

BIM-ENABLED LEARNING FOR BUILDING SYSTEMS AND TECHNOLOGY

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SUMMARY: *This paper presents a series of educational case studies for the BIM-enabled pedagogical approaches for learning building systems and technology in the early stages of architectural education and provides evidence-based arguments about the influence of BIM on the students' learning processes. Using a dual-channel pedagogical framework the study employed an object-oriented ontological approach tightly integrated with the parameterization of building components and their behaviors. Students experienced a fully BIM-enhanced course for learning fundamental concepts of building systems and technology where the creation of parametric BIM models was the main vessel for comprehensive understanding. The results show significant conceptual and practical advantages of BIM-enabled learning as well as the observed challenges in an educational context. The study also suggests positive educational transformations due to carefully devised BIM-based pedagogical frameworks for the understanding of building systems through parametric thinking and modeling. Based on a grounded theory approach, the findings are synthesized in a theoretical learning model including the systemic relationships between building technology content and parametric BIM methodology.*

KEYWORDS: *Building Information Modeling, Parametric Modeling, Object-Oriented Building Ontology, Integrated Education.*

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1. INTRODUCTION

Being a multi-dimensional methodology, process and technology, building information modeling (BIM) possesses significant pedagogical potentials for more integrated and informed learning for architecture and construction. Rapid adoption and diffusion of BIM and Integrated Project Delivery (IPD) methods especially for the innovative AEC practice still motivate novel and integrated educational studies focusing on different interdisciplinary domains of architectural education (Friedman 2007; Özener 2009; MacDonald and Mills 2013).

Keeping pace with the growing interest in the AEC industry, many architecture and construction schools have implemented different and novel strategies for integrating BIM into their educational programs especially in the last decade (Barison and Santos 2010; Becerik-Gerber et al. 2011; Abriad and Dossick 2016). As the key driver for these incentives, BIM-centric transformations in learning emerge as a pedagogical necessity since the demand for BIM use and high building performance has become critically important in the practice domain. In this regard, current BIM tools with parametric building components, intelligent building object behaviors with embedded assembly methods, performance simulation modules and rapid feedback mechanisms have the potential for significantly altering the educational processes for learning high-performance design and integrated building systems. From a different perspective, the BIM methodology defines all building processes in computational, parametric and relational behaviors and also provides both a thinking and application medium which is very close to physical reality (Haliburton et al. 2011; Sacks et al. 2018). Despite these advantages and potentials, the current state of BIM tools as industry-centric solutions still possesses many challenges for educational use and invites tailor-made strategies and approaches through well-organized case studies. This also brings the discussion of teaching BIM as a separate topic in schools —*which is a quick, straightforward and relatively effective response*— or providing BIM understanding in the context of knowledge acquisition and execution in specific domains of architecture, design and construction which may realize the aforementioned potentials of BIM in education (Ambrose 2012; Shelbourn et al. 2016).

As a specific iteration of a BIM-enabled educational research case, this study base on the idea of *BIM-in-the-context*. The scope of the study included: (1) the analysis and evaluation of learning processes at the intersection of BIM and building systems and technology and; (2) the proposition of a novel pedagogical framework that can be used for creating new courses and workshops in architecture and construction schools. The research study employed instrumental case study methods within a qualitative and exploratory educational inquiry. This study differentiates from the advanced level educational experiments and cases as it is focusing on the learning process of building systems and BIM in the “early stages” of architectural education and suggests a novel pedagogic approach based on solely parametric BIM methods and tools.

2. BIM PEDAGOGIES FOR LEARNING BUILDING SYSTEMS

Building systems and building technology courses have significant importance in architectural education since these courses set the knowledge basis for building production and design detailing for architectural and construction practice. From a more detailed point of view, these courses cover specific subjects like building elements design and tectonic relationships; building subsystems; materiality and material properties; requirements for structural design using existing teaching methods and graphic conventions (Silver and McLean 2013). The learning process is mainly organized around theoretical classes and related production of 2D drawings and representations in different detail levels. Acquired know-how and abilities from these courses are directly transferred to design studios in various levels and construction project courses (Clayton 2006; Allen 2009). However, these architectonic design and construction principles comprise many interrelated and multifaceted concepts beyond 2D projections and theoretical understandings and even they become more complex with the developing building construction methods and fabrication technologies (Kieran and Timberlake 2003). When approached from the BIM perspective, the majority of these topics are significantly compatible with full BIM utilization for learning in order to overcome the problems of conventional teaching also provide students a new learning experience for preparing them for a techno-centric AEC practice (Guidera 2006; Tsai 2019).

Beyond its operational capabilities for better visualization, modeling and documentation, BIM is a live simulative environment with parametric flexibility and object behaviors that has distinct potentials to catalyze the integrated learning processes (Cory 2012). Students can develop both knowledge and skills through virtual design and construction using intelligent building components and quick performance feedback. As a result, the process of learning by representation can transform into learning through parametric creation and simulation of building

components and systems (Kymmell 2008). The main idea here is clear and it sounds effective in theory, but the task requires relatively more effort for linking the course content with a decent level of BIM literacy and multi-dimensional parametric understanding.

2.1 Challenges of BIM Integration into Education

The challenges for the effective implementation are multi-faceted which have different ties to the current state of BIM tools; BIM processes in the profession and pedagogical practices in architectural education. The long-time argued the complexity of BIM tools and their interfaces still pose a problem since they are designed for industry-level production (Cheng 2006). The software usage patterns and modeling procedures are designed for professional architects and engineers with a degree of experience but the priorities are different in education since students have different cognitive attitudes and relatively slow learning curves with modest experience levels. Especially in the early stages, students face major challenges while learning essential course concepts and developing BIM software literacy simultaneously. Here, opportunistic and disintegrated attempts to implement BIM without thoughtful methods and strategies are likely to disrupt design learning and decrease BIM's value for education (Kocaturk and Kivinemi 2013). Puolitaival and Forsythe (2016) argued the current practical challenges such as the need for simplicity for students and finding the balance between theory and practice; technology and process; traditional and emerging methods in AEC practices. Underwood and Ayoade (2015) also discussed the obstacles to BIM adoption in higher education. According to their report with BIM academic forum in the UK, the disconnect in BIM-related disciplines is apparent and the BIM awareness and maturity are not at desired levels. Despite the general support from academic initiatives the level of conviction for a BIM-centric curriculum transformation is not evident as the study suggests. The typical architectural curriculum adds another dimension to this problem. The studio and building technology courses are taught separately and the continuity of BIM-enabled building system courses is very rare (Hu 2019). Particular course groups in building systems do not base on the strategic use of BIM for facilitating integrated learning across the curriculum. In the majority of architecture schools, the core intent is to equip students with tacit design mastery, representation skills and construction knowledge based on well-established ideologies for a conventional practice (Fisher 2004; Starzyk and McDonald 2010). This belief often neglects BIM's process-driven nature (Lim et al. 2015) and creates an obstacle for educators to develop comprehensive BIM skills for instruction (Gerber et al. 2015). Unlike state-of-the-art engineering programs, architecture schools do not leverage modern programming concepts and object-oriented approaches which are essential for comprehensive BIM understanding.

2.2 Current Approaches and Experimental Studies

The current literature provides both theoretical and practical arguments for implementing BIM in the education of architecture and engineering students. Some scholars in this particular field approach this problem from a pedagogical perspective and discuss concepts, possible pedagogical models and integrated learning environments. In detail, Succar et al. (2013) emphasized the importance of core BIM competencies with a hierarchical model including “*competency sets, topics and items*” to facilitate BIM capability development and to work as a knowledge base for educational initiatives. Likewise, Shelbourn et al. (2017) made a comprehensive focus group study with students from US and UK schools and identified six key areas required for BIM to be inclusive in higher education: *collaborative curricula, space, teamwork, relevance to the industry, technical/technological skills and the role of the educator*. From an educational transition standpoint, Underwood et al. (2013) proposed three progressive stages of the development of BIM education as *BIM-aware, BIM-focused and BIM-enabled*. The BIM-enabled stage truly lays the foundation for an innovative AEC education where BIM acts as an integrated vehicle for learning.

The literature also includes wide-range case studies and action research examples for implementation. As an example, Mathews (2013) stressed the importance of BIM-based learning in a collaborative studio environment through an in-depth case study focused on the facilitator role of BIM in the cognitive learning of architectural technology in the studio. The educational case study was based on the creation of complex and shared BIM models that were designed and iteratively developed during the case study. In particular, the research results illustrated significant changes in the studio environment and student attitudes during the collaborative design and modeling processes. A parallel study was made by Jin et al. (2018) around a complex project that prioritized interdisciplinary integration and collaboration using BIM methods. The research stressed the importance of changing dynamics and challenges of the AEC industry as addressed by the current standardization documents –*such as BS1192*, Integrated

Project Delivery (IPD) principles and the need for well-rounded pedagogical strategies that include interdisciplinary communication and team working. The study documented project workflows for the BIM-based project teams in an educational setting and widely argued the pedagogical dimensions of BIM in the theoretical context of project-based and active learning approaches. Gerber et al. (2015) provided an extensive survey study on computing in the AEC education. The findings showed the positive change in student abilities in computer applications but underlined the sharp disconnect between the fundamental computer science concepts and the current educational approaches. The study also discussed the importance of future educators with competent skills in fundamental BIM concepts and the growing need for improved learning approaches.

A recent study on building technology education was conducted by Benner and MacArthur (2019) for BIM, sustainability and building performance in a project-based learning setting. The research elaborated on the pedagogical strategies which are tailored for the simultaneous learning of BIM and data-driven design through wide-range environmental simulations. Based on the theoretical lenses of both “*experiential learning*” (Wang et al. 2015) and “*Bloom’s Taxonomy*” (1956) the study posited that BIM-enabled pedagogies were highly effective in students’ engagement and comprehension levels for learning data-driven design for high-performance buildings. In a similar inquiry, Tsai et al. (2019) provided a comprehensive BIM course framework for civil engineering students. Aligned with the previous studies above, the proposed course outline employed a project-based approach along with online instruction methods. In a flipped-learning context, the study showed that a tailor-made course organized around specific milestones and complexity levels made students develop both modeling skills and understanding of building systems efficiently. Although there are similarities with this paper in terms of building systems content, the study does not involve design processes that require a different pedagogical approach than building comprehensive BIM skills. Apart from their BIM-rich technical content for learning, these studies rigorously discussed “*constructivist pedagogies*”, “*experiential learning*” and “*problem-based learning*” from a theoretical perspective with their conceptual links to BIM-enabled settings and setups. As the literature documents numerous studies and research on the successful implementation of BIM and its effectiveness, the viewpoints and arguments from these studies also support the continuous need for reinvented pedagogies, new perspectives, innovative courses and experimental learning environments for integrating BIM methods for the 21st-century architectural education. It can also be argued that the generation of novel theoretical and practical perspectives through the lens of *object-oriented pedagogies* may push the envelope for the educational use of BIM. Such incorporation of object-oriented programming (OOP) concepts and principles into architectural education may seem challenging, however, it is appropriate for shifting the pedagogical paradigm in all AEC disciplines like architecture and design, civil engineering and construction science.

3. PEDAGOGICAL APPROACH AND CASE STUDIES

3.1 Research Methodology

The methodological framework of the study employed the qualitative “*grounded theory*” approach (Glaser and Strauss 1967) as it enables educational researchers to explore the theoretical reach of novel pedagogies and to provide tacit meanings and explicit processes for learning mechanisms (Creswell 2012). This approach is also suitable for educational research in architecture in the real-world context with empirical inquiry in design studio settings. Aligned with the previous studies using this methodological approach, the research objective was to explore students’ perspectives and actions in a BIM-enabled learning process and generate an in-depth theoretical understanding through the synthesis of a suggestive pedagogical model (Urquhart 2013). The nature of the inquiry can be defined in exploratory and descriptive dimensions. The exploratory dimension included the theorization of the proposed pedagogical content with a broad understanding of BIM-enabled learning settings (Stebbins 2001). Built on the first dimension, the descriptive part attempted to describe the whole learning experience with related processes, cycles and student responses (Boeije 2010). Extending these methodological considerations, the study focused on the key phenomenon of BIM-enabled pedagogies with a particular set of factors and corresponding qualitative measures for comparative evaluations (Roller and Lavrakas 2015). Based on the previous studies on BIM-based education, these factors laid the foundation for data gathering, conceptual concept analyses and the theoretical constructs derived from the grounded theory approach (Table 1).

Table 1. Pedagogic Factors and Qualitative Measures

Pedagogic Factors	Qualitative Measures
Learning mechanisms	Processes, cycles, behaviors, perceptions
Design thinking and abstraction	Parameterization schemes, conventional vs. object-oriented comprehension for building systems design
Modeling processes/model production	Communication patterns, model/visual layouts, modeling procedures, use of relational data structures
Social aspects of learning	Conventional vs. BIM-enabled interactions, social links, networks and knowledge exchange

As the initial stage of the research study, a thorough literature search was made to devise an experiential pedagogical framework organized around parametric BIM ontology and problem-based learning (PBL) methods for further exploration. Using this prototypical framework, a series of instrumental case studies were conducted in the Department of Architecture at (Anonymous) University to understand the learning mechanisms focusing on building systems and explore the potentials of BIM-enabled learning in the subject context. (Gillham 2000; Creswell 2009; Yin 2009). The research design included one “control group study” and three iterative “intervention group studies” to make evidence-based comparisons between conventional approaches and BIM-enabled pedagogies for learning building systems and related construction technologies. During these case studies, qualitative research techniques were used like “participant observations” (Spradley 2016) and on-site “peer interviews” through activity coding and field notes. Following the control and intervention groups case studies, several “focus group interviews” were conducted to evaluate the BIM-enabled learning experience from the perspective of study participants (Krueger and Casey 2014). Collected data from these stages were transcribed, coded, and analyzed with “content analysis” methods for corroborating and interpretation of the research findings (Krippendorff 2018). As the outcome of the research study, the proposed “dual-channel pedagogical model” was conceptualized around the study findings and experiences from the case studies along with reasoned arguments and discussions. Figure 1 shows the study flowchart with the research phases and Table 2 illustrates these phases with the research outcomes.

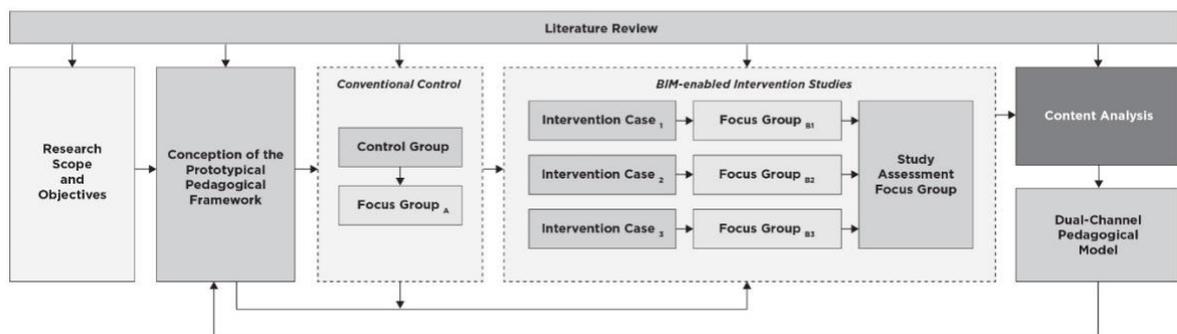


FIG. 1: Research Study Flowchart

Table 2. Research phases and the summary of outcomes

Research Phase	Research Outcomes
Literature Review	Study of theoretical perspectives, understanding existing pedagogical approaches
Conception of the BIM-enabled Pedagogical Framework	Creation of the course outline and objectives, application of object-oriented pedagogical content
Control Group Study	Focus Group A
Intervention Group Case Studies	Group 1 Focus Group B1 Group 2 Focus Group B2 Group 3 Focus Group B3
Full Focus Group Evaluation	Participating student responses and experiences
Coding and Content Analysis	Identification of BIM-enabled learning schemes; occurred trends and patterns during case studies
Synthesis of the Dual-Channel Pedagogical Model	Pedagogical approaches, theoretical assertions, viewpoints and suggestions; hypothesized discussions



The research findings and arguments are limited to similar educational settings and setups due to the qualitative content of the research study.

3.2 Pedagogical Approach

A prototypical pedagogical framework was devised around the current architectural curriculum, course syllabi, literature and previous educational case studies using BIM. The critical approach here was the reinterpretation of fundamental topics in building technology in the milieu of parametric BIM methods. This was aimed to provide an understanding that will enable students to comprehend parameterized building components, materials and their interrelational behaviors as holistic architectonic systems and allow students to make all their productions using BIM within a dynamic, continuous and efficient learning process. The experiment included mutual pedagogical agendas based on the duality of the prototypical course framework. The first layer included specific building technology topics and corresponding BIM subjects in 12 modules to simulate a semester-long course plan. The second layer included the fundamental concepts of BIM and parametric modeling. As the study participants were entry-level students, the course was also held as a first stage introductory BIM training for the undergraduate level. The building technology content of the course outline was adequately suited with this pedagogical intent (Table 3).

Table 3. Case study outline

Modules	Building Technology	BIM Topics	Exercise
Module 1	Building Tectonics	Parametric Building Ontology and Modeling with BIM	Parametric building grid and layout
Module 2	Structural Systems	Modeling Loadbearing Systems	Parametric modeling of columns and shear walls
Module 3	Structural Systems	Modeling Beams and Slab Systems	Parametric modeling of beams and slab systems
Module 4	Building-Ground Relationship	Foundation Systems	Generation of substructure foundation elements
Module 5	Circulation-Vertical	Parametric Stairs and Types	Parametric stair modeling
Module 6	Mid-Term Submission		
Module 7	Building Interior Systems	Modeling Interior Walls and Separation Systems	Parametric wall generation and wall structure/layers
Module 8	Building Interior Systems	Modeling Interior Walls and Separation Systems	Parametric door modeling
Module 9	Building Envelope	Modeling Exterior Walls	Parametric wall generation and wall structure/layers
Module 10	Building Envelope	Modeling Windows and Daylight Control Elements	Parametric window generation and systemic elements
Module 11	Building Envelope-Roof Systems	Parametric Roof Elements	Roof modeling
Module 12	Final Submission		

More specifically, the first layer comprised the core concepts of building systems and technology which included (1) analysis, design and integration of building elements with pre-defined design criteria and constraints: external wall systems, window and door systems, floor systems, vertical circulation systems, roof systems, partition systems, (2) architectonic integration of building structure, materials and assemblies in building element design, (3) interaction building element design process with the building envelope, intermediate floor, stair and partitioning systems and (4) creation of comprehensive virtual models of designed building elements and assemblies. The second layer concentrated on the fundamentals of BIM: (1) creation and management of information through parametric modeling and building object database (2) parametric thinking and abstraction in the context of object-oriented BIM ontology and (3) creation and utilization a building components and systems database using shared seed models.

During the course iterations, students were expected to develop building element design abilities and critical thinking skills —such as *inductive/deductive design reasoning and inferential evaluation of building systems*— through specific BIM tasks and assignments. The learning objectives were (1) to comprehend core concepts of building systems and technology; (2) to develop fundamental skills for building element design and systems integration (3) to understand building elements, properties and system relationships through object parameterization; (4) to build modeling skills with nested data structures, parametric building components and object behaviors. The first two learning objectives were common in control and intervention case study groups in order to make comparative arguments.

3.3 Study Setting and Setup

The research study consisted of a control group and three consecutive BIM-enabled case study iterations. The Control group case was a conventional building technology course largely based on analog 2D representations with 12 students in total (FIG.2). This study was conducted to compare and contrast with new case studies and identify different characteristics of traditional learning schemes and also confirm pre-study arguments and motivations for the research study. The BIM-enabled case study research was conducted in three iterations. These iterations included 13, 13, and 15 students respectively. All of the participating students were freshman and sophomore architecture students without prior knowledge and skills in BIM tools, software and CAD systems. The testbed for the case study was a compact, small-scale residential building with essential functions and a program. Students initially followed an inductive design and development process from forming basic building elements to whole building design. After the first couple of alternatives, all building subsystems were deductively modified for design consistency. Basic parameters and numeric limits for all components were also given for reliable and objective evaluations during analyses. Autodesk Revit™ was selected as the primary BIM platform for its availability with student licenses. All models and parametric sub-components-families were stored and shared on a Dropbox™ cloud space.



FIG. 2: Workshop Environment.

3.4 Ontological BIM Framework

The most critical pedagogic intent was to provide students an ontological understanding derived from the object-oriented programming (OOP) paradigm using an ontological BIM framework. This multi-layered parametric framework was expected to be compatible with the current knowledge level of entry-level students which they can understand building systems and technologies in a hierarchical object-oriented approach. The ontological BIM framework was configured around the content of different properties of building systems and components in a *top-down object database* fashion with “*nested object classes*”. More of a simplification of existing BIM standard data model schemes and implemented family sets, the core idea was to provide students basic knowledge of object-oriented data structures, hierarchies, classes and connected variable types –*numeric, boolean string, etc.* which are parametrically representing a generic building.

Using fundamental OOP concepts, building components are represented with their properties and building system dependencies. These are abstracted in (1) physical parameters and variable sets as *objects* (2) intersystem parameter/object relationships as *structures*, and (3) assemblies and internal component behaviors as *methods*. Based on this notion, the framework included the following: (1) Building system hierarchy, construction priorities and major system and subsystems sets like *structural system, façade system, roof, walls, circulation, etc.* (2) building sub-systems sets including internal objects, form, size and geometry, material properties (3) relationship types like external system connections, internal system connections, object and component dependencies/interdependencies and assemblies. Such algorithmic relationships and dependencies are given as rule sets and conditional functions. These are either implemented by students in component modeling stages or retrieved from the used BIM platform. All of these concepts, behaviors and processes were further explored during

parametrization and modeling sessions to ensure that students' understanding of building systems is switched to a parametric abstraction of the physical reality.

Table 4 illustrates some generic examples for given object definitions in the case studies. Starting from simple to more complex components students were expected to make parametric abstractions for all building components with their modifiable object parameters and variables. This strategy was implemented in all the exercise iterations as a parallel pedagogical agenda.

Table 4. Parametric Object Definition Examples

Building (Generic)				
System: Structure (Generic)				
Component	Form	Structure	Identifiers	Relationships
Beam (Generic)	Geometry (x)	Core (x)	Floor (x)	Internal System Connections: Column (x), Slab (x), Foundation slab (x)
	Size (x,y,z)	Core (x). material (x)	Room (x) ID# (x) Coordinates	
				External System Connections: External Wall (x), Internal Wall (x), Finishings (x), Roof (x)
Building (Generic)				
System: Division (Generic)				
Component	Form	Structure	Identifiers	Relationships
Internal Wall (Generic)	Geometry (x)	Layer (x)	Floor (x)	Internal System Connections: Internal Wall (x)
	Size (x,y,z)	Layer (x). material (x)	Room (x) ID# (x) Coordinates	
				External System Connections: External Wall (x), Slab(x), Finishings (x), Door (x), Opening (x)

3.5 Case Study Process

Although the pedagogical framework was based on weekly consecutive classes, particular learning and implementation stages emerged in every case study iteration. During the first four weeks, students oriented themselves with the learning content, BIM fundamentals and parametric building ontology. This initial stage also required direct instruction and assistance in both learning sets. The second stage was the longest one with more student interaction and collective effort. After gaining familiarity with building technology topics and BIM concepts, students created a social network among themselves for sharing both theoretical/practical knowledge, parametric models and building objects. During the class sessions in this stage, students needed specific assistance for understanding building component behaviors, tectonic systems and related parametric modeling tasks and operations. As the study was based on a parallel pedagogical agenda for providing knowledge about building technology and BIM, the learning settings and setup were devised to balance or integrate both channels. This required relatively more effort in the initial stages of the case studies. As a response, both just-in-time and net-based asynchronous instruction methods were employed for learning and application effectiveness. Such collective assessment and instruction sessions were held according to the student needs while learning to use the BIM tools. The third stage encompassed the last two weeks and it was based on refining parametric models with more detailed building components and communication of design documentation for the final BIM models and particular building subsystems with their tectonic properties.

4. RESEARCH FINDINGS

Qualitative content analysis was used to analyze data. The unit of analysis was the complete interview transcripts and observation notes. All units of text were reviewed multiple times to get a sense of the whole context. Subsequently, an inductive content analysis was carried out (Krippendorff 2018). The qualitative data gathered from systematic observations, focus group interviews and activities were condensed, recognized and coded with key concepts for seeking possible saturations. Following this step, the latent content of the categories was formulated into themes (Table 5).

The frequent feedbacks and common themes were identified for conceptual classification, interpretation and triangulation using the content analysis framework (Tables 6 and 7). Categories and themes were further scrutinized until an agreement was reached. The common themes were concentrated on (1) parametric thinking, comprehension and learning; (2) virtual model production using the acquired knowledge during the course; (3) BIM experience and usability; (4) design process of parametric building components and integration; (5) social aspects of the BIM-enabled learning settings. The research findings and derived arguments from the content analysis are also grouped under the identified themes and common patterns.

Table 5. Examples from the content analysis process; meaning units, codes and categories corresponding to the identified five themes

Unit	Code	Category	Theme
"While defining the building components in the given parametric frame, I also thought about the changes and possible design alternatives I could make."	Parameterization of properties Component models	Parametric representation of specific building components.	Parametric thinking, comprehension and learning
"While creating our models, we thought of the different building subsystems as both a whole consisting of parameters and components of that whole, by associating them with each other."	Creating virtual system models	Content of parametric BIM models	
"When we first started modeling, the software interface seemed very complex and difficult to understand. I had to model iteratively to understand commands, parameters and processes."	Parametric modeling Building element design	Understanding UI	BIM experience and usability
"While producing system sets, the use of seed models with modifiable parameters led me to create different design alternatives."	Generating system alternatives Seed model use	Model creation and modification	Virtual model production
"It was interesting to see the façade and its elements directly related to the structural system. Finding such balances between those required lots of modeling with different parameters..."	Assembling Building envelope design	System integration and assemblies	Parametric design process
"To give an example, sharing sample models of different staircase types and collective evaluations were very useful in terms of learning."	Vertical circulation system Building system design Model sharing	Parametric model sharing and information exchange	Social aspects of the BIM-enabled learning settings

Table 6. Case studies and meaning units

Study	Focus	Number of Units
Control Group	Focus Group 1: Conventional	50
Case Study 1	Focus Group 2: BIM-enabled	83
Case Study 2	Focus Group 3: BIM-enabled	76
Case Study 3	Focus Group 4: BIM-enabled	71
Post Study Evaluation	Full Focus Group + Observations	148

Table 7. Frequencies of common themes and categories

Theme	Frequency	Category	Frequency
Parametric thinking, comprehension and learning	96	Parametric representation of specific building components.	29
		Content of parametric BIM models	23
		Transition in design representations, modes, and scales	21
		Differences between conventional and BIM-enabled learning	23
BIM experience and usability	53	Understanding the BIM UI	28
		Learning problems during the development of BIM skills	25
Virtual model production	85	Model creation and modification	38
		Extension of the design and modeling content	22
		Creation of nested system models	20
Parametric design process	62	System integration and assemblies	25
		Simultaneous design feedback	20
		Utilization of parametric seed models	17
Social aspects of the BIM-enabled learning settings	38	Parametric model sharing and information exchange	25
		Changes in instruction, modes and roles	13



Based the employed grounded theory framework the concepts and themes from the content analyses were used to synthesize explanatory constructs with the corresponding research findings which are later elaborated in the proposed theoretical model. The constructs and key findings are summarized in Table 8.

Table 8. Explanatory Constructs and Summary of Findings

<i>Explanatory Constructs</i>	<i>Key Findings</i>
Learning mechanisms through parametric BIM ontology	<p><i>Examination of the systemic relations and sub-system alternatives within the framework of parametric object relationships.</i></p> <p><i>Effective use of time for learning, comprehension of course topics and visual communication using parametric models and components.</i></p> <p><i>Extension of scope of the course beyond the typical building systems class with the flexibility and possibilities of BIM methods.</i></p> <p><i>Comprehensive representations using explanatory BIM models for complex building systems, sub-groups and their relationships.</i></p> <p><i>The student need for just-in-time support for software use and interface usability.</i></p> <p><i>The necessity of interface and function limitation for effective use for students.</i></p> <p><i>Duality of learning subjects and instruction modes for building systems and BIM.</i></p>
Parametric design thinking, abstraction and design synthesis	<p><i>Cognitive alteration of thinking building systems and assemblies through parametric abstraction and object-oriented understanding</i></p> <p><i>Observable cognitive mechanisms of decision making through BIM interaction.</i></p> <p><i>Change in the design process through parametric and simulative modeling</i></p>
BIM-enabled modeling processes and design production	<p><i>Change of conventional drafting into parametric modeling which is more complex, multi-dimensional and scale transitive</i></p> <p><i>Evaluation of multiple alternatives through model modification</i></p> <p><i>Effective propagation and modification of seed models resulting in an increase</i></p>
BIM-enabled social interactions and communication channels	<p><i>Formation of an informal social network for BIM-enabled collaborative production and collective learning</i></p> <p><i>Exchange of modular and adaptable model sets among students which catalyzed learning and knowledge transfer</i></p>

Findings from the research study, post-study focus group and observations suggest significant changes in students' comprehension and learning mechanisms of building technology, tectonic systems, building element design and development. These findings are further described and scrutinized in the following narrative for the target audience for exchanging the experience that may help to organize similar learning settings.

When compared according to the learning objectives, both groups showed satisfactory performances that meet the expectations of "conventional level" classes, especially in the comprehension of building systems integration and basic skill development. The assessments were made according to the criteria set derived from the learning objectives the design quality of architectural composition of building components, system sets and assemblies; and the precision levels were used to evaluate student works. The depth of representation and comprehension levels with created visual information was also considered. The final submissions in the control group were based on 2D drawings and manual 3D projections which can be argued as limited for wide-range comprehension of learning subjects. However, the transformation of the students in the control group was significant as the students were able to understand, communicate and represent their designs with a "parametric language" and discuss the different design possibilities and system modifications. The BIM methods also enabled case study students to examine the complex systemic relations between building systems and elements and create custom elements and sub-system alternatives within the framework of parametric object relationships. In this context, it can be said that the depth of the discussions and production levels in the BIM-enabled case study groups were deeper and comprehension levels were significantly higher due to the occurred cognitive alteration through parametric abstraction.

The post-study focus group revealed interesting information about the students' experience and their perceptions during the learning process. In a semi-structured fashion, a set of questions were directed to understand the specific issues like learning parametric thinking, comprehending building systems with parametric objects, development of BIM skills and execution of acquired knowledge. The most important feedback was the students' enthusiastic embracement of BIM concepts, processes and tools. BIM was perceived as an extension to what they are experiencing with other tools and mobile apps. Many students reported that the new process was more resembling popular life simulation games which they were playing since their childhood. In detail, students emphasized the interaction with BIM and virtual construction media was familiar and convenient without any restrictions like defined learning space or controlled learning modes with predetermined drawing tasks in the school. It was also reported that making radical changes was possible with BIM even though they were learning two parallel sets of topics. In addition, the issue of "time" was elaborated in the focus group study. According to the students, the use of BIM was not decreasing the dedicated time for learning but significantly transforming its content. Students reported that the time was effectively used for learning, comprehension of learning topics and communicating both models, parametric components and also the gained knowledge rather than long hours of drafting.

Students confirmed the effectiveness of parametric seed models during the early stages of the study however they needed vastly modified models and families for their own specific needs in more advanced phases. It was also reported that virtual design and construction with BIM motivated students to embrace their projects as if they were constructing them in real life (FIG.3). Students also underlined the potentials of BIM for learning building technology-related topics like materiality, acoustics, building physics and energy modeling based on their own internet searches and discussions about BIM methods during the study.

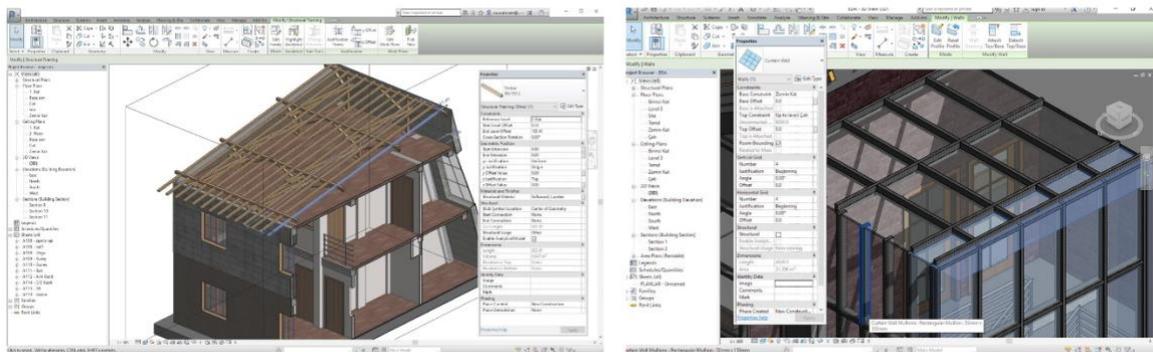


FIG. 3: Parametric Implementation of Building Systems.

The focus group feedback was corroborated with the systematic observations from the case study iterations. These observations showed that students can better understand the systemic relationships between building elements and systems through parameterization and simulation with BIM models. The control group with conventional course content emphasized 2D and solid representations of building systems with standard development and drafting procedures. Observations and students' responses revealed that the main motivation during control group exercises was the creation of the requested drawings with appropriate drafting conventions rather than the learning of fundamental concepts of the course. It was also reported that the abstraction level in the projected 2D drawings of building subsystems was making it harder to comprehend due to partial and disconnected representations in different scales and detail levels.

As compared to these conventional approaches, the employment of BIM methods allowed students to create 3D parametric building components, detail sets and BIM-specific parametric object behaviors with simultaneous software feedback. The seed models enabled students to create such alternatives for particular building components and understand the sub-components and their assemblies (FIG.4). The use of BIM also helped students to instantly realize many interconnected and complex problems regarding building systems which were not possible with conventional course schemes. The main problem here was the learning curve especially in the first couple weeks for understanding key concepts of building technology and BIM while using a "complex user interface" —as described by the participating students. Students told that this particular stage was the most critical part for the overall success of the study.

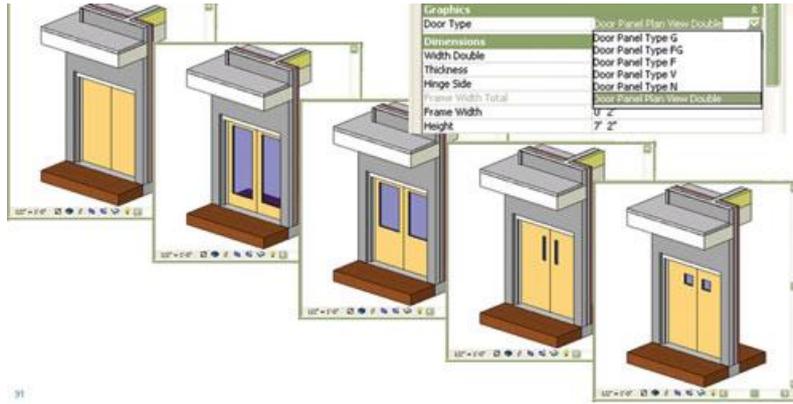


FIG. 4: Seed Model Modifications for Building Components.

These findings point out a significant transformation in two levels: (1) drafting action changed into modeling which is more complex in content also multi-dimensional and scale transitive; (2) the creation process of building systems involved observable cognitive mechanisms of decision making through BIM interaction. It can be said that students developed new thinking levels which were based on and parametric abstraction of building components and object behaviors. While creating parametric building components, students iteratively examined their sub-components by modifying properties like form, dimensions, geometry and material relationships (FIG.5).

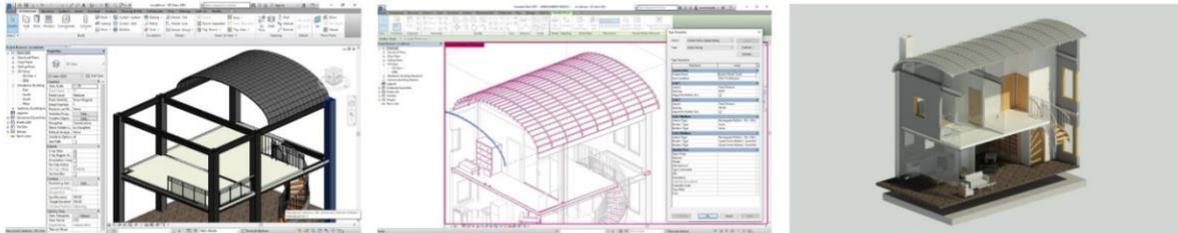


FIG. 5: Model Development Process with Parametric Building Components.

The digital models included building component families propagated from seed models which were created during collective sessions or student collaborations. The exchange of modular and adaptable model sets among students positively catalyzed learning and knowledge transfer. The representation depth was comprehensive and also substantially explanatory with complex building systems sub-groups and their relationships through 3D sections and perspectives. Students were also able to explore their component database after modeling with building component lists and quantity take-offs which may be an initial learning step to understand BIM in nD levels for cost, scheduling and maintenance.

From the observations, other explicit benefits of parametric BIM can be listed as the rapid design of various building components through testing them in the whole building system and the increase in the number of alternatives during the short course timeframe (FIG.6).



FIG. 6: Models Alternatives with Parametric Building Components.

It was also observed that the scope of the course was extended beyond the typical building systems class with the flexibility and possibilities of BIM methods. The discussions among students evolved into the exchange of design-focused knowledge and strategies from the macro to micro level. Students stressed the influence of schematic design and space configuration decisions on overall architectonic layout, materiality and building details. Students' comprehension of these transitive processes —*even in the early phases of their education*— was aligned with the well-documented advantages of BIM for integrated design (Clayton et al. 2010).

Another important pedagogical dimension of the study was the transitions between instruction modes according to students' reactions during the learning process. As explained very briefly in the previous section, the study started with direct instruction of building technology basics and the fundamentals of parametric BIM methods. This ensured the effective transfer of critical knowledge and skills of parametric thinking and modeling using BIM tools. During the later stages, the instructor role changed more into a learning facilitator with just-in-time instruction for the specific needs of the students. Orchestration of the whole learning experience emerged as a central task with the organization of small group discussions or collective assessment sessions when students encountered common problems or critical points. With this indirect instruction support, students were also able to create their own solutions with the information they gathered from these short instructions or given examples and internet resources.

The observations and student feedback pointed to the existence of a *social network* that was formed gradually during the case studies —*especially in the second iteration* as students developed an understanding of parametric building modules and propagation and adaptation of model sets. This was a student-led effort that was not encouraged by the workshop facilitators. As the designs progressed with different building subsystems students created a shared model repository and a digital pinboard for exchanging parametric models in categorized folders. According to the students the inspiration came from the fundamental BIM discussions and practical examples of model-centric collaborations. Such social media services were also used for instant communication. The collaboration occurred in many levels such as (1) conception of parameter schemes for building components (2) creation of basic model sets (3) solving problems of software use (4) adaptation and modification of seed BIM models and (5) assessment of building systems alternatives and sub-system set designs. The shared repository grew larger with the process where students used it extensively for communication and collaboration.

Similar challenges occurred in all cases. Such problems can be listed as (1) the learning curve of BIM software that was clashing with the course content in the first couple of exercises and (2) difficulties in the effective use of complex user interface of the BIM software. As reported by the students in the focus group study, such irregularities in the learning curve were also experienced due to the procedural differences in modeling for each teaching/training module. The key approach to overcome such problems with the learning curve was to provide modular training sessions for specific tasks. As the initial modules were focusing on basic building components, the study facilitators used this opportunity to provide students a familiarity with the software interface and its basic functions. Based on the course objectives and the learning content, such usage limitations with specific modeling procedures also helped students to comprehend the parametric BIM modeling logic connected with certain software capabilities. The common problems with the software use significantly decreased after the first four modules with the help of just-in-time instructions and collective assessments of common or specific problems. In all case study iterations, the second half of the study after the midterm submissions was more fluent in terms of software use and modeling procedures. Students also reported that suggested online training resources were effective and helped them to solve their problems or understand the capabilities of the tool. These operational problems are very likely to occur in future iterations however it is manageable through creating proactive coaching strategies and strategic course preparations for BIM software literacy. As an extension of this matter, it can be argued that BIM-enabled learning environments necessitate vibrant social communications among students. During the research study, both digital and verbal information exchange supported the students' perception of parametric BIM concepts and significantly increased the development of BIM software skills. As mentioned in the case study introduction, participating students had no prior skills in CAD software. This was not a barrier or a negative factor for students to learn and utilize BIM software and modeling tools. Commonly accepted as a superset of CAD systems, the deployed BIM software provided direct interface interaction and a necessary 3D working environment for students.

5. THE “DUAL-CHANNEL” PEDAGOGICAL MODEL

The findings from the study were synthesized in a theoretical pedagogic model for further use in BIM-enabled case studies and educational experiments. This model is more suggestive rather than descriptive since it is based on the employed grounded theory approach with explanatory constructs, observations and findings from the study. The model is influenced by the pedagogical approaches that are presented in the literature review such as *problem-based learning*, *experiential learning* and the hierarchy levels of cognitive domain described in Bloom’s Taxonomy (1956). These are *knowledge, comprehension, application, analysis, synthesis, and evaluation*. Similar concepts are also derived from the “*design methods*” theories which provide a sound basis for describing cognitive mechanisms during the design process (Jones 1992; Lawson 2006; Cross 2007). In this perspective, Lawson’s (2006) map of the design process also attempts to describe the thinking and application modes for a given design problem as *analysis, evaluation and synthesis*. Considering the cognitive content of these modalities and concepts the proposed model is based on three consecutive and cyclical learning modes that are interrelated in terms of parametric understanding, thinking and doing using BIM methods and tools. These are (1) the mode of *instruction*; (2) the mode of *comprehension* and (3) the mode of *production*.

The first mode *instruction* involves the formation of an ontological foundation for BIM along with the building systems and technology learning topics. The dual-channel pedagogical agenda prioritizes parametric thinking related to basic object-oriented understanding. The general object-oriented programming ontology lays the theoretical basis for all learning activities. The parameterization of physical building components and their dimensions, relationships, behaviors and hierarchies is matched with the actual properties for the synchronous learning of building systems and BIM concepts. The key approach here is to facilitate learning through *just-in-time instruction* for both theoretical or conceptual topics as well as the practical use of BIM software for more of an operational agenda.

The second mode is *comprehension* which includes the development of a systemic understanding of building components and architectonic systems through parametric components and their object behaviors. As seen in the model the hierarchical BIM object scheme is suitable for any building system learning topics and course syllabi. The scheme can be defined as the nested data constructs of parametric objects and connected constructive behaviors (FIG.7). This hierarchical scheme can be synthesized in generic seed models for further development and experimentation for understanding parametric BIM models.

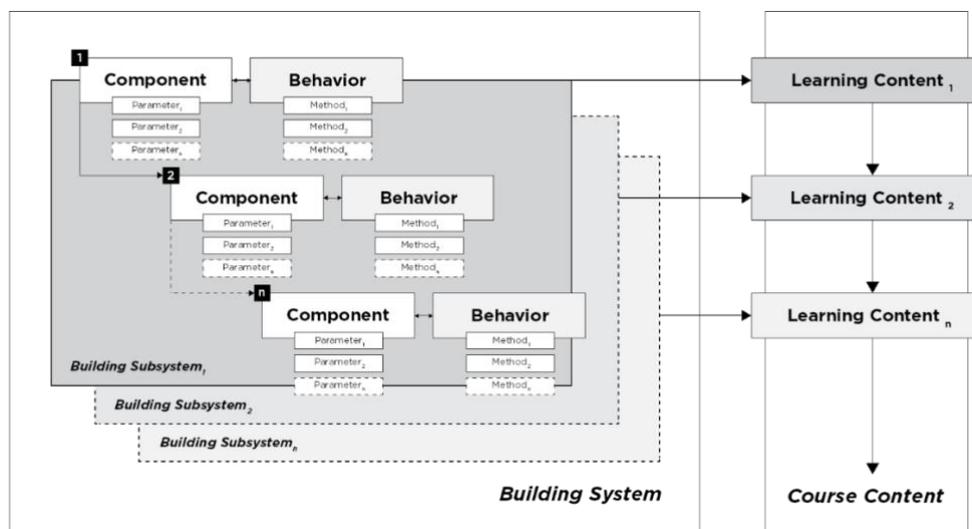


FIG. 7: Learning Process with Nested Model Structure.

The third mode is *production* that comprises the application of acquired knowledge from the previous modes. The iterative cycles of parametric production refer to comprehension mode as it contributes to the in-depth understanding of object-oriented building ontology. As seen in the model this can also be considered as synchronous learning and doing processes through the synthesis of interconnected building systems and assessment of their constructive relationships with adaptable BIM models (FIG.8). From the learning environment point of view, this mode is mainly base on the formation of a social network among students which may catalyze

learning with information and model exchange and knowledge dissemination. The exchange process is expected to prompt model propagation for students to customize the seed models and alter detail sets for their own building system designs. The final design model serves as the holistic synthesis of the learning content through parametric BIM methodology and object-oriented thinking. The design alternative its virtual construction model conveys the composition of building system sets, hierarchical relationships and assemblies through a progressing artifact that represents *a system of systems*. It also helps as a multi-layered deliverable to evaluate the overall performance of the student including comprehension of building systems design, fundamental construction technology and parametric BIM literacy.

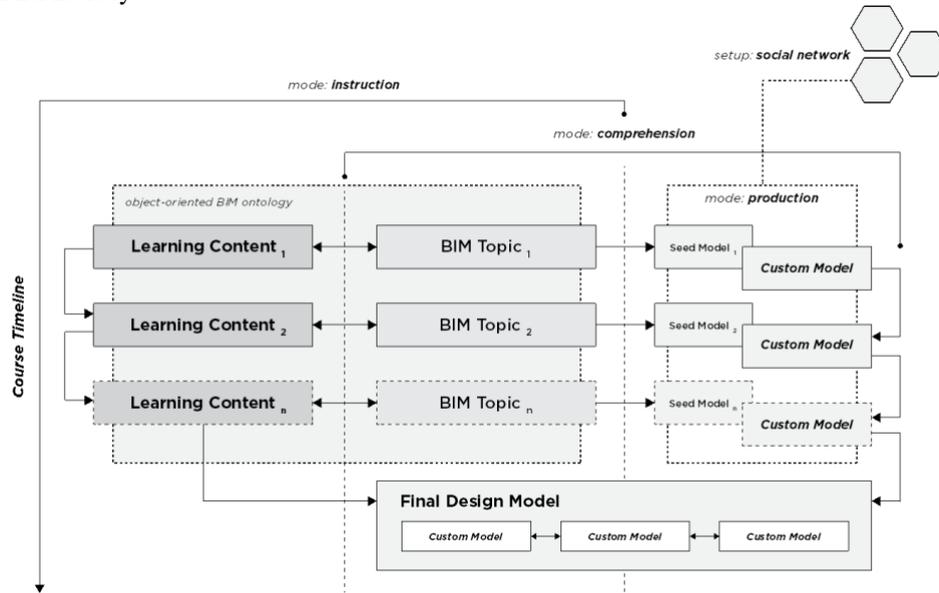


FIG. 8: The “Dual-Channel” Pedagogical Model.

Based on the aforementioned dual-channel process, two feedback modes are included in the pedagogical model concerning the design process and BIM use. Assessments of design alternatives in a desk-crit fashion and collective evaluations of group performance. The feedback cycles base on the design quality of alternatives, architectonic content of the building components, systemic relationships and appropriate execution of parametric BIM methods. This has two dimensions like the quality of the design part was evaluated more implicitly largely organized around socratic dialogs in a desk-crit discussion fashion. The parametric modeling schemes are assessed explicitly with the given BIM learning objectives and parametric integrity of BIM models. Iterative feedback cycles are facilitated with shared BIM models where students and instructors can access and provide rapid feedback about building component design and the composition of system sets. The following table includes the core subjects and criteria set for the feedback cycles (Table 9).

Table 9. Feedback Cycles

Design Feedback Mode	BIM Feedback Mode
Building component design (form, material, size)	Object parameterization of the given component
Composition of system sets	Related object behaviors and methods
Assemblies of building systems	Intersystem relationships through parameters
Holistic design quality and architectonic configuration	Integrity of the BIM model and parametric execution

The assessments are made using the similar criteria set for the feedback cycles and learning objectives of the study. The level of parameterization scheme of building components, the robust configuration of object-oriented BIM object structures, successful implementation of object behaviors and system assemblies, and progression of design tasks are the key indicators of student performance.

Complementing this pedagogical framework, *problem-based learning* (PBL) is an effective instructional methodology by the introduction of appropriate problems to initiate the instruction-learning cycle and provision of the context and motivation for the learning activity (Prince 2004). PBL is active and collaborative or cooperative

and it necessitates self-directed learning –*involves both design and parametric modeling tasks* on the part of the students which is adequate for a BIM-enabled course. The pedagogical objectives of PBL fairly suit the fundamental concepts of BIM as it prioritizes highly integrated and collaborative activities which are crucial for learning building systems design and technology (Leite 2016). Here the instruction and learning cycle is initiated with the open-ended design problems and the learning context is organized around parametric BIM methods. Core aspects of comprehensive problem-based learning are also addressed in the model as the following: (1) the setting and setup is organized around an intriguing and open-ended design problem (2) the need for parametric understanding and building new BIM skills are essential (3) the inquiry for object-oriented thinking and BIM-enabled design is required for reasoned decision making (4) student-led processes, teamworking and social interactions are encouraged (5) and iterative feedback cycles are incorporated in both channels (Duch et al. 2001).

The proposed model ensures the sharp transformation of learning mechanisms for building systems and technology with object-oriented/parametric thinking and understanding. Within a tangible pedagogical stance, the diversion from conventional and formal teaching methods is targeted to change the process of conceptual comprehension, knowledge acquisition and application of parametric know-how which is compatible with the current trends of innovative AEC practice.

6. CONCLUSIONS

From a general pedagogical point of view, this research study confirms the theoretical potentials of BIM for learning complex building systems with well-reasoned arguments and empirical research results. The study took the opportunity to introduce BIM-in-the-context in the earliest phase of architecture education. This initial stage focused on the parametric ontology and thinking for laying the foundation for more advanced educational applications like collaborative student teamwork with multi-layered shared models; BIM database management; cost estimations; 4D construction visualizations and building energy simulations.

Both the prototypical pedagogical framework and strategies in this study combined with the research findings provide replicable and conveniently transferrable know-how for further educational experiments as it is previously explained in the synthesized theoretical model. Similar learning environments and course syllabi can be developed centered around the duality of specific learning subjects and the corresponding BIM topics. Based on the findings from the research study, significant advantages are evident with carefully devised learning settings, detailed course content and proactive solutions for the operational problems of BIM use. With new studies in similar educational settings, more insights and advantages will be revealed in different stages of architectural education.

In light of the findings from the study and its main motivation, the key discussion is the transformation of building technology learning with parametric thinking and understanding. This shift brings new cognitive and tactile skills that are completely apart from conventional pedagogical methods and inevitably necessitate novel strategies. Here, the study suggests that such possibilities for pedagogical innovations can be achieved by altering well-established teaching traditions with techno-centric approaches and hybrid learning settings through the synthesis of BIM and the specific learning subjects. The embracement of BIM and parametric understanding can be the vessel of new-age learning for building and construction technology at all levels which can be realized with deliberate intent as presented in this study. From the social learning point of view, it can be hypothesized that BIM-enabled learning is suitable for the Y and Z generations for its highly techno-centric content —*which was underlined by the students as the main motivation source* and compatibility with current networked social interactions among students.

For the concluding remarks, the study provides the necessary arguments for changing how we educate future generation architects and construction professionals along with the current developments in the AEC. From this perspective, a full parametric BIM-based studio —*even in the early phases*, organized around building technology education has vast potential to tackle the rapid changes in design, manufacturing and fabrication methods for preparing students for a knowledge-based AEC industry of the 21st century.

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