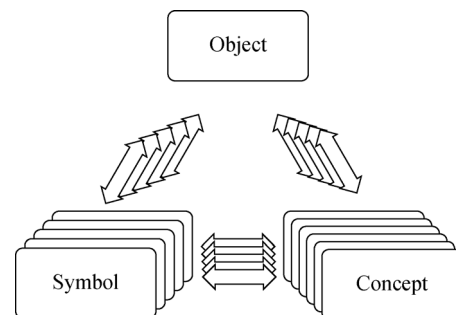


Fig. 4 Multitude of Symbols and Concepts while teaching and learning about the same object.

In teaching and in science this is not much of a problem. The conceptualizations are for human use. Teacher and student are humans. A student can switch from one conceptualization to another as she moves from class to class. Scientists in their silos each study the world with their own conceptualization.

4.3 Communication in construction industry

In practice, things are different. The solution for the “islands of automation” problem is supposed to be BIM – a common symbolic representation of the real world building that any software can use to get information from and add information to. There is a single real-world object that everyone is contributing to – the material building being built. And there is a single social network of all people involved. These three elements – real world building, its digital representation and the social network are the three elements that are “integrating” construction industry and countering the fragmentational forces that are a result of specialization of professions (Fig. 5).

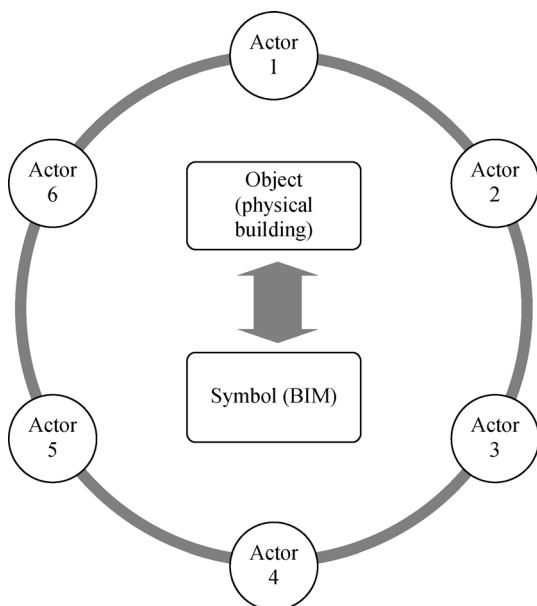


Fig. 5 Single building, single symbolic representation, and single social network of collaborators are integrating construction in practice.

In this framework, construction is about changing the real-world objects as specified in the symbolic representations of building designs. Construction is happening on the S-O edge of the triangle which has hardly been touched during the education process. Symbols (drawings, plans) are indeed interpreted by humans, but also by software and increasingly robots and other automation devices.

The communication in the industry used to be transactional – various people were communicating with each

other, often inventing the symbolic representation fitting just the purpose of that communication act and that particular problem’s conceptualization. What was going on in the industry was similar to what was happening in the classroom.

The communication in the industry now is through sharing a BIM model. The information is not exchanged but shared and there exists a single symbolic representation for all purposes.

5 Scenarios of BIM impacts

The key problem identified in the Sections above, therefore, is the growing divide in how the industry manages knowledge and information and how this does the academia. The industry is forced – by the obvious fact that there will be a single material building in the end – to integrate information and knowledge. With BIM and related tools, it got powerful methods to do this. Not so in academia. During studies, in academic context, learning remains in silos or in islands unless connected to real life problems. Among main shortcomings of higher education is the lack of learning on the C-O edge of the triangle. Students are only exposed to this when they enter the workforce. Therefore, the curriculum needs to change because of BIM technology. In this section, we present five scenarios – five different levels – on how BIM is changing education.

5.1 Level 1: BIM modernizes teaching of CAD

In this scenario, the design communication courses that used to teach descriptive geometry, technical drawing, and later CAD teach BIM as well. Instead of teaching the students how to document the designs using drawings, 2D or 3D geometrical models, students are taught the use of BIM modeling tools such as Revit, ArchiCAD or AllPlan. Skilled BIM modellers and BIM operators are a result.

Additional elective courses can be offered, for example, Building Information Management for future BIM managers or BIM coordinators. Elective programming courses can be offered for languages such as C#, Python etc., to educate future developers of smart BIM objects and BIM software extensions.

There are hardly any changes in the big picture of the engineering curriculum. BIM is confined to a couple of courses.

5.2 Level 2: BIM modernizes construction management

In this scenario, the courses that teach skills that by their nature have an integrative role in the construction processes, take note of BIM. Such courses are courses about construction management. Management integrates various processes, people, knowledge and resources into a

construction process delivering a construction product. Project planning becomes BIM-based. Crude Gantt and Pert charting evolve toward proper 4D BIM. Quantity take-offs assume the existence of BIM. Financial flow management introduces the financial dimension of 5D BIM. Organization and management courses educate future BIM coordinators and BIM managers. Creation of BIM Execution Plans, Information Delivery Manuals and similar documents becomes an integral part of the construction management process and future engineers learn about that as a part of construction management courses. Elective courses on strategic management of and with BIM may be offered as well.

Effects of BIM on education are still localized, however, a need for project-based learning is starting to emerge so that management and design communication topics are taught integrally.

5.3 Level 3: Shallow BIM is used in vertical courses

Students use BIM tools to document designs created in vertical courses such as Masonry Structures, Steel Structures, Reinforced Concrete, Bridges and Tunnels, etc. In this scenario, these topics are still taught in isolation. Specialized software for the design of, for example, reinforcement, is still taught and used in isolation, however, to document design and communicate results, students switch to BIM software. They learn the language used in BIM software to discuss these concepts and can compare the attributes in a BIM software with the theoretical ones in the vertical courses.

5.4 Level 4: Deep BIM is used in vertical courses

In this scenario, vertical engineering courses recognize not only the usefulness of BIM to document and share solutions but start using shared conceptualizations introduced by the BIM software and standards. Vertical engineering courses take note of the concepts, their properties and their relations, as defined in BIM tools and vocabularies. There is an increasingly unified mapping between an attribute in BIM data structures and a variable in equations being explained. It is assumed all inputs can be retrieved from BIM database and all outputs can be stored into the BIM database. Analysis software that is used shares conceptualizations and exchanges information with the BIM databases.

5.5 Level 5: Knowledge is “BIMified”

In this scenario, not only is BIM used to represent designs and to provide information source and sink for the analysis software. Also, professional knowledge, best practices, rules and standards – the knowledge of engineering – is beginning to be encoded as extensions in BIM software or an extension to model checking software such as Solibri

(2018). Gradually, vertical engineering knowledge taught to students is not represented in natural language, textbook format, but in a machine readable and automatically computable way. Teaching a vertical topic, for example Reinforced Concrete, becomes teaching about the principles behind the modules that can model-check that part of the model or propose design alternatives for that particular detail.

Of course, teaching follows the technology as model checking progresses into more and more intelligible tasks.

6 Toward a new structure and integrated curriculum

The last three levels in the Section above call for an increasing change in the language and the structure of all engineering courses. Traditionally, specialized vertical courses are isolated from each other, as is the information and knowledge that they manage. However, several courses are addressing the issues of the same building, each from its own perspective. In engineering practice, BIM creates a shared representation of a building. This calls for an integrated curriculum, which allows connections between learning contents across disciplines and learning contents with real life.

There are three known approaches to integrated curriculum: interdisciplinary, multidisciplinary, and transdisciplinary (Volk et al., 2017). The integrated curriculum involves concepts of all curricula involved, which requires teachers to identify connecting elements and integrative continuum. Following Fogarty (1991), there are three basic approaches of an integrated curriculum: (1) within a single discipline: fragmented, connected, and nested; (2) across several disciplines: sequenced, shared, webbed, and threaded; (3) focused on learners: the immersed and the networked model.

Based on Gagné’s knowledge levels, we can discuss engineering students’ knowledge on three levels, conceptual, procedural and problem-solving level (Gagné et al., 1992). To act in a real industrial environment, students need to apply their knowledge and competences in diverse new situations. Instructional methods need to provide a learning environment, which is closer to real life, which is possible when technology-assisted learning environments integrate course objectives and contents with real life.

Real life problems are not isolated, they emerge crossing disciplines. Teaching conceptual, procedural and problem-solving knowledge involves representations on concrete, visual, and abstract level. According to Goldin (1988), internal development of conceptual structures and scaffolding of internal and external representations is needed. Bruner (1966) argues for the three-stage learning process: enactive, iconic and symbolic.

Instructional design for “BIMified” industry needs

to support various combinations of representations integrating disciplines and representational combinations according to the learner's needs. Students should be able to select between options and during tasks, they should receive feedback which includes diverse aspects (energy efficiency, static stability, building lifecycle). In this way, the integrated BIM curriculum is engaging students in real life problems and offers them the possibility to apply real-life solutions. It has potentials for authentic learning which is student centered and requires a systematic approach to competence development (Reeves et al., 2002). Therefore, to organize teaching with BIM, one should follow principles of deep learning, model-based learning and project-based learning.

6.1 T-shaped structure

In terms of structure, such a curriculum calls for “T shaped” courses (Fig. 6) where the vertical element in the letter “T” deepens the specialized knowledge that the course historically offered. However, the horizontal element of the “T” represents the way to break out of the course silo in several ways. (1) It connects to the common information model of the building and the common vocabulary used in theory and practice, (2) it connects to the deep learning and the “model-based learning” paradigm, and (3) it represents an interface to the project students are working on as a part of project-based practical work. The second way is presented in Fig. 6 though the figure would be similar for the first and third way as well. In other words, integrating BIM into the learning process supports the learning objectives at the conceptual, procedural and problem-solving level.

6.2 Project-based exercises

The project-based learning adds to reduction of divide between academic and real-life by supporting integration between siloes of knowledge (shallow BIM in vertical courses) through real-life problems. BIM supports integration between siloes of knowledge of professional disciplines providing uniform language – a common symbolic representation of the real-world building. Project-based learning also establishes a connection between the academic and industrial contexts utilizing real-world environment, tasks, and experts.

The mapping between the abstract and the real is involved, as it requires divergent sources and perspectives, and frequent transitioning between them. The project-based learning – connecting sources from a diversity of civil engineering courses with BIM – is becoming a reality. The decontextualisation of learning from real life project should no longer be the case. The integrated curriculum is contextualizing learning to diverse disciplines and real-life contexts. The potentials of technology-assisted learning for authentic learning are recognized.

Reeves et al. (2002) define several features of technology assisted authentic learning: having real-world relevance, addressing ill-defined and complex problems, have multiple perspective and resources, go beyond domain specific knowledge, involve different disciplines, and allow a diversity of outcomes. All this is addressed in project-based learning where T-shaped courses contributed to a single project exercise which is represented in a central information model (Fig. 6). An interface to most of these features are the horizontal bars of the “T”s in Fig. 6. Of course, all these features should be seamlessly integrated into the assessment.

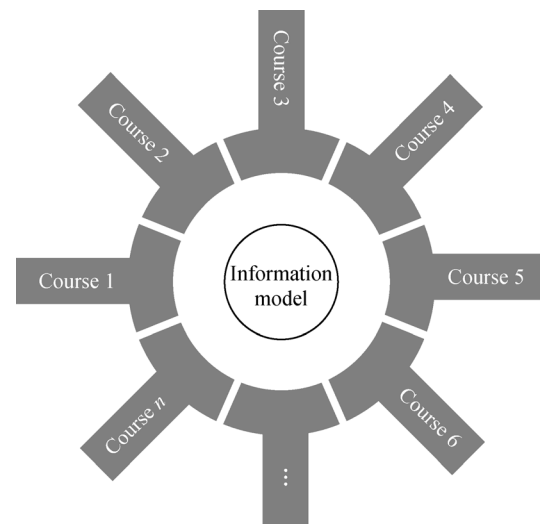


Fig. 6 “T” shaped courses, integrating construction education around BIM.

6.3 Deep learning and model-based learning

Due to multimodal information processing, BIM offers the foundation for deep learning methodology in advanced engineering communication and visualization. In terms of method, BIM calls for model-based learning, including learning with models and learning by modeling. Learning by models is more convenient for procedural learning and less demanding than conceptual learning. Learning with modeling is more suitable for advanced conceptual learning. Model-based learning is based on project-based learning, inquiry learning, and situated experiences (Milrad et al., 2002). Therefore it is more organic, more similar to what goes on in the industry and would- in the age of BIM- be model-based. Such learning supports representations on the symbolic and visual level.

Model facilitated learning could improve the learning of concepts, procedures and problem-solving in complex domains such as engineering. In the learning process models of concepts, procedures and problem-solving are used. They could refer to domain knowledge, problems, systems, and semantic structures. Models could be

inductive, deductive, semantic, and systemic.

The real-life complexity is achieved by the interaction of the learner with the task which takes place in a simulated real-life context. Model-based learning is introduced concerning learning content of a range of courses which in real life practice occur in projects that professionals face in their practice.

Fundamental teaching and learning principles include project-based work integrating across-curriculum, model-based learning integrating combinations of representations. Model facilitated learning could improve the learning of concepts, procedures and problem-solving. It could refer to domain knowledge, problems, systems, semantic structures.

7 Conclusions

The paper has provided arguments on why BIM should cause deep changes in how we teach future engineers. The entire curriculum will need to be modernized because the industry is communicating using BIM. In the industry, islands of automation are growing together toward computer integrated construction. Walls of the silos of activities are being taken down. In academia, silos of knowledge are still tolerated, because the bridging of knowledge is accomplished manually or rather in the minds of intelligent humans. BIM is enabling integrated design and construction. Integrated construction calls for integrated education.

In the paper, we have presented five different levels of responses of academic teaching to BIM. Responses start with (1) teaching BIM in isolation as a better CAD, then (2) include BIM in integrative topics such as management and finally (3, 4, 5) increasingly rely on BIM in vertical, specialized engineering courses. First (3) for documenting designs, then (4) by designing in BIM terms, and finally for (5) encoding knowledge in a BIM compatible way.

The path to integrating education of engineers is by introducing “T”-shaped course structures that combine the existing “I”-shaped silo knowledge with the “-” horizontal bar that connects not only to related courses but is, more importantly, an interface to the shared representation of the building. Education becomes model based – conceptually shifting toward a shared conceptualization of a building that is also at the core of BIM. The execution of the education becomes project based – thus simulating the practical industrial environment.

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