STUDIO EDUCATION FOR INTEGRATED PRACTICE USING BUILDING INFORMATION MODELING

A Dissertation

by

OZAN ÖNDER ÖZENER

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2009

Major Subject: Architecture

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Approved by:

Chair of Committee,	Mark J. Clayton
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ABSTRACT

Studio Education for Integrated Practice Using
Building Information Modeling. (December 2009)
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Chair of Advisory Committee: Dr. Mark J. Clayton

This research study posits that an altered educational approach to design studio can produce future professionals who apply Building Information Modeling (BIM) in the context of Integrated Project Delivery (IPD) to execute designs faster and produce designs that have demonstrably higher performance. The combination of new technologies and social/contractual constructs represents an alternative to the established order for how to design and how to teach designers. BIM emerges as the key technology for facilitating IPD by providing consistent, computable and interoperable information essential to all AEC teams. The increasing trend of BIM adoption is an opportunity for the profession to dramatically change its processes and may potentially impact patterns of responsibility and the paradigms of design.

This study showcases a repeatable framework and a theoretical model for the integrated studio using BIM and provides answers to the pedagogical questions raised by BIM, integration, and performance-based design. Using a formative and exploratory action-research design, the study proposes a comprehensive pedagogical framework using the established theories of design studio education, building integration, and BIM. The framework was refined and triangulated in a set of focus group studies that include academics, design firms and AEC industry representatives, as well as students.

Instrumental case studies implementing the pedagogical framework were conducted as courses in a graduate architecture program. Students' design processes and collaboration schemes were observed using systematic methods that included a broad range of data in conformance with a multi-method research approach.

Content analysis of the data provides qualitative evidence for the effectiveness and encountered challenges of BIM methods that is related to proposed studio framework. These findings are corroborated by descriptive statistics and numerical data from the surveys, simulations, reports, and BIM models.

Findings of the study illustrate that a carefully designed set of course exercises that incorporate BIM can enhance design processes, increase the depth and the number of alternatives studied, catalyze an interoperable and integrated educational environment, and expand the scope of design learning. Case studies presented here suggest common patterns of collaboration between designers and consultants during the integrated design process using shared BIM models. The findings from the study are synthesized in two theoretical models for the BIM enabled integrated studio and collaborative processes.

DEDICATION

To my family

Güler, Tahsin and Örsan Özener

ACKNOWLEDGEMENTS

First and foremost, I would like to express my deepest gratitude and appreciation to all of my committee members. Dr. Mark Clayton, my committee chair, gave me enthusiastic encouragement, scholarly guidance and tremendous support throughout my doctoral studies. Robert Johnson helped me increase my understanding of research methods and provided constructive criticism throughout the entire research process. Wei Yan generously dedicated his time and gave valuable expertise to improve my work, while José Fernandez-Solis provided me with sound suggestions and deep theoretical insight.

Furthermore, I would like to thank Jorge Vanegas, Charlie Culp, Valerian Miranda and Donald House for their contribution and suggestions. I also thank Autodesk Educational Department for their generous support during the research process.

Moreover, I am grateful to my friends, professors and colleagues, as well as College of Architecture students and staff for their continuous help and support. More specifically, I am very thankful to my friends and colleagues Carlos Nome, James Haliburton, Francisco Farias, Billie Graham, and Kashif Dafedar, for providing sincere help, expertise, and suggestions when most needed.

Special thanks to my close friends Ahmet Uğursal, Cem Yüksel, Dilhan Ilk, Cansin Yaman Evrenosoğlu, Can Atila, Taner Özdil, Masha Sukovic, Zeynep Doğan, Ceylan Öner, Gamze Erdem, and Zeki Melek, who made these past five years memorable and fun for me and offered their help and encouragement when it was most needed.

Many thanks to Phillip Rollfing for being such a great supervisor and a friend, as well as Kathy Waskom, Melinda Randle, and Jill Raupe for helping me solve all the administrative issues I came across while working on my dissertation.

Above all, I wish to express my deepest thanks and love to my family for always being there for me and for their unwavering belief in me and my work in spite of many hardships we've faced in the past five years. They are the most wonderful family anyone could ever wish for, and for that I am truly grateful.

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CHAPTER I

INTRODUCTION

The technology of Building Information Modeling (BIM) coupled with innovative partnership contracts known as Integrated Project Delivery (IPD) has the potential to disrupt current architectural practice and replace it with a model of practice that is substantially more productive. As the academy attempts to keep pace with the profession, it can be challenging for educational institutions to adopt new technology and create effective teaching strategies. This research study posits that an altered educational approach to design studio can produce future professionals who apply BIM in the context of IPD to execute designs faster and produce designs that have demonstrably higher performance. By coupling the technology of BIM software with the process of integrated, collaborative design using an evidence-based decision paradigm, educators can reform the design studio to tailor it to the 21st century context of advanced information technology, multi-disciplinary collaborative design, and demand for high performance architecture.

The findings of this research address fundamental changes to studio education by incorporating new opportunities derived from the integrated practice and BIM

This dissertation follows the style of *Journal of Planning Education and Research*.

methods and technology. This research is based on the interconnected relationship between practice and the design studio, which forms the practicum for the education of future designers (Schön 1987). Using this premise, the study focuses on three major domains related to this study:

> **Theory of BIM:** This domain includes definitions, the premises, and implications of BIM; development and implementation of Building Product Models (BPM); technological and process components of BIM; interoperability and data standards for effective information exchange; and the relationship between BIM and performance based design.
>
> **Integrated Practice:** This focus domain encompasses the major dimensions of the architectural practice and the AEC industry, current social-economic and environmental influences for AEC integration; current and expected transformations in the AEC industry and architectural practice; demand for interdisciplinary collaboration and contractual changes; and BIM as the catalyst of integrated project delivery and integrated processes.
>
> **Integrated Studio Education:** The last domain of this study focuses on current and future practices for studio education, motivation for integrated studio approaches and incorporation of BIM in the design studio as a comprehensive method for performance based design.

Figure 1.1 illustrates the dimensions of these three domains and overlapping concepts that are the cornerstones of this research study.

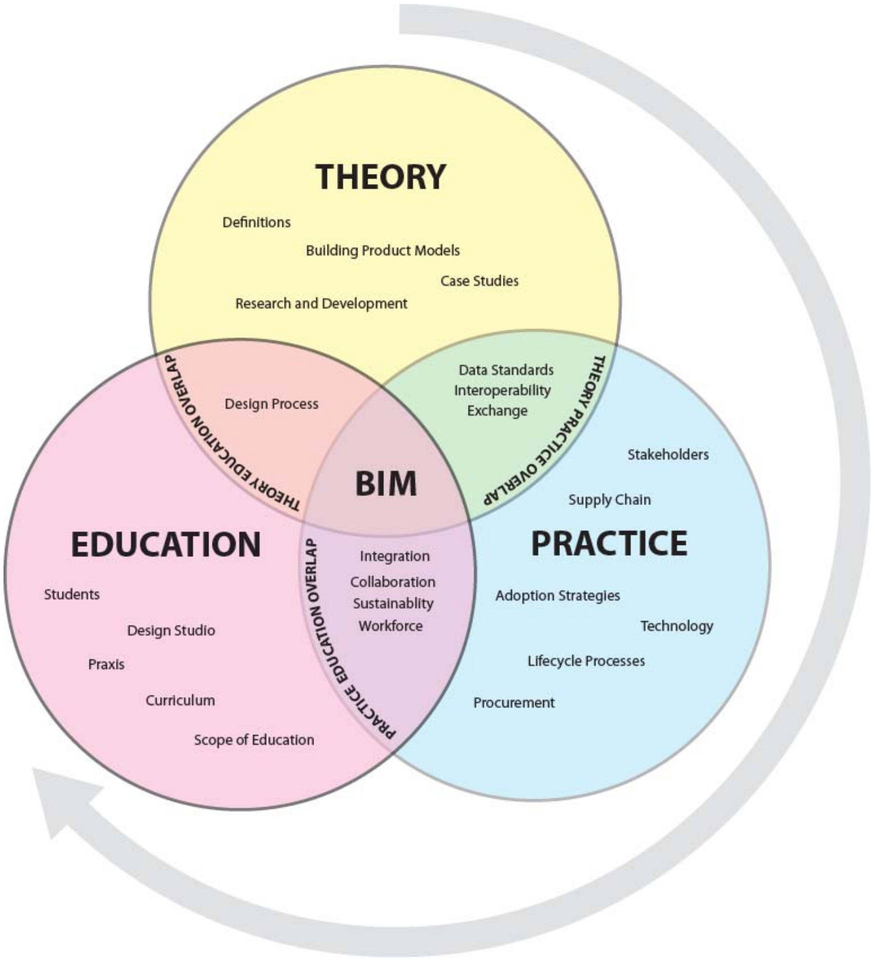


Figure 1.1: The interactions between research domains and the inquiry process

The study incorporates a review of the theoretical premises of BIM, critical examination of the typical studio educational setting and objectives, and identification of change

patterns in architectural practice. Furthermore, it envisions a new model for studio that targets the preparation of students for IPD using BIM, and investigates the model in a series of instrumental case studies.

The results of the study show the existence of a significant transformation in the AEC industry, including various adoption strategies for BIM. Identified patterns of change and different value propositions, which necessitate new educational forms and pedagogical practices, are described through an analytical model. A proposed pedagogical framework emphasizes the distinctions between traditional and integrated approaches, provides well-reasoned methods and strategies for integrated studio education, and describes the roles and components of this education environment. Instrumental case studies provide qualitative and quantitative evidence for the establishment of a theoretical framework of the new "practicum" for the integrated education. Findings from the case studies suggest that BIM supports an integrated feedback cycle that results in the expansion of scope, faster production, and comprehensive assessment of the studio projects. Results also reveal both the effectiveness measures and challenges of the proposed pedagogical approach. Findings of the study are synthesized to an evidence-supported, theoretical studio model including pedagogical scope, learning objectives and tools. The emerged schemes of design process and information exchange in the case studies are explained in a descriptive and empirical integration model between designers and the consultants.

1.1 Problem Statement

Arguably, the conventional design studio course assumes and promulgates an outmoded model of practice that emphasizes tacit knowledge and highly hierarchical and authoritarian organizational forms for project teams (Anthony 1991; Fisher 2004; Hamilton and Watkins 2009). However, the 21st century professional environment must address the dynamics of a changed professional context that includes technological innovation, acute environmental issues, imperatives for sustainability, socio-economic changes, and globalization (Krygiel and Nies 2008). This new context demands that architects have a wide range of skills and be capable of comprehensive decision-making utilizing reliable and explicit information. Therefore, it is critical to societal success that students learn to design and build faster, more efficiently, at higher quality and with higher performance (Clayton 2006; Freidman 2007).

Traditional methods involve “design drawing,” not only for the purpose of communicating with others, but also as a part of the thinking process of design (Lawson 2006). The conventional Computer Aided Design (CAD) approach transformed the representation methods from analog to digital media but, by being limited to graphic representation, failed to provide broad information for design, analysis, and construction of buildings. BIM has the potential to transform and expand this process from “design by drawing” to “design by modeling and simulation” through the creation of information based on parametric building models and automation of expertise by specific software tools (Kieran and Timberlake 2004). In addition to this information-centered approach, theory and practical applications of BIM have the core intent of process integration (Eastman 2008; Krygiel and Nies 2008). Current BIM tools and available data standards are capable of facilitating collaborative activities in the building lifecycle, supporting design processes, and increasing the efficiency of communication between designers and consultants by creating consistent and reliable information about the building performance. As a whole, BIM is not an improved CAD technology for advanced representation and documentation; BIM is a comprehensive method of design and information production which is facilitated by the appropriate information technology. In brief, BIM can be viewed as the underlying technological layer of IPD.

Because of its capabilities of integration and automation, BIM has the potential to enhance the processes within architectural education. BIM provides tools for students and educators to create parametric building models, spatial simulations, and the capabilities to create a wide-range of performance information about design alternatives in terms of sustainability and constructability. When applied in an educational setting emphasizing integrated design, incorporation of BIM can achieve outcomes that parallel the benefits observed in practice and predicted by theory.

Despite the fact that interest in BIM is rapidly increasing in the field of integrated education and performance-based design, the literature of architectural education lacks an empirical understanding of integrated studio environments that use BIM methods and technology. By implementing integrated design and BIM, a studio framework can be transformed into a collaborative learning environment. Students and consultants can leverage BIM for in-depth assessment of studio projects through dynamic, continuous and cyclic design processes. To achieve these goals, it is essential to have a comprehensive understanding of integrative pedagogical methods for BIM and the design studio education that is based upon empirical research studies.

1.2 Research Objectives

The primary purpose of this study is to provide a comprehensive understanding of the potentials of BIM methods and technology in the context of integrated architectural education. Pursued research objectives included the following:

1. Critical examination of theoretical premises of BIM, design methods and existing studio practices;
2. Identification of trends and patterns of BIM adoption in the AEC industry and resulting transformations in the business models and project delivery methods;
3. Development of a well-reasoned pedagogical framework for the integrated studio using BIM;
4. Exploration of the prototype framework with carefully designed case studies;
5. Assessment of case study results and synthesis of a theoretical model for the integrated design studio.

The study also sought to illustrate student demographics, responses, attitude changes and the changes in the scope of design. Both qualitative and quantitative data collected in this study provide evidence to describe the mechanisms of integrated design process through the use of BIM.

1.3 Research Questions and Hypotheses

The study used action research to test the hypothesis that students who have skills in computer methods, design synthesis, and architectural technology can learn a new design process that is more effective for performance based design than the conventional process as taught in typical academic design studios. This new form of design studio employs BIM methods, which necessitate an integrated approach.

The research questions of the study are grouped in the aforementioned domains of the research and they correspond to the specific research objectives given in the previous section. Each main research question is followed by the related sub-questions that are addressed in this dissertation:

Research Question 1: What are the theoretical propositions of BIM for integrated and performance based design?

Sub-questions:

a) What is the underlying motivation for BIM for performance based design process and product improvement in architectural practice?

b) What are technological and organizational aspects of Integration in the AEC?

The research study addresses these questions by using evidence from established literature on BIM; integrated practice; R&D activities and findings from the previous research; and expert opinions.

Research Question 2: How does BIM influence the AEC industry and the practice of architecture?

Sub-questions:

a) What are the current trends of BIM Adoption in the practice?
b) What are the dimensions and mechanisms of integrated design in current architectural practice?
c) What are the desired skill set and capabilities for the future professional for BIM-enabled IPD?

The evidence for this question set included the recent research reports; focus groups findings; opinions of industry representatives and experts; as well as collective case studies that incorporate integrated processes and BIM methods and technology.

Research Question 3: Does BIM catalyze performance based design learning in an integrated studio environment?

Sub-questions:

a) What are the pedagogic and strategic dimensions of an integrative studio framework?

b) How does BIM influence the scope, process and the outcomes of the integrated studio?

c) What are the mechanisms of integration and collaboration among students during an integrated studio process?

The evidence for this last question set consisted of a broad range of data and findings such as demographics of the students, pre-studio and post-studio surveys results, shared BIM models and visualizations, simulations and reports from the instrumental case studies, and expert opinions and evaluations.

1.4 Significance of the Research and Contributions

Addressing the research objectives and the research questions, the study provides a comprehensive understanding of integrated studio education through BIM. The study explains the current trends in the practice domain using an analytical adoption-performance model. The model forms the cornerstone for the prototypical pedagogical framework. The pedagogical framework includes strategies, tools, roles, studio settings, and setups for further experiments. Findings from the instrumental case studies document the responses of the students to the integrative studio environment using BIM tools. Observations provide in-depth understanding of process phases, emerged design and communication patterns, and collaborative design schemes. The study discusses both effectiveness and challenges of the proposed approach.

Findings are synthesized in two comprehensive theoretical models: Studio 21 and CircleX. Studio 21 model provides theoretical foundations, pedagogical strategies and implementation procedures for integrated studio using BIM. CircleX integration model explains the collaboration and integration mechanisms in the integrated studio during early phases of design.

1.5 Organization of the Dissertation

The dissertation is organized into following chapters aligned with the expletory and formative character of the research inquiry:

1. This first chapter provides the motivation, basic concepts and significance of the study.

2. The second chapter provides a rigorous description of methodological considerations, employed research techniques, instruments, and the relationship between the research problem and the multi-method research paradigms. Additionally, this section outlines the research design and the functions of each research technique for the triangulation of the theory, findings from the focus groups regarding BIM adoption and the case study process and results. Finally,

the content analysis framework tailored for the research study is explained in detail.

3. The third chapter provides a critical literature review that summarizes the theory of BIM, process integration, architectural education, studio practices, and integrated design processes. The extensive literature review establishes the anchors for references and identifies the knowledge gap that justifies the research study. This research assumes the existing literature as a qualitative data source and uses the arguments from the critical review as the theoretical basis of the proposed pedagogical framework.

4. The fourth chapter includes the focus groups and the pilot study. The analysis of the transcribed texts and collected case studies lead to the identification of BIM adoption strategies, patterns of change in the AEC industry, architectural education, studio practices, and required changes in the studio for integrated education. The arguments and theoretical precedents are synthesized in a performance model-adoption model for BIM. An in-depth discussion for BIM and design methods is provided as the theoretical foundation. A detailed pilot study shows the results from a conventional studio experiment with BIM. Evaluation of findings from these research efforts is used to formulate the pedagogical framework for further investigation. The prototype pedagogical

framework describes the roles, educational settings, pedagogical objectives, and the underlying idea for an integrated studio environment for further investigation.

5. Chapter V includes the instrumental case studies for the exploration of the proposed pedagogical framework. The case studies simulate an integrated studio setting through the use of BIM. The chapter provides student demographics, findings from the surveys, examples of student work, energy and constructability simulations, in-depth analyses, and evaluations.

6. Chapter VI provides the synthesis of the findings utilizing two theoretical models. Using the evidence from the research study, the Studio 21 model suggests strategies and techniques for an integrated design studio that incorporates BIM technology and design teams organized around IPD concepts. The CircleX model describes the cognitive, social and procedural aspects of early phases of the integrated design process based on the case study observations and findings.

7. The last chapter, summarizes the findings and delineates the conclusions. The dissertation closes with the significance of the study and provides new research directions that are complementary to the study.

1.6 Limitations, Reliability and Validity

This research is grounded in both qualitative and quantitative research methods and techniques, which have their own strengths and limitations. The study follows the methodological suggestions for validity and reliability introduced by Miles and Huberman (1984), Merriam (1988), and Creswell (1994). The research methods are used in a complimentary manner in order to triangulate findings and address the validity and reliability issues. The researchers participated in the focus groups and case studies both as facilitators and observers, thus minimizing the distance between the researcher and the research phenomena. The research study provides a consistent research approach across the studies in the architectural research field. Based on Yin's (2003) assertions, the research study documents all of the procedures, the settings of the case studies, and tools and methods in a comprehensive fashion to ensure replicability. The qualitative validity and reliability of the study are reasonably high, yet the research study has potential limitations, which are the following:

1. Generally speaking, it is not possible to have a completely randomized sample of students. Students were recruited from the M.Arch programs of the Department of Architecture at Texas A&M University and the Department of Architecture at Prairie View A&M University. Instrumental case study approach in these particular environments may decrease the external validity from a pure methodological point of view due to their program curriculums, student demographics and educational objectives. This is an expected situation for architectural research on studio practices. However, the results and the proposed

pedagogical framework have high degree of applicability to graduate students of similar level and graduate programs with performance-based design orientation.

2. Focus group participants for industry-oriented efforts were selected from the local AEC professionals in the state of Texas. Although the selected firms from the AEC industry and architectural practice have both national and global presence, gathered data and analysis may have limited generalizability.

3. Design problems will be specific to each studio. Every design problem has some unique properties and required tasks in the studio process.

4. Interfaces, capabilities and the properties of the used BIM tools may provide a limited generalizability. However the conceptual basis/principles of BIM have existed for several decades. There are similarities in majority of the tools available in the market in terms of interface, components, data structures and usability.

Despite these limitations, the research has contributed theory and models that may have a significant impact upon architectural education and the practice of architecture.

CHAPTER II

METHODOLOGY OF THE STUDY

This chapter lays out the methodological approaches and considerations that were employed in this research study. Using qualitative research paradigms, the study incorporated a diverse set of research techniques and methods in an emerging and inductive approach typical of action research. Specific techniques drawn from a variety of research methods, such as use of theory, instrumental case studies, focus groups, systematic observations, and conceptual content analysis, were used to tailor an appropriate research framework. The qualitative research approaches align with the objectives of this study and the complexity of the research problems.

According to Leedy and Ormrod (2001), qualitative research methods focus on the phenomena that occur in natural settings and study the complexity which forms the holistic existence of the research phenomena. Therefore, qualitative researchers rarely simplify what they observe but they recognize the issues with many dimensions and layers for portraying it in its multi-faceted form. Furthermore, qualitative research does not aim to discover single and ultimate truth. Instead it focuses on multiple perspectives held by different individuals, components of systems or social settings.

Following established research theory, the choice of qualitative approaches in this study serve the following purposes of the study (Peshkin 1993):

1. *Description* of the BIM adoption and its application in the architectural design practice using analytical models;

2. *Interpretation* of collected data to gain insights about BIM-enabled integration, as well as develop pedagogical frameworks and theoretical models for integrated studio through BIM;

3. *Evaluation* of developed pedagogical frameworks for their effectiveness and their role in the integrated design studio.

2.1 Research Design

As explained in the introduction, this research is formative and exploratory; thus it relies on different qualitative research techniques combined with quantitative techniques for the corroboration of the findings (Creswell 1994; 2009). The key assumption for employing the multi-method research designs is drawn from the dynamic nature of BIM methods, technology and the educational practices. The adoption of BIM is connected to many different variables and confounding factors which have interactive effects in a holistic context. The technology and tools are rapidly evolving, and BIM is becoming more pervasive across the professional practice (Gilligan and Kunz 2007; Gonchar 2006, Eastman 2008). Parallel to these developments, existing literature shows a growing interest in BIM and integrated education among academic initiatives aligned with the environmental and socio-economic changes. Tracking of the moving direction of the research problem necessitated a flexible research approach and methodology. The developed approach provided the regeneration of research directions, adding new dimensions and aligning the research with the advancements in the BIM methods and technology.

The methodological progress of the research study can be explained in the theory of conjectures and refutations (Popper 1972). Using Popper's terminology, the given problem situation (PS_1) refers to the conventional pedagogical practices in the design studio which is criticized for its lack of integrative design knowledge and collaboration. As a response to the problem, proposed pedagogical approaches can be labeled as the Tentative Theories (TT_1) which are subjected to rigorous testing for justification or falsification. The case study process provides the Elimination of Errors (EE_1) process for building a solution proposal to $PS_{1,}$ but it simultaneously creates new problem situations and challenges (PS_2) for the integrated studio approaches through BIM (Figure 2.1).

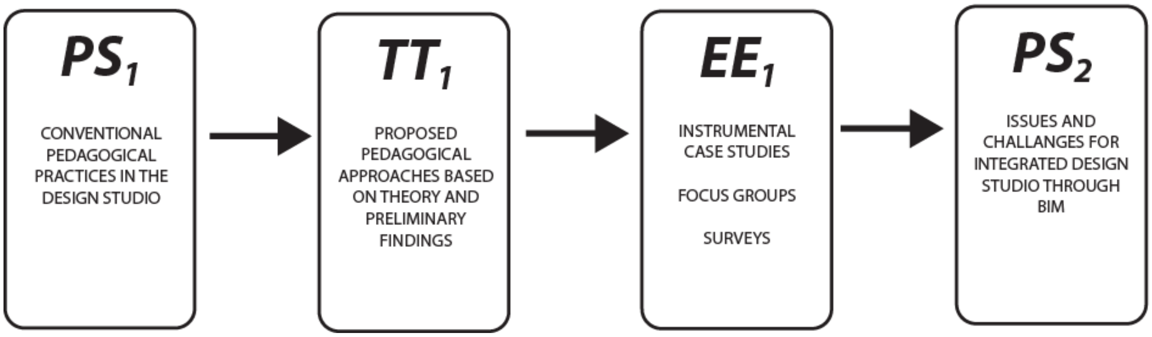


Figure 2.1: Methodological progress of the research study (Adopted from Popper 1972)

Based on these precedents the study includes the following methodological steps:

a) A review of the theoretical premises of BIM, critical examination of the typical studio educational setting and objectives, and identification of change patterns in architectural education and practice;

b) Development of guiding hypotheses, research directions and an outline for the pedagogical framework;

c) Identification of focus group participants from the AEC industry and the local faculty;

d) A pilot case study in a graduate level design studio using BIM as the preferred design medium with surveys, observations and evaluations;

e) Refinement of theoretical models and formulation of the pedagogical framework that is triangulated in a set of focus group studies that include academics, design firms and AEC industry representatives, and students;

f) Carefully designed instrumental case studies implementing the pedagogical framework in two graduate architecture programs;

g) Identification of students' demographic profiles and attitudes with surveys;

h) Observation of students' design processes and collaboration schemes using systematic methods that include collection of text, visual data, design artifacts and outputs from simulations, and computations in conformance with a multi-method research approach;

i) Identification of students' attitude changes and experiences with surveys;

j) Evaluation of the case study results with faculty and experts; and

k) Data analysis, triangulation and synthesis of findings.

Figure 2.2 illustrates the conceptual and methodological relationships of the different components of the study and its inductive framework. Note that the figure does not represent a sequence for the inquiry but different activities of the research pursued simultaneously.

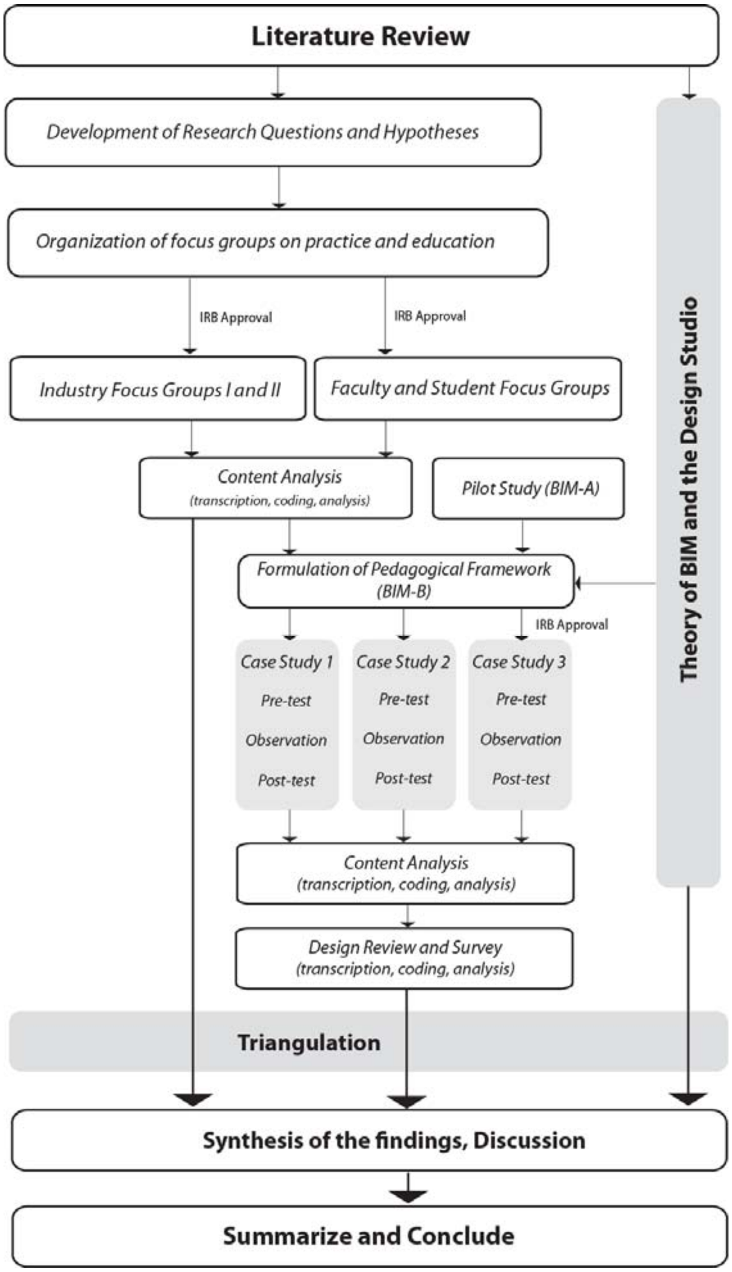


Figure 2.2: Employed methods, research components and relationships

2.2 Employed Research Techniques

A set of research techniques was employed to obtain a wide range of data from different research elements in a complementary fashion. The techniques in this study were: comprehensive literature review, focus group studies, instrumental case studies, observations, and surveys.

2.2.1 Literature Review

In this research, critical literature review is used as a component of the qualitative research framework for supporting the developed theoretical models and making comparisons with the existing theoretical propositions for BIM and architectural education. The resources for the literature search were key journals on computing in architecture and construction. Citation lists in web electronic databases of the publishers such as ISI Web of Science, Science Direct, Blackwell, and CUMINCAD facilitated the search procedure and assisted in the identification of key authors and researchers in this area of research. Books on the research subjects and research manuscripts revealed the theoretical basis for BIM methods and technology, technology adoption, and value propositions. Pedagogical approaches in design studio and its traditions were reviewed from books, reports from ACSA, AIA, AIAS, NAAB, and journals.

The literature review includes the following sections:

1. Definition of BIM and its theoretical premises;
2. Data standards and interoperability;

3. Integrated Project Delivery, drivers of IPD and BIM for IPD;
4. Fundamentals and traditions of architectural design studio; and
5. BIM in architectural education.

All the references were captured in annotated style with Endnote citation database during the whole research process. Citations styles and arrangement were also done using Endnote.

2.2.2 Focus Groups

The use of focus group in this research study falls under two categories described by Greenbaum (1998). The first category is “habits and usage studies,” used to obtain information from the participants about their usage of different products and services. The second category is “idea generation,” which is frequently employed to obtain preliminary information about problems and needs in a particular product category. According to Krueger and Casey (2000), the researcher can identify trends and patterns in a specific subject through a systematic analysis of the focus group discussions.

The findings from analyses are often used for the creation of new ideas, strategies and solutions. In the context of this research study, focus groups are employed for the identification of the trends and patterns of BIM adoption in the AEC/FM industry and formulate a pedagogical framework for integrated studio through BIM methods and technology.

The key issues that emerged in this research regarding the planning of the focus groups were the following:

1. *Identification of participants with substantial expertise in BIM and integrated practice*: Industry participants were selected based on their previous experience with BIM methods and their technological capabilities. Almost all participants were representing firms who accomplished comprehensive projects using BIM methods and technology. Faculty participants were selected according to their expertise and experience with studio teaching and integration of digital methods in architectural education.

2. *Design of the focus groups in order to collect comprehensive information from different audiences*: A multiple category design was used with different audiences as industry representatives and faculty (Krueger and Casey 2000). The participants represented a broad audience including large and mid-size architectural design firms, structural engineering firms, MEP firms, contractors, and administrators. Faculty audience represented a diverse expertise in architectural education, teaching of technology, CAAD, and digital design. Students were selected from the M.Arch program with the additional requirement being that they had taken at least two studio courses.

The details of the focus groups are given in Table 2.1

Table 2.1: Focus groups information

Phase	Number of participants	Participants	Duration
Industry Focus Group 1	16 participants	Large and Mid size design firms, R&D firms, Contractors, structural engineering firms and owners	4 hours and 15 minutes
Industry Focus Group 2	15 participants	Large and Mid size design firms, structural engineering firms, MEP firms, and owners	5 hours and 10 minutes
Faculty Focus Group	9 participants	Studio instructors, structural design instructors, professional practice and technology instructors.	4 hours and 5 minutes
Student Focus Group	11 participants	Students from the M.Arch program participated in the Pilot Study	3 hours and 10 minutes

All of the focus groups were videotaped, transcribed and coded for conceptual content analysis. The questions and agenda for the focus groups were developed based on the preliminary research questions and research objectives.

2.2.3 Instrumental Case Studies

Previous works suggest that research on design studio studies is largely based on carefully structured case studies and collection of data from all stages of the studio process. Donald Schön's (1985; 1987) methodological approaches show the appropriateness of qualitative and ethnographic research designs for understanding the studio process, learning mechanisms, communication schemes, and pedagogical dimensions of the design studio.

Using these methodological precedents, the instrumental case study approach was employed in three selected courses. Gillham (2000) describes the term “case” using several notions which are considered in this study. According to Gillham, a “case” is a unit of human activity embedded in the real world which can be studied or understood in the context. This activity merges in with its context so that precise boundaries are difficult to draw. This description aligns with the dynamics of the design studio and its contents. The case studies were designed to investigate the students’ design process based on BIM enabled integration in the context of design studio environment. This process and the use of information are bound to interrelated factors like design problem, scope, time, setting, used technology and students’ existing knowledge and attitudes. As Gillham suggested, isolation of these factors is a challenging process, as the factors are not meaningful when taken out of the context. Table 2.2 shows the number of participants, participant information and durations of the case studies.

Table 2.2: Case study information

Research Phase	Number of Participants	Participants	Duration
Pilot study	17 participants	M.Arch. students, Ph.D. students and the studio instructor	One semester of studio work
Case Study 1	10 participants	M.Arch. students, MSCM students, MS Arch students, Ph.D. students and the course instructor	One semester with a total of 45 contact hours
Case Study 2	9 participants	M.Arch. students, MSCM students, MS Arch students, Ph.D. students	One semester with a total of 45 contact hours
Case Study 3	17 participants	M.Arch. students, external consultants and the course instructor	One semester with a total of 45 contact hours

Focusing on design and data collection in the case study methods, Stake (1995) states that it is crucial to gather data from different data sources which have relationship to the studied research phenomena. To achieve this objective, case studies were devised to produce wide range of information about different activities that are collected using multiple methods and instruments.

A modified form of pre-test/observation/post-test was used in the case studies. Drawn from the methodological suggestions by Yin (2003) and Gillham (2000), a wide range of data was collected with various type of verbal, textual and visual information, including the researcher as a participant observer. These are:

a) Demographic profile of participants and the change in attitudes, knowledge and beliefs during the case studies documented by pre-tests and post-test surveys;

b) Status of the design and developments in each phase by computer files and short reports;
c) Student design development process by systematic visual output from software screenshots;
d) Information exchange schemes and flow of information by systematic participant observations;
e) Decision making during integrated design process by written reports;
f) Quantitative performance, cost, and schedule data of the design alternatives derived from the simulation tools;
g) Assessment of design alternatives by videotaped discussion sessions;
h) Evaluation of final projects by written surveys and videotaped discussion sessions.

2.2.4 Observations

The study involves the interaction of the researcher with students in the design studio. The role was a *participant-as-an-observer* as described by Jorgensen (1989). To manage the researcher's bias, the role emphasized that of an observer more than that of a participant. This method is expected to minimize the distance between the researcher as the studio participant and the informants, i.e., the students in the case studies. The focus of observation was the process of integrated design using BIM methods and technology. Two sub-process layers of integrated design and BIM utilization were observed through the collection of visual data, just-in-time notes, BIM models, and report sheets. Figure 2.3 illustrates the observation variables for the case studies.

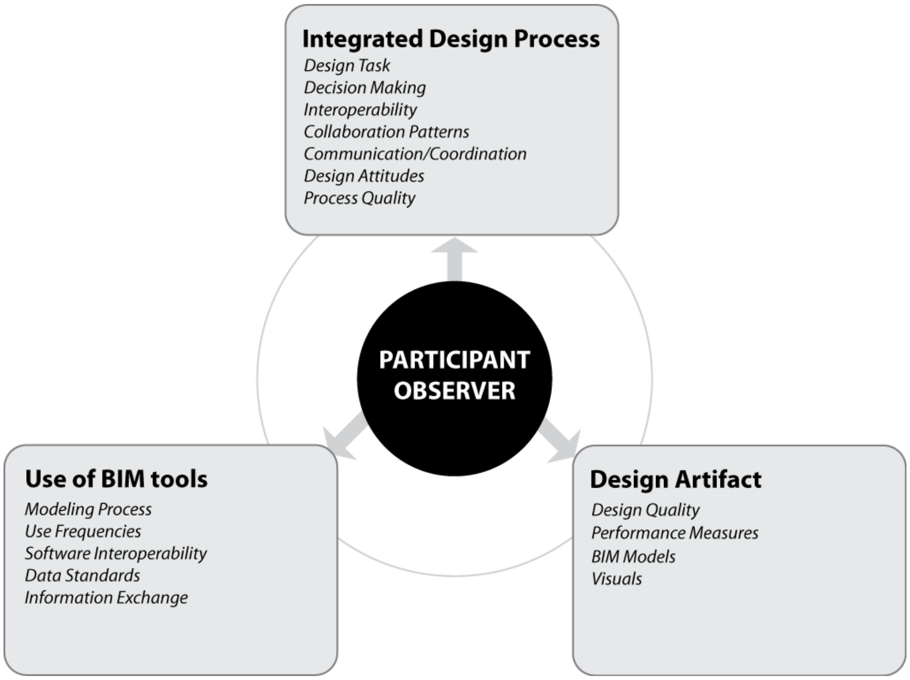


Figure 2.3: Focus of observation and variables

2.2.5 Surveys

In order to determine the demographics, attitudes, and opinions of participants in this study a comprehensive survey was conducted on conformance with the research design. Questions were developed using the findings from the focus groups and literature survey.

A similar survey was given to all case study participants to document the experience during the process and changes in attitudes in comparison to the pre-study survey in terms of decision making, design learning, and utilization of technology. Students were also asked to compare the experience to their typical studio processes. Questions consisted of matrix of choice questions as well as open ended questions to obtain in-depth feedback about the experiences and concepts.

Final projects and design artifacts from the case study processes were further assessed by a group of professionals and faculty. The projects were evaluated using building performance criteria, and were also compared to typical studio processes and results. Evaluators also were asked to give feedback about the content and scope of the study.

A Web-based commercial system – *www.surveymonkey.com* – was utilized to administer all the surveys. Data were collected, arranged, and analyzed using the web interface and MS Excel. Reporting and visualization features of the system made the analysis process rapid and effective.

2.3 Data Analysis

Data was analyzed using qualitative and quantitative methods that included conceptual content analysis, frequency counts of concepts, and simple statistics.

2.3.1 Content Analysis

The data collected from focus groups and open questions in the pre and posttest surveys consisted of text and related material such as visual documents and digital artifacts. The study utilized *conceptual content analysis* method for the analytical analysis of the collected text.

Krippendorff (2004) describes content analysis as a research technique for making replicable and valid inferences from texts and other meaningful matter. In his terms, this method of analysis provides new insights, increases a researcher's understanding of particular phenomena, or informs practical actions. This underlying definition shows the strong relationship between the selected data analysis method with the overall research approach of this study with its objectives and research questions. Below figure is adopted from Krippendorff's content analysis framework by considering the study content as BIM enabled-integrated studio education.

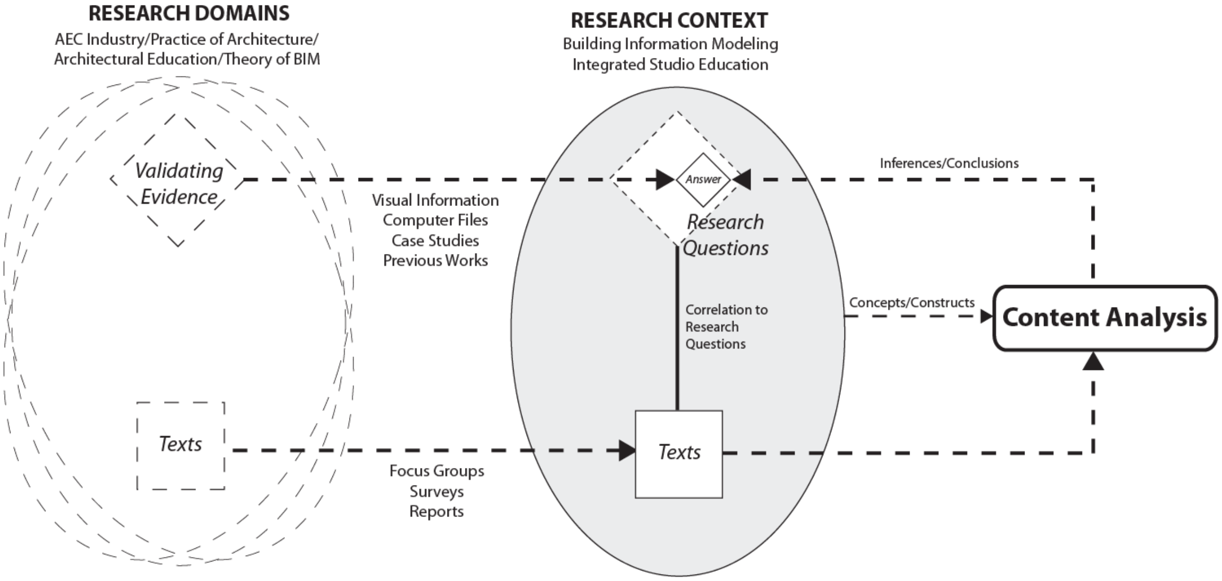


Figure 2.4: Content analysis framework of the study based on Krippendorff's (2004) model

As a sub-class of the content analysis methods, *conceptual content analysis* includes the quantification and identification of research related concepts within the text and related material (Carley 1990). The researcher's role in this process involves mainly making subjective judgments and deciding the level of implications of determined concepts related to the research phenomena. This analysis process relies on *selective reduction* where transcribed texts are reduced into categories consisting of a word, a phrase or a concept. Qualitative content analysis methods have procedural steps and components to build well-reasoned and reliable conclusions. This study includes the following steps, as indicated by Carley (1990):

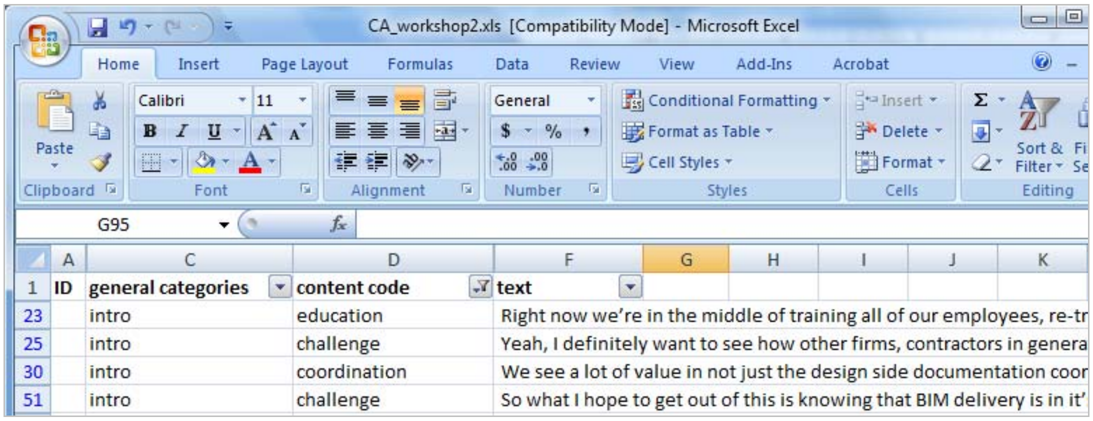
a) *Decision on the level of analysis*: For this study, transcribed texts were coded by single words relating the concepts and terminology existing in the BIM and integrated practice literature;

b) *Determination of the concepts for coding*: For the coding process an interactive approach was developed. Parts of the text were coded using predefined concepts and terms related to the study by adding new ones while they appear in the text;

c) *Development of the rules for coding and categorization*:Two layers of identification tags were developed for categorization of the text as "general categories" and "content codes" based on the study concepts. The general categories represent the overall understanding of the given part of the text and the content codes label it using BIM related concepts;

d) *Coding of the text*: Considering the amount of text and the complexity of conceptual relationships existing focus groups and reports, the analysis was carried out manually using the digital media. Transcribed texts were broken down into meaningful chunks based on participants' communication protocols. These text chunks and sentences were coded using a pre-determined coding scheme based on concepts and qualitative variables derived from the literature review and the established theory of BIM methods and technology. Figure 2.5 shows a screenshot from the coding process with MS Excel;

e) *Analysis and reporting*: Coded texts were examined and conclusions were drawn based on the patterns, trends, and relationships that emerged in the transcribed texts. The frequencies which the concepts occurred in the texts were reported using graphs and tables.



	A	C	D	F	G	H	I	J	K
1	ID	general categories	content code	text					
23		intro	education	Right now we're in the middle of training all of our employees, re-tr					
25		intro	challenge	Yeah, I definitely want to see how other firms, contractors in genera					
30		intro	coordination	We see a lot of value in not just the design side documentation coor					
51		intro	challenge	So what I hope to get out of this is knowing that BIM delivery is in it'					

Figure 2.5: Screenshot from the text coding process

2.3.2 Simple Statistics

Data from the pre-study, post-study and evaluation surveys were collected and analyzed using simple numerical methods for supporting the findings from the case studies. Responses to matrix-of-choice questions included several versions of 5-point rating scale. Using this technique, qualitative variables like effectiveness, use frequencies, design priorities, confidence levels, and design quality measures were converted to meaningful numerical representations.

For some variables, rating averages for the corresponding variables were calculated using weighted means by complementing the choice distributions among the case study participants. More specifically, 5-point matrix choices were assigned values from 0 to 4 and the weight for each value was derived from the number of students as shown in the following equation:

$$\bar{x} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i},$$

Use of simple statistics provided convenient interpretation of students' attitudes and tendencies regarding the given variable. Graphs and tables were created as visual supplements.

2.4 Synthesis and Reporting of the Findings

The research study includes a collection of research methods and techniques. As a result, the research design urged a cyclic data analysis and interpretation procedures in order to transfer the findings from one research step to another. All research steps include variables, basis, and findings from the prior research step.

Procedure suggestions from Creswell (2009) were adopted for the reporting and synthesis of the findings. In detail, the research study provides:

1. Detailed descriptions of the focus group and case study settings;

2. A detailed portrait of study participants as culture sharing groups like AEC professionals, faculty or students;
3. In-depth analysis of one pilot study and three case studies;
4. Analytical and theoretical models generated from the data and findings.

Reports of the study include quotes from the focus groups, surveys results and case study examples, visual materials, and design artifacts, as well as hard data from the simulations and project development process. Descriptive models explain the relationships between variables and research phenomena related to IPD, BIM methods, and collaborative design processes. As the most significant outcome of the research effort, the study provides a prescriptive studio model based on the evidence and the findings from the instrumental case studies.

CHAPTER III

LITERATURE REVIEW AND THE THEORETICAL BASIS

In this research study, literature review is employed as a key method to establish the theoretical basis. This step provides the established body of knowledge on BIM, IPD, and integrated design education. Concepts and research variables for the research steps were obtained from the literature review. Synthesis of findings was conducted using the theoretical basis and the results from other research steps.

The literature review is organized into three major sections:

1. Theories on Building Product Models (BPM) and BIM, previous research works and applications, and data standards for interoperability;

2. Current status of AEC/FM industry in the context of Integrated Practice and BIM;

3. Fundamentals of studio education, use of BIM, CAAD and knowledge based systems in architectural education, and pedagogical basis of integrated design education.

The literature review scope is focused on the key theoretical articles and latest works from outstanding research and industry initiatives. The literature review shows the existing gaps in the research literature and establishes a foundation for the corroboration of the proposed theoretical models for BIM Adoption, Studio 21 Model, and CircleX Integration Model.

3.1 Description of Building Information Modeling

Early examples of BIM and Building Product Models (BPM) emerged in the 1980's parallel to the developments in computer science and applied engineering. These concepts evolved rapidly in the 1990's. Research initiatives concentrated on developing standard information models for the AEC industry. Early examples of these efforts are AEC Building Systems by James Turner at University of Michigan and GARM and RATAS model from Dutch and Finnish National R&D Programs (Gielingh 1988; Bjork 1989; Turner 1990). Eastman (1992) and Kalay (1989) proposed sound foundations for the object - oriented building product modeling. They introduced novel data structures, concepts and system components for the production of electronic building models.

The underlying idea for the BIM and BPM is described by Eastman (1999) as "to develop an electronic representation/model of a building, in a form capable of supporting all major activities throughout the building lifecycle." This concept was further refined as a "modeling technology and associated set of processes to produce, communicate and analyze building models" (Eastman 2008).

Tolman (1999) approached product modeling standards from a "process integration" point of view for the improved production processes in the AEC Industry. According to his "levels of integration" approach, integrated design and construction processes require integrated technologies, which require integrated tools and software applications, integrated knowledge, and integrated data, as shown in Figure 3.1.

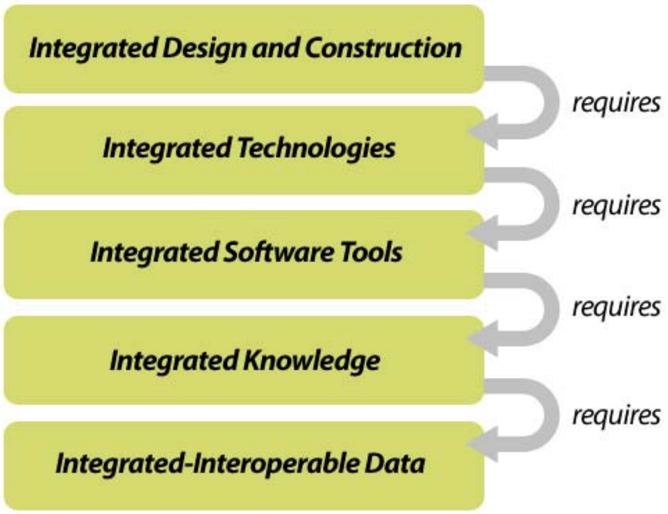


Figure 3.1: Levels of integration (adapted from Tolman 1999)

Although these arguments establish a sound basis for the definition of BIM, it is very hard to state a widely accepted definition in the AEC/FM industry where scope of "building information" varies according to:

a) Roles of the project team members;

b) Design process and employed methods;

c) Tasks and operations;

d) Technological capabilities; and

e) Content of the required information.

Different perspectives of scholars and key industry initiatives have been well documented in the literature for the past couple of decades and they address the theoretical and practical implications of BIM. Nevertheless, the common understanding of BIM implies two of its major components as “the process” and “the information,” which are facilitated by the adequate technology. This involves the generation and utilization of coordinated, consistent, and computable “information” in all stages of the building lifecycle (Clayton et al. 2009).

More specifically, BIM can be approached as a collection of concepts which are directly related to the utilization of IT and information management in the AEC tasks and processes. This study assumes that BIM includes virtual and digital modeling, parametric modeling, performance simulation and assessment, building product models, database management, networking, interoperability and digital communication in the context of design, construction and operation stages.

Smith and Tardif (2009) further elaborated the difference between the process and the information dimensions. In his terms, any compilation of building information in any form corresponds to a *building information model*. Any simulation of any activity related to building is the process of *building information modeling*.

3.1.1 Concepts of BIM

As explained in the previous section, BIM has different dimensions based on novel technological concepts. These concepts highlight the distinction of BIM from existing technologies and its relationships to building lifecycle processes. In brief, BIM comprises all essential information domains like 3D modeling, representation, project database, interoperability, and simulation (Figure 3.3). The fundamental concepts include:

Virtual Models with Parametric Components: A common approach to conventional 3D modeling is based on Constructive Solid Geometry (CSG), where shapes are generated using 3D primitives through simple or combined Boolean functions. Similarly, surface models are widely used for representing 3D components with their visible surfaces and serve to provide the user with flexible manipulation capabilities and rapid visualization of the design artifact.

Most of the BIM tools provide 3D modeling interfaces with built-in components and tools for modification. Different from the CSG and the surface models, BIM elements are based on object-based parametric models (Eastman 2008). Instead of creating an instance of a building component, the user defines an object class with embedded data structures that involve a set of relations and rules to control the object. 3D models and other properties of the building component are propagated by parameter modification (Kymmell 2008). Some BIM software has the capability to convert conceptual mass models to a set of parametric objects. Figure 3.2 shows a parametric wall object with various properties and associated views.

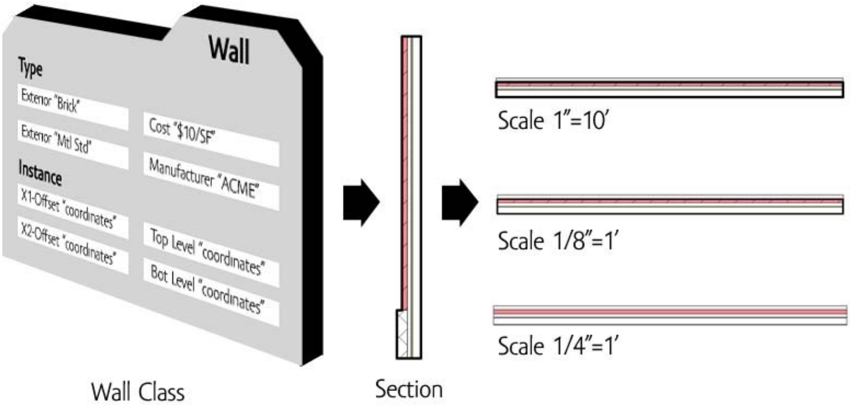


Figure 3.2: Example of a parametric wall object in BIM and associated views

In addition to parametric components, certain BIM tools can create complex geometries and surfaces like B-splines and NURBS connected to parametric generation rules. New file formats like FBX allow users to link high-end surface modelers with BIM software to convert complex surfaces to parametric building objects.

Project Database: A BIM model of a building consists of different parametric elements, where each behaves according to its context. Embedded information in a parametric BIM model forms an object-based, relational, and hierarchical database –a project information backbone--where different queries can be performed for various tasks in design and construction process. Reports regarding quantity take-offs, cost tables, occupancy, and cost can be derived from the database (Figure 3.3).

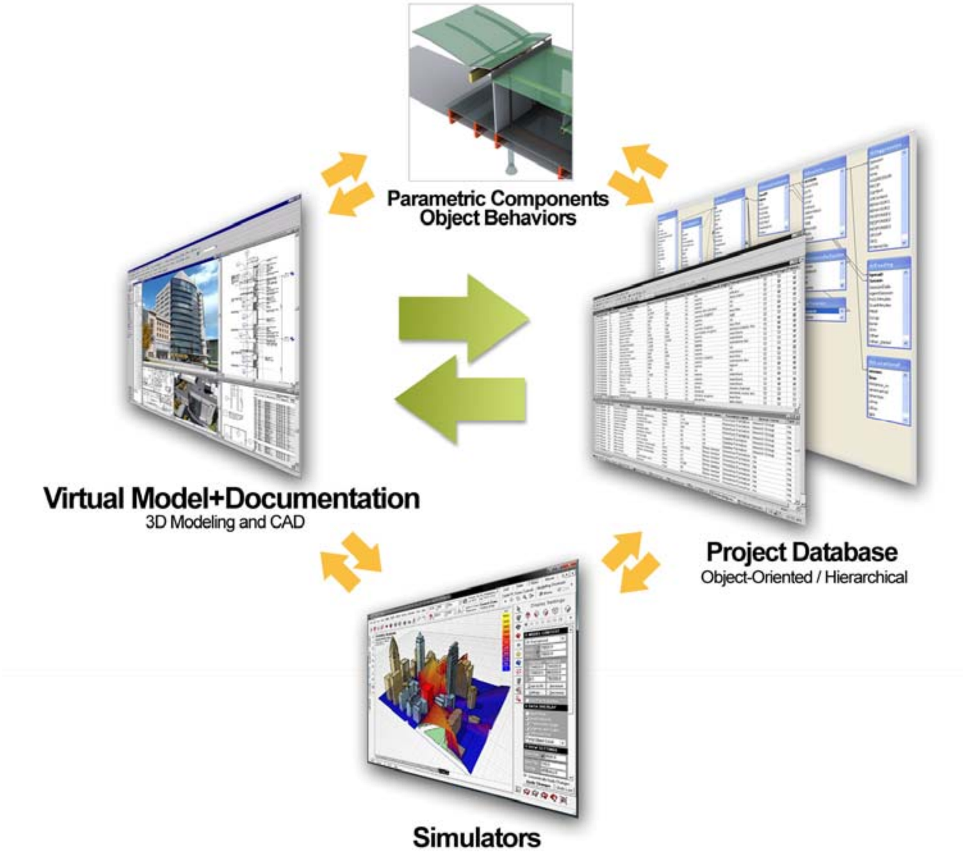


Figure 3.3: Essential components of BIM

Representation and Documentation: Documentation of the project in 2D and 3D resembles the report generation tasks. 2D and 3D information stored in parametric models allows the user to create automated documents like plans, sections, elevations, and perspectives. Model link from these visual reports also give access to modification modules.

Lifecycle Processes: Eastman's description of BPM and BIM implies the uses of BIM in the AEC industry during all lifecycle processes. According to Kymell (2008), these processes fall into the following four major groups:

a) The processes enabling all members of a design project to develop an accurate understanding of a project;

b) The processes for the design, development and analysis of the project with virtual models and simulations;

c) The processes for the management of procurement and construction of the project; and

d) The processes related to operations management during the actual use.

Collaboration and Interoperability: Collaboration in an integrated process depends on the shared and accessible information. Core intent of BIM is to streamline the information exchange between project members. Consistency and reliability of the shared information are essential to integrated processes. Improved interoperability is expected to reduce the costs of communication, amount of rework, and time (Gallaher et al. 2004).

Simulation: Majority of the off-the-shelf BIM software is capable of exporting analytical analyses models from the BIM models. The conversion process includes the building geometry, interior layout, and building envelope components. Simulators parse the converted analytical model and run analyses for different performance measures like energy use, water balance, renewable potentials, daylighting performance, etc. Simulator connections in BIM tools are becoming tighter to get rapid feedback about the building performance. Latest examples from the best practices suggest performance simulation as a core component of the BIM concept (Krygiel and Nies 2008).

3.1.2 BIM Software Market

Currently there is a large spectrum of BIM solutions for the general and the specific needs of the AEC/FM industry, and software vendors have different strategies and perspectives for the development of BIM technology and specific sotware design. Revit® Series of Autodesk®, ArchiCAD® and Constructor® of Graphisoft and Bentley® BIM Products can be given as the major off the shelf solutions that form the significant portion of the BIM software market. There are also numerous solutions like Nemetschek VectorWorks Architect® and Allplan FT®, more specifically DProfiler® and Affinity®, that focus on pre-design and programming phase or Tekla Structures® which is a hi-end tool for precast concrete/steel design and construction. In addition, 4D and integration software like NavisWorks® and Innovaya®are being utilized by A/E teams for the coordination of information derived from different BIM and CAD software. Sustainability related software provide links to BIM models through an analytical analysis model based on the BIM models. Autodesk Green Building Studio®, Autodesk Ecotect®, and IES® are the widely used energy, lighting, and sustainability analysis solutions connected with BIM software.

3.2 Previous Works

Existing literature includes well-reasoned arguments and studies for the effective use of advanced IT, to support building design. According to the recent articles and research papers, Building Information Modeling is receiving intense attention in the AEC/FM Industry. This attention is partly driven by marketing efforts of software vendors as well as by growing recognition of the theory of information integration and the resulting process efficiencies that are described in industrial papers and reports.

Recent works from Georgia Tech's research initiatives demonstrates the capabilities of BIM/BPM approaches in specific building components and possible utilization in construction processes. Their research team developed a process-centric product modeling method - Georgia Tech Process to Product Modeling (GTPPM) - that enabled capture of domain-specific information and work processes through process modeling. The research team also produced building object behavior (BOB) description notations for designing, validating and sharing the design intent of parametric objects. These methods and information models were validated through projects on precast concrete (Sacks, Eastman et al. 2004; Lee, Sacks et al. 2006; Lee, Sacks et al. 2007). As an extension of this research effort, they further explored and defined the functional requirements for a BIM standard for architectural precast concrete, focusing on the multiple exchanges between architect and precast contractor.

Another cutting-edge example from the AEC industry is Disney Concert Hall designed by Frank O. Gehry and Associates (FOGA). The complex design of the building prompted all A/E teams to coordinate their work on a 4D virtual building model. A collaborative effort with Gehry Technologies, M.A. Mortenson, Walt Disney Imagineering, and Stanford CIFE researchers resulted a the 4D prototype software and a research effort for testing the applicability and usefulness of 4D modeling in this particular project (Haymaker and Fischer 2001). Research findings suggest that the 4D models helped the construction team find many schedule inconsistencies; resolve access, scaffolding, and hoisting issues for the exterior and interior construction in a timely manner; inform more stakeholders of the approach to construction and of the schedule; and engage subcontractors in the scheduling process. These improvements in the process were reflected on the bottom-line measures through significant reduction in RFI's and minimum change and field orders.

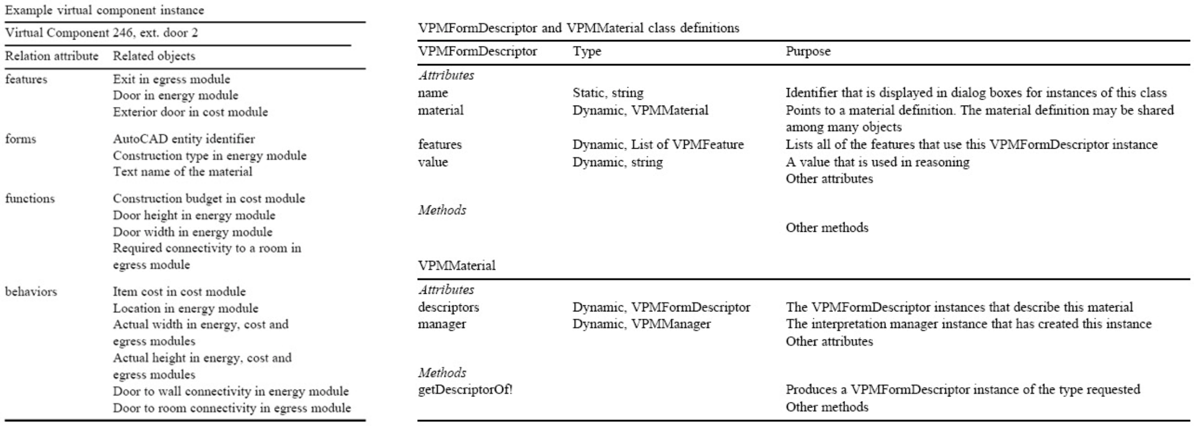
The building project, which had a unique type of design and production process, further used models with 3D geometric information and embedded attributes, dependencies, and relationships that are utilized by construction engineers as a validation case for the introduction of new parametric data (Haymaker, Kunz et al. 2004). They formalized new reusable modules of information called Perspectors, which engineers can use to automatically construct and visualize a task-specific engineering view from geometric perspectives and transform this information into task and process based dependency graphs called Narratives. Their proof of concept implementations on Deck Attachment test case in WDCH project returned better and faster integrated project views for AEC.

Jongeling, Kim et al. analyzed the efficiency of 4D models using real case studies (Jongeling, Kim et al. 2008). They studied the construction timeline with traditional and 4D enabled processes. Three types of analysis addressed the workflow, workspaces and space buffers; temporary structures; and crew productivity and production costs based on the temporal and spatial data extracted from 4D models. The study showed the usefulness of up to date 4D model methods and BIM technology by providing evidence that early analyses of 4D model content may limit the risk for time–space conflicts in production. This research also illustrates the potentials of 4D content utilization to improve construction processes like workspace usage and resource usage.

Yang and Zhang’s (2006) paper about semantic interoperability in building design introduced an approach and its software implementation for the development of building design objects with semantics of interoperable information. They proposed a set of methods to address the issues of IFC compliant object-based building information representation. They attempted to solve this problem by using exchange of interdisciplinary information approach. The research developed extensions of IFC models with the supplementary information and semantic annotation of the interoperable and extensible information sets as well as a Web-enabled software tools for effectively generating, managing, and reusing the semantically interoperable building objects.

Semantic information and interoperability can be identified as the key components of the integrated production process “design phase”. Usefulness of product modeling approach in the design phase was explored by Clayton (1998) who introduced design specific product models –Virtual Product Model- of a building as a consequence of the designers’ actions in drawing and evaluating the design (Clayton 1998; Clayton, Teicholz et al. 1999). This approach differs from the object based product modeling approach by looking at the product modeling concept from the perspective of design methods and cognitive processes. The research by-product software “Semantic Modeling Extension” employed flexible and modifiable product models that involved key design concepts: form, behavior, and function. The research introduced a principled way of structuring product information that can support the automatic emergence of a comprehensive product model from the design process. Table 3.1 shows an example of virtual component instance and a Form Class Definition. Figure 3.4 is a screen shot from the evaluation and interpretation module of the prototype software.

Table 3.1: Semantic mapping of a CAD window object to IFC property extension mechanism (Clayton 1998, used by permission)

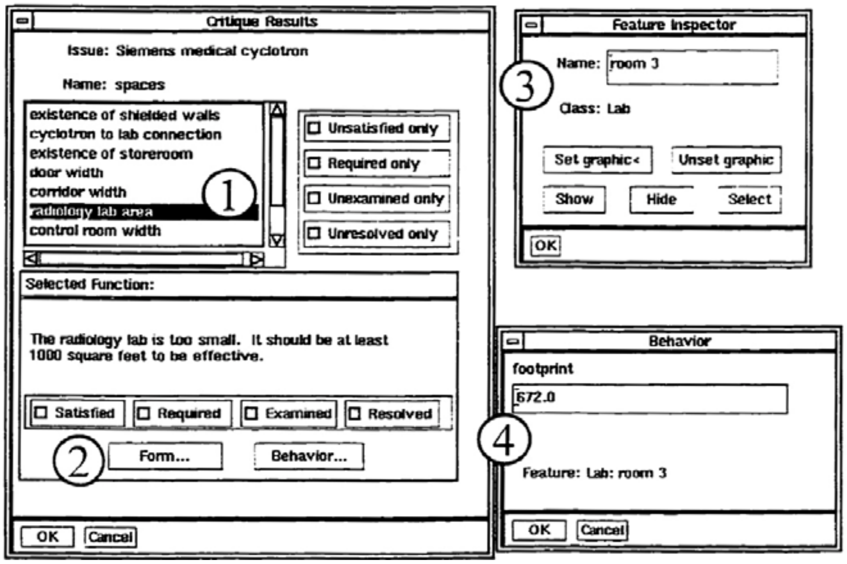


Example virtual component instance

Virtual Component 246, ext. door 2	
Relation attribute	Related objects
features	Exit in egress module Door in energy module Exterior door in cost module
forms	AutoCAD entity identifier Construction type in energy module Text name of the material
functions	Construction budget in cost module Door height in energy module Door width in energy module Required connectivity to a room in egress module
behaviors	Item cost in cost module Location in energy module Actual width in energy, cost and egress modules Actual height in energy, cost and egress modules Door to wall connectivity in energy module Door to room connectivity in egress module

VPMFormDescriptor and VPMMaterial class definitions

VPMFormDescriptor	Type	Purpose
Attributes		
name	Static, string	Identifier that is displayed in dialog boxes for instances of this class
material	Dynamic, VPMMaterial	Points to a material definition. The material definition may be shared among many objects
features	Dynamic, List of VPMFeature	Lists all of the features that use this VPMFormDescriptor instance
value	Dynamic, string	A value that is used in reasoning
		Other attributes
Methods		
		Other methods
VPMMaterial		
Attributes		
descriptors	Dynamic, VPMFormDescriptor	The VPMFormDescriptor instances that describe this material
manager	Dynamic, VPMManager	The interpretation manager instance that has created this instance
		Other attributes
Methods		
getDescriptorOf!		Produces a VPMFormDescriptor instance of the type requested
		Other methods



Issue: Siemens medical cyclotron

Name: spaces

- existence of shielded walls
- cyclotron to lab connection
- existence of storeroom
- door width
- corridor width
- radiology lab area
- control room width

Selected Function:

The radiology lab is too small. It should be at least 1000 square feet to be effective.

Name: room 3

Class: Lab

footprint

672.0

Feature: Lab: room 3

Figure 3.4: Semantic mapping of a CAD window object to IFC property extension mechanism (Clayton 1998, used by permission)

This early work for incorporating BIM related concepts to design development and evaluation phase still portrays a significant issue for the BIM adoption in the AEC industry. Clayton (2006) further discussed this particular issue focusing on the current BIM methods and technology). According to him, existing BIM methods lack design reasoning due to being based on form and behavior model. Therefore, Clayton suggests that the addition of “function” concept to BIM for making the building model should be much more capable of representing the cognitive process of design and of supporting design reasoning. Based on this approach, he proposed reorganization model for architectural programming and design process based on form, behavior, and function, which may be facilitated by function enabled BIM.

Bédard illustrated the ongoing adoption of new generation of computing technologies in the AEC industry and recent developments in the area of collaborative work and integration across disciplines for the conceptual design of building structures (Bédard 2006). He further asserted the existence of a relationship between integrative approaches and the development of capable IT technologies and data standards.

From an architecture practice point of view, Krygiel and Nies (2008) have provided a comprehensive framework for BIM adoption to support green building design addressing BIM technology, process, and organizational change in architectural design practice. Selected case studies from their practice stressed the interrelationship of BIM technology with altered design process. From the technical point of view, their examples focused on BIM as the information repository in all stages of the project process. They linked models with various environment and energy analysis tools to show BIM's functionality in green building design. The major point they made is the interconnected and iterative design process by using BIM models of building envelope, spatial configuration, and hard data from BIM-based simulators. Optimization of the building's environmental performance is given as a major design objective in an integrated design process. More specifically, they proposed the following aspects of the components a *Green BIM* model and analyzed building design alternatives using analytical models derived from a central BIM model:

a) Building orientation
b) Building massing
c) Daylighting
d) Water harvesting
e) Energy modeling
f) Renewable energy
g) Materials

They asserted that the scope of parametric modeling would be expanded with the sustainability information, which results in an immediate performance feedback of the building model according to its environmental context. They further asserted that the true value of BIM's will be the integration capacity as it relates to more sustainable environment, particularly at the front-end of the design process. Figure 3.5 shows major design and production tasks supported by BIM methods.

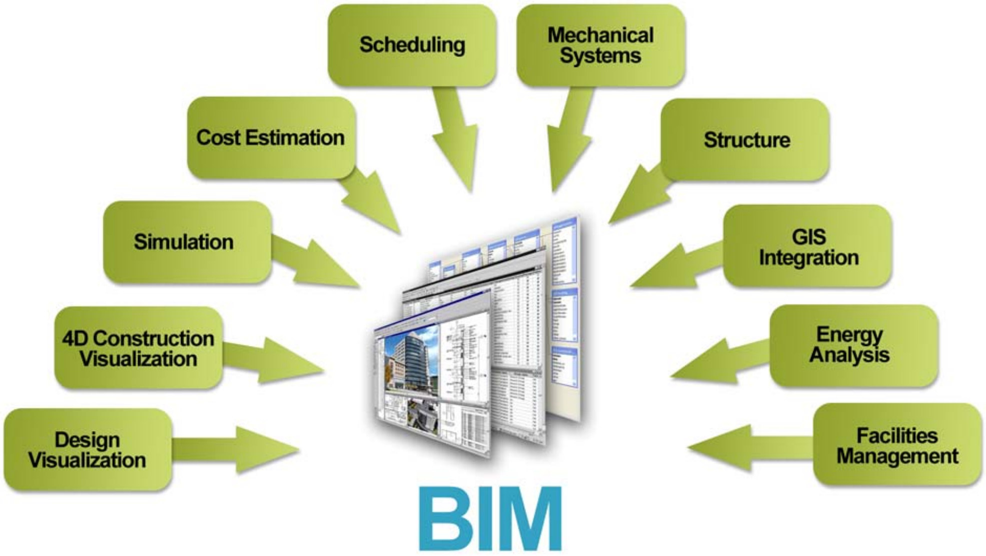


Figure 3.5: Tasks supported by BIM

Kieran and Timberlake (2004) have brought up very strong viewpoints about contemporary architectural construction by comparing to emerging manufacturing methods in the aerospace and automotive industries. More of a manifestation for the architecture for the 21st century, their statements depicted the changing relationships between the major aspects of architecture like aesthetics, art, form, production, and commodity. Their vision for the future is that the new architecture will not be about style but it will urge the methods and processes that underlie making.

According to Kieran and Timberlake, the 20th century's segregated specialization model is no longer sustainable where the production becomes a part of the design process by working with assemblers from the outset. Here the designer functions not only as the form maker, but also the producer who delineates how things are made, and provides the sequence of assemblies and joining systems. The new mass customization paradigm posits hybrid processes and automated design as well as manufacturing techniques with the ability to achieve unique results.

As an implementation of this theoretical manifestation, Kieran and Timberlake (2008) stress the importance of parametric modeling and BIM for the whole design and construction process of Loblolly House. The process narrative manifests this new paradigm of design as *“simulation not representation.”* Paraphrasing Kieran and Timberlake, with the current complexity of building programs and systems the new tools of today rejoin thinking and making and this is possible through parametric modeling with a wider set of integrated tools of BIM.

The process in Loblolly House is based on a *“kit of parts”* approach through the intensive use of parametric BIM models to simulate construction process and optimize the supply chain. Design and detail development were made with iterative cycles of parametric modeling. They merged all system layers of the building, used parametric components provided by suppliers, and created specific reports and documentation from the *“integrated building model,”* Sunlight studies and environmental analyses were also performed using the model (Kieran and Timberlake 2008).

Recent literature on BIM documents comprehensive case studies and in-depth process examples for various building types; design and construction processes using BIM; and best practices (Eastman 2008, Krygiel and Nies 2008; Kymmel 2008; AECbytes 2009; AIA TAP 2009; Smith and Tardif 2009). These research works and practical applications of BIM highlight the implications and challenges of advanced IT methods when it comes to design and construction. They emphasize the need for organizational transformation and changes in project delivery processes in conjunction with technology adoption.

3.3 Interoperability and Data Standards

Research and development efforts regarding the streamline of the information flow highlight the importance of interoperability. Although early research on BIM posits meta-BIM model as the central information repository for true interoperability, current BIM and interoperability approaches involve specific but tightly connected BIM models through data exchange. Smith and Tardif (2009) brought major criticisms to the *single model ideology* as being a danger to real progress. Ownership and the integrity of the model are the key concerns which also contradict with the business processes in the AEC industry. Instead of the single model idea, Smith and Tardif emphasized the applicability and effectiveness of the *standard information exchange approach*. Likewise, Turk (2001) asserted the necessity of combination of domain models in the AEC tasks instead of a central and gigantic product model. According to Turk, the connection between the modeler, task, and the model involves not only the objective reality but also the modeler's understanding of that particular reality. These arguments confirm the large research and implementation activity in the BIM research domain concentrated on the handling of design data -encoding, storing, utilization- integration and interoperability among the AEC teams (Eastman 1996; Kim, Liebich et al. 1997; Luiten, Tolman et al. 1998; Fu, Aouad et al. 2006; Roddis, Matamoros et al. 2006). These research activities involved the utilization of object oriented mark-up languages and industry standard development environments such as: STEP-EXPRESS, IFC, XML, and UML, as well as process modeling language, IDEF0. Parallel to the current discussions for the process changes in the AEC industry, researchers continue to provide novel computational methods, concepts, and case studies for future implementations.

Starting from mid 1980's standardization of product data, representation and exchange became inevitable to optimize production and manufacturing processes of engineering products. The International Organization for Standardization (ISO) initiated a development activity to address the lack of data formats in order to overcome the complexity of the information that includes geometry, attributes, and relations (Fowler 1995; Eastman 2008). These efforts produced a collection of classes and new set of technologies in an ISO standard framework ISO 10303, later known as STEP-Standard for the Exchange of Product Model Data.

The parts of STEP-standard are given in the following table:

Table 3.2: Parts of STEP (reproduced from http://www.tc184-sc4.org).

Environment
- Parts 1x: Description methods: EXPRESS, EXPRESS-X
- Parts 2x: Implementation methods: STEP-File, STEP-XML, SDAI
- Parts 3x: Conformance testing methodology and framework

Integrated data models
- The Integrated Resources (IR), consisting of
  - Parts 4x and 5x: Integrated generic resources
  - Parts 1xx: Integrated application resources
  - PLIB ISO 13584-20 Parts library: Logical model of expressions
  - Parts 5xx: Application Integrated Constructs (AIC)
  - Parts 1xxx: Application Modules (AM)

Top parts
- Parts 2xx: Application Protocols (AP)
- Parts 3xx: Abstract Test Suites (ATS) for APs
- Parts 4xx: Implementation modules for APs

As seen in Part1, the data definition language EXPRESS was one of the products that adopted object-oriented concepts and also included data structures that allow users to represent objects, materials, geometry, assemblies, processes, and relations.

This language was further used by International Alliance for Interoperability (IAI) for developing the Industry Foundation Classes (IFC), in order to overcome the similar interoperability issues in building production, procurement, and supply chain management. Other data standards based on ISO STEP technology are AP 225-Building Elements Using Explicit Shape Representation and widely deployed CIS/2 CimSteel Integration Standard (Eastman 2008).

Successful implementations of STEP-standards and use of EXPRESS in Aerospace, Automotive and Petro-Chemical industries eventually formed well-established conventions, integrated production processes and industry-wide interoperability. Boeing’s 747 project can be given as a breakthrough example where new product models were introduced to integrate entire engineering and manufacturing processes (Beeby, 1982). The company further developed product models based on STEP-standards and widely implemented for the optimization of design, engineering, procurement and manufacturing that still involves all the sub-contractors and the service providers of the product lines.

Following these developments, IAI issued first version of Industry Foundation Classes (IFC) in 1997. IFC was intended to provide increased interoperability between AEC software applications with a data exchange model for supporting all of the building lifecycle processes in pre-development, architectural design, HVAC engineering design, and facilities management. This standard was mainly developed with EXPRESS data definition language. IFC was designed to be a modular and extensible framework model for the creation of a large set of consistent data representations of building information.

More specifically, IFC is structured as a top to bottom hierarchical approach aligned with the IAI process models for each phase in the building lifecycle. IFC has four layers of information sections that define the product model framework. This layered information architecture is adopted from the parallel works of ISO-STEP adapted for the

AEC industry stakeholders, needs and processes. Certain IFC layers provide similar facilities which are provided by STEP Integrated Resources. Using the EXPRESS term "entity" for each object in the IFC model structure, latest release IFC 2x3 includes 383 kernel level entities, 150 shared entities, and 114 domain specific entities in the top level (Eastman 2008).

The National Institute of Building Sciences' National BIM Standard (NBIMS) initiative can be identified as the most important effort for interoperability and standardization of BIM models across the AEC industry (NIBS 2007). The intent of NBIMS is described as the provision of the framework and foundation to encourage the flow of information and interoperability between all phases of a facility's life from inception onward. Current status of the standard includes the scope of the standard, process frameworks, components and development stages, and exchange architecture and implementation strategies. According to the preliminary phase report, the development of NBIMS will reference IFC's and *OmniClass* construction Classification System.

Another recent development is the deployment of ISO 15926 interoperability standard for facility lifecycle information management (FIATECH 2009). The FIATECH ADI project drove prominent technology vendors to implement a BIM-IFC derivative standard to hi-end tools for capital projects management. Demand for the deployment is coming from owners, contractors, and other industry stakeholders and it is expected that the diffusion of BIM and related data standards will increase in AEC and FM in the short and mid-term.

3.4 Integrated Practice and Value Proposition of BIM

This section highlights the changes, social and economic challenges, and solution proposals in the AEC industry. The challenges arise from the demands of growing populations, diminishing resources, increasingly fluid markets, and intensifying environmental stress, coupled with weaknesses in 20th century forms of design and construction practice. The opportunities arise largely from the increasing sophistication of business models and accelerating innovation in information management. Vast majority of the articles, books, and whitepapers on BIM underline these changes as the drivers for BIM adoption and Integrated Project Delivery (Eastman 2008; Kymell 2008; Smith and Tardif 2009).

Arguably, there is a crisis within the architecture and construction industry caused by the wasteful activities and inadequate interoperability during project cycles. National Institute of Standards and Technology report "Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry" states that $15.8 billion in annual interoperability costs were quantified for the capital facilities industry in 2002 (Gallaher et al. 2004.) Recent studies also indicate that AEC industry consumes $1.2 trillion and wastes a minimum $120 billion every year (LePatner, Jacobson et al. 2007). Aligned with this information, productivity index between 1964 and 2003 illustrates the stagnation in the AEC industry compared to non-farm industries which doubled the productivity during this period (Teicholz 2004). This situation is sourced from the existing delivery processes, stakeholder roles, and the resulting segregation culture of disciplines in the AEC industry. In order to address these issues the Construction Users Roundtable (CURT) has directed an initiative to evaluate how alternative processes—namely, use of information technology combined with changes in project structure and delivery processes—might address productivity issues in the industry (CURT 2004, 1). The main goal of this initiative found in the technical report is very relevant to the defined problems and potential solution alternatives:

> *The goal of everyone in the industry should be better, faster, more capable project delivery created by fully integrated, collaborative teams. Owners must be the ones to drive this change, by leading the creation of collaborative, cross-functional teams comprised of design, construction, and facility management professionals.*

According to the suggestions delineated in the report, owner-driven full collaboration through information sharing early in the project process is most likely to achieve the desired outcomes: fast, efficient, effective, and cost-bound buildings. Below diagram describing this concept is widely recognized by industry professionals and scholars. It briefly base on the relationship between the ability to impact cost and the cost of design changes throughout the whole building lifecycle. Desired line labeled as 4 shows the optimized effort/time curve which may be obtained by pushing the middle to the early stages. This result is expected to be achieved by integrated practice and project delivery methods which are facilitated by BIM (Jernigan 2007).

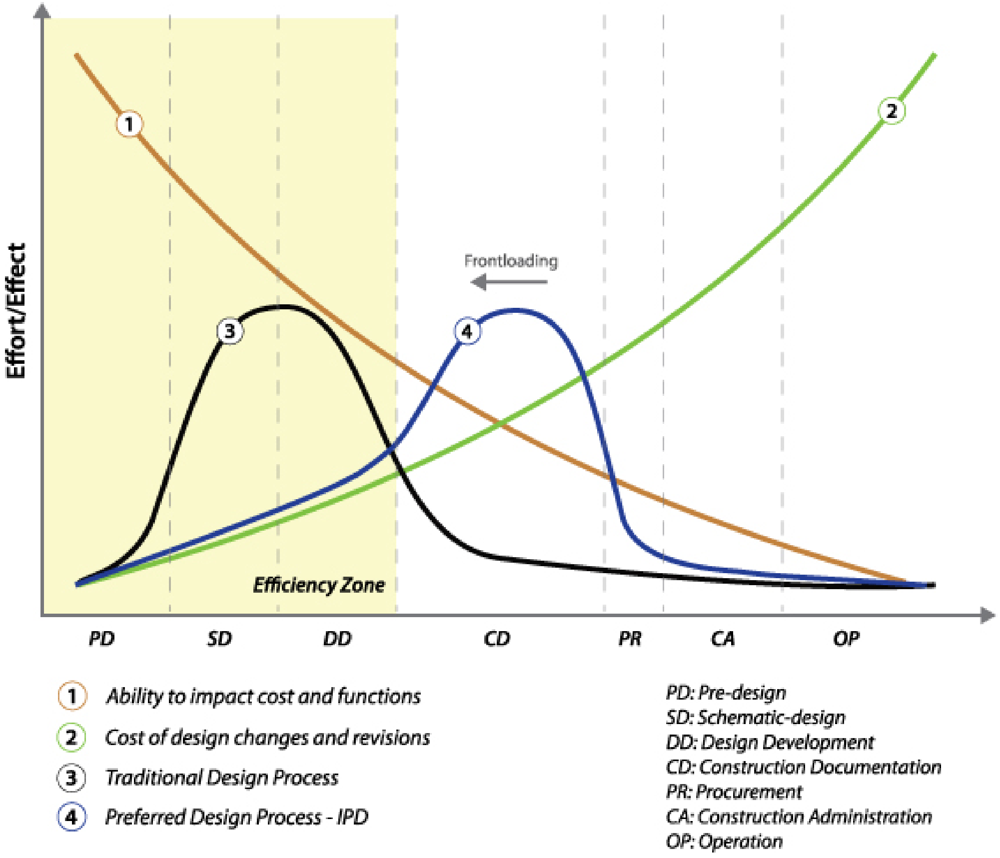


Figure 3.6: Project stages and relationship between cost and design changes (reproduced from CURT 2004)

Like the CURT's initiative for a robust AEC industry, FIATECH consortium's Technology Roadmap is a notable effort of a broad range of participants like associations, consortia, government agencies, academic institutions, and industry representatives from AEC and EPC domains (FIATECH 2009). The purpose of the technology roadmap is described as accelerating the deployment of emerging and new technologies that will revolutionize the capabilities of the capital projects industry. The effort has been justified as a response to population growth and demographic shifts; aging buildings and structures; pressures on natural resources; globalization of business; economic pressures in both the public and private sectors; and workforce issues. Roadmap has put very clear objectives and measures over the short term. Therefore, it is beneficial to review the roadmap as it provides information about the future practice in the building industry. FIATECH identifies nine roadmap elements, two of which are directly related to BIM and integrated education (Figure 3.7).

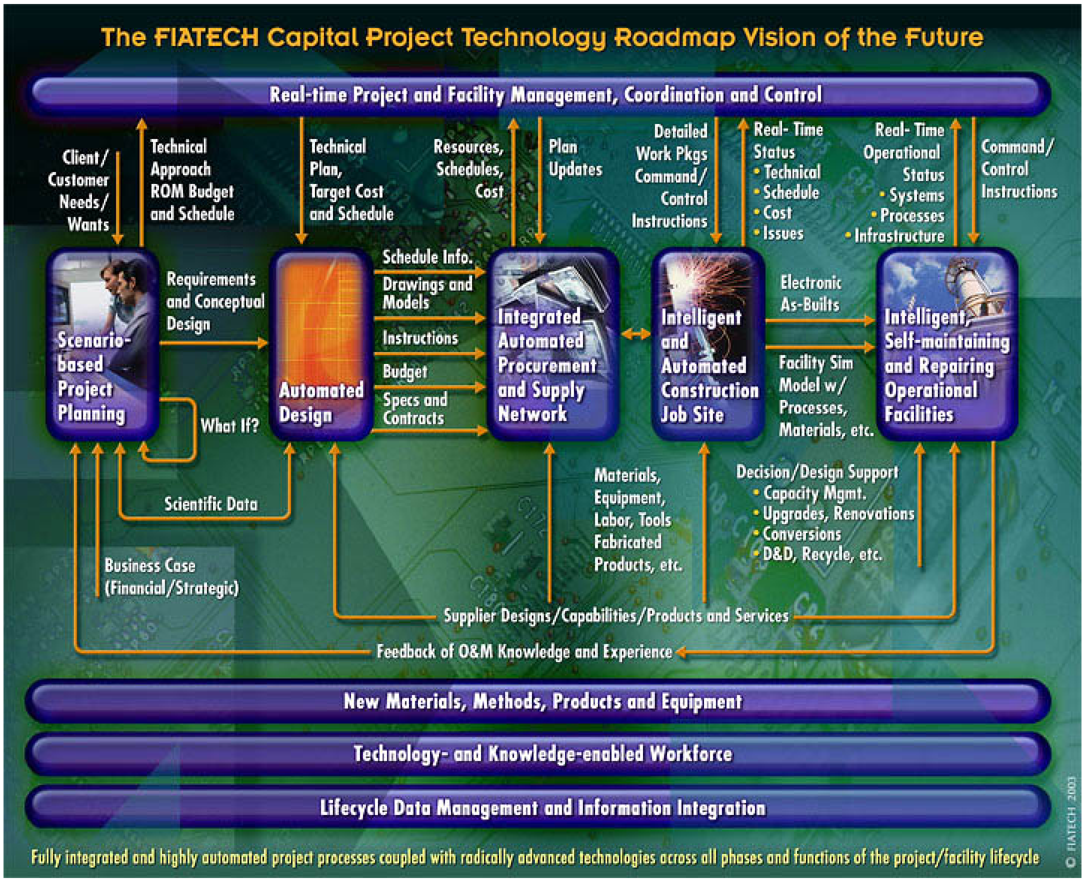


Figure 3.7: FIATECH Technology Roadmap (used by the permission of FIATECH)

Referring to deployment of BIM and effective interoperability standards, FIATECH describes the goal of Element-Lifecycle Data Management & Information Integration as

> *…to create the foundation for a lifecycle data management and information integration environment of the future that is adopted throughout the capital projects and facilities industry, centered on the need to deliver the right information, at the right time, to the right place.*

Furthermore, the goal of the Element-Knowledge-Enabled Workforce is described as an attempt *"to define the steps needed to improve technology assimilation rate in the industry, to transform the workforce to a highly productive environment, where rapidly evolving technology, tools and process can be quickly implemented."*

The document states that the current and outdated industry tools and processes do not appeal to new generations, and productivity in the industry has been lagging behind other industries. FIATECH's suggested strategy to achieve the objective is to embed new practice models across the industry; reengineer the methods, systems, and equipment; and enable proactive use of emerging technologies in training and education, thus providing interactive multimedia instruction and monitoring to assure compliant practice. The FIATECH roadmap can be given as a significant reference for illustrating the near future of the AEC and the integrated design practice.

Regarding the integration issue in the AEC, Bernstein (2005) emphasizes the negative effects that result from discontinuity of processes and poor exchange of information among stakeholders in the building design, procurement, construction, and operations processes (Figure 3.8). BIM can be a catalyst for integrated practice with greatly expanded benefits and is not merely a method for improving internal tasks and processes. These viewpoints validate the growing recognition of BIM related theories and propositions of industry-wide integration and required changes which were discussed a decade ago by Eastman, Tolman and other researchers (Eastman 1996; Tolman 1999).

Elvin (2007) also provided sound insights about BIM's role in integrated practice by stressing the importance of knowledge representation, IT, collocation, early information user input, and a common database. Elvin stated that all these make information exchange faster, more accessible, communal, and adaptable, as well as enable project teams to expand their services into knowledge management over the full life cycle of the buildings. He discussed the benefits of BIM within the integrated practice like better coordination and control, speed to market, increased productivity, quality increase, and expansion of architects service scopes. Underlined challenges are given by Elvin as the process of adoption, creation of BIM enabled workforce and current software capabilities.

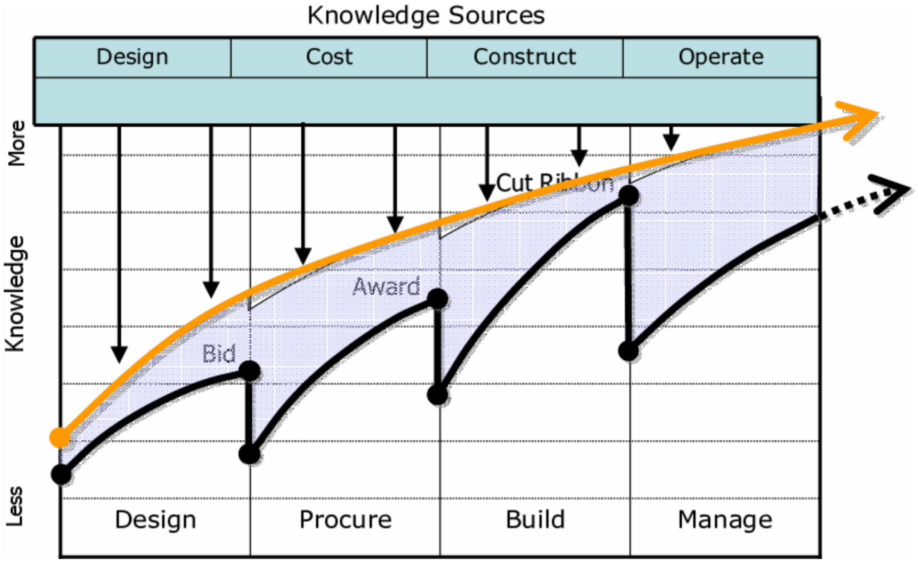


Figure 3.8: Bernstein's chart plots the rise and fall of project knowledge through the basic phases of project development (reproduced from Bernstein 2005)

Another major issue in the AEC industry sources from the emerging environmental challenges and contribution of the built environment to climate change. The International Panel on Climate asserted the building sector as the simplest and most promising way to reduce energy consumption and greenhouse gas production (IPCC, 2001). According to Energy Information Administration annual energy report, buildings in the US consume 40% of primary energy, and are responsible for 39% of CO2 emissions (EIA 2008). Research studies suggest that green buildings can reduce energy use 24%-50%, CO2 emissions 33%-39%, water use by 40%, and solid waste by 70% (Kats 2003; Turner and Frankel 2008; GSA 2008).

Because of the aforementioned issues, the need for high-performance and “green buildings” is rapidly increasing and USGBC’s market and consensus-based LEED standards are being adopted by the industry (Kibert 2008). Yudelson (2009) states that the push for LEED-certified high performance buildings is the driving force, along with the growing emphasis on carbon-neutral solutions for the paradigm shift in project delivery approaches. He further asserts that effective integrated design can produce significant innovations, cost savings, and better performance.

Integrated design processes or integrated practice are characterized by early significant collaboration of project participants. This early phase frontloaded stages expected to return higher values in terms of higher construction efficiency, better building performance and reduced environmental impact (Kibert 2008). Definition of integrated processes, as the result of a National Workshop on Integrated design process in Canada in 2001, provides a comprehensive understanding of this phenomenon:

> *The Integrated Design Process (IPD) is a method for realizing high performance buildings that contribute to sustainable communities. It is a collaborative process that focuses on the design, construction, operation and occupancy of a building over its complete life-cycle. The IDP is designed to allow the client and other stakeholders to develop and realize clearly defined and challenging functional, environmental and economic goals and objectives. The IDP requires a multidisciplinary design team that includes or acquires the skills required to*

> *address all design issues flowing from the objectives. The IPD process proceeds from whole building system strategies, working through increasing levels of specificity, to realize more optimally integrated solutions.*
>
> ***Excerpt from "The Integrated Design Process: Report on a National Workshop held in Toronto in October 2001." March 2002***

In the report, main elements of the integrated design process are the following:

1. *Interdisciplinary work between architects, engineers, costing specialists, operations people and other relevant actors right from the beginning of the design process;*

2. *Discussion of the relative importance of various performance issues and the establishment of a consensus on this matter between client and designers;*

3. *Budget restrictions are applied at the whole-building level and there is no strict separation of budgets for individual building systems, such as HVAC or the building structure. This reflects the experience that extra expenditures for one system, e.g., for sun shading devices, may reduce costs in other systems, e.g., capital and operating costs for a cooling system.*

4. *The addition of a specialist in the field of energy, comfort or sustainability;*

5. *The testing of various design assumptions through the use of energy simulations throughout the process to provide relatively objective information on this key aspect of performance;*
6. *The addition of subject specialists (e.g. for daylighting, thermal storage, etc.) for short consultations with the design team;*
7. *A clear articulation of performance targets and strategies, to be updated throughout the process by the design team.*
8. *In some cases, a Design Facilitator may be added to the team, to raise performance issues throughout the process and to bring specialized knowledge to the table.*

AIA also stressed the issues of segregated processes in the project cycle. Latest AIA report on Integrated Project Delivery (IPD) Guide proposed the essential principles of integration and business model framework for building an integrated project team. The document highlights the BIM technology component to overcome the disconnection issues between multidisciplinary project teams. The report states that it is possible to achieve IPD without BIM, but recommends BIM as an essential driver with distinct potentials to support IPD activities (AIA California Council 2007).

Briefly, the guide presents a frontloaded process framework where phases are either expanded or extended with interdisciplinary information. This approach is driven by two key concepts: the integration of early input from all stakeholders of the project; and the ability to model and simulate the project accurately using BIM tools. The guide redefines the project phases and the identification time of the project stakeholders. Preliminary phases of the process, i.e., Conceptualization, Criteria Design, and Detailed Design, involve more effort and use of information than their counterparts in the traditional flow. The following phases are expected to require less effort and start with a higher completion level with more accurate information. Stages of the integrated design process in comparison to the traditional design process are given in Figure 3.9.

Integrated project approaches strictly mandate the use of shared, consistent and reliable information between project stakeholders. The research and development efforts focused on integration and interoperable software technology provided models of integration and prototype tools nearly a decade ago. Fischer and Kunz (1993) assessed the effectiveness of existing integration models and proposed the circle integration model as a testable approach to structure the integration of AEC software applications.

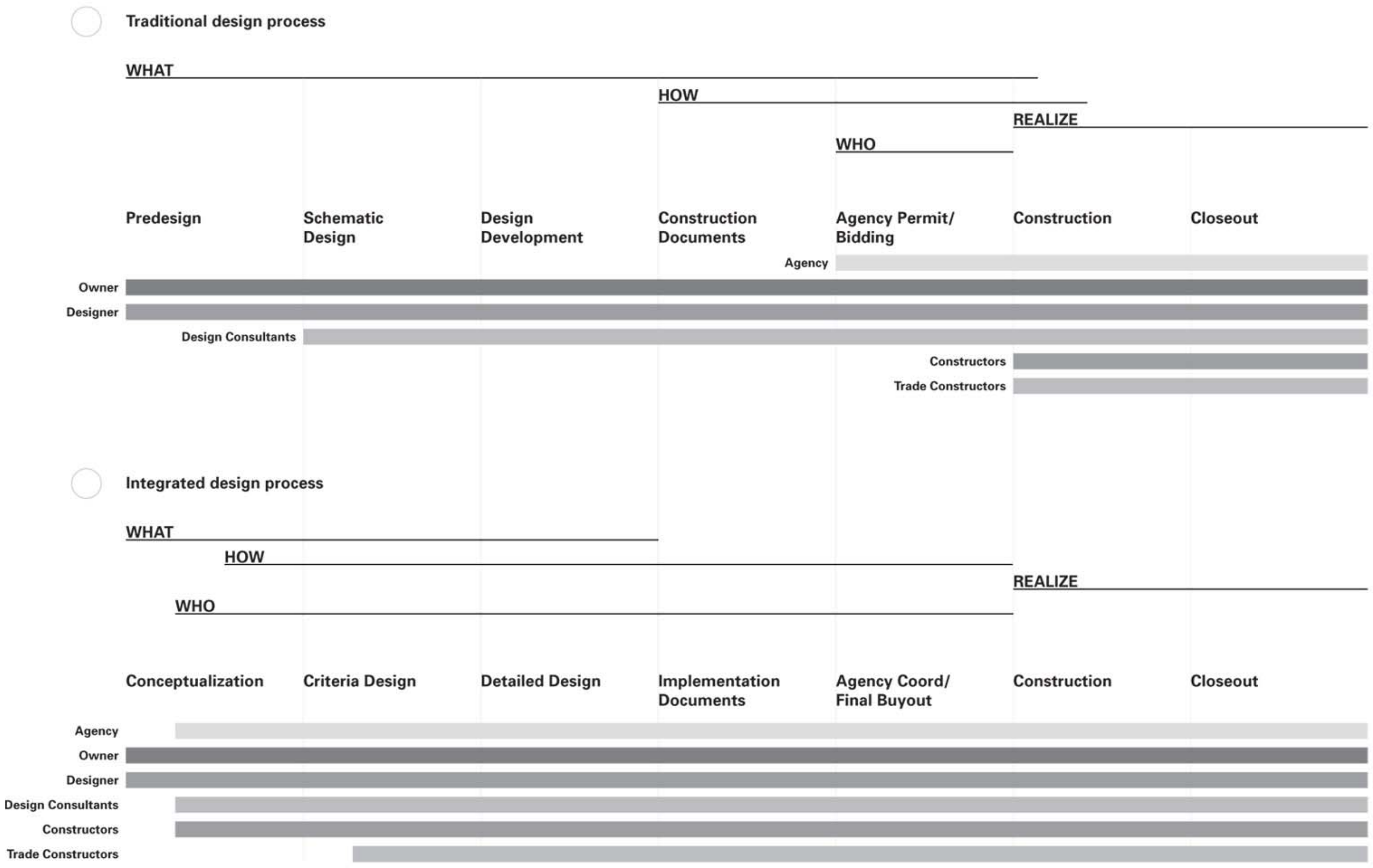


Figure 3.9: Process stages of traditional and integrated design processes (AIA California Council 2007, used by permission of the AIA)

They discussed the alternative integration architectures during the project planning and pre-construction phase in engineering. Their proposed model emphasized the role of software applications for the integration of the pre-construction operations, which encompasses a broad set of characteristics and tasks including client requirements and specification of functional systems. Integration models discussed in the study are the following:

1) *Organizational integration*, which involves the discussion and information exchange between clients and various discipline experts and among discipline specialists within project teams.

2) *Technical Integration*, which connects software applications with increased interoperability that support discipline experts. Kunz and Fischer described two types of technical integration: multi-node and circle.

    a) *Multimode integration*, which links each application to a central controller that receives and dispatches the changes from applications to other relevant applications. Implementation of central IFC database servers with connected application models can be given as an example to multi-node application.

b) *Circle integration* base on a single predecessor and a successor application that together form an information exchange cycle and a feedback loop.

There is a layered relationship between organizational and technical integration. In the proposed model, circle integration refers to the cyclic information exchange among software applications where process integration described as the organizational integration (Figure 3.10). In brief, circle integration model involves the information exchange from a predecessor application to a successor application around a circle. Kunz and Fischer claim that if each node has an independent and identical copy of the integrated set of applications, users for each discipline can initiate an evaluation loop to all subsequent disciplines and receive feedback regarding effects of the proposed design decision.

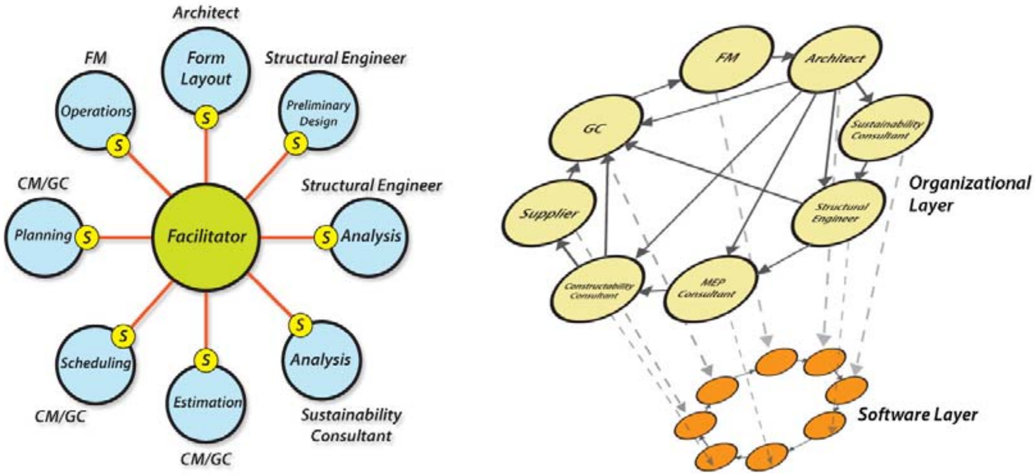


Figure 3.10: Multi-node and circle integration (adapted from Kunz and Fischer 1993)

According to Kunz and Fischer, both multi-node and circle integration mechanisms potentially increase the rate of feedback and improve the content of design information and overcome the problems of organization integration. Based on Dyson's (1992, *in* Fischer and Kunz 1993) suggestions, they stated that software will support the proposed design and engineering tasks and provide a more flexible response to dynamic nature of project processes like client needs and handling exceptions during the building lifecycle operations. The study also shows that the complexity and communication needs of different disciplines are crucial across the design, procurement, and construction phases for successful coordination and integration.

When compared with the AIA's integrated project delivery model, pre-construction is a subset of the building design and construction process. Pre –design and pre-construction phases have different contents and deal with different levels of ambiguity. Nevertheless, the study provided well-reasoned arguments about software applications as the catalysts for new models of integration. One important point in this study is the role of integrated set of software applications with independent functions and the information exchange between the members of the applications set.

3.5 Trends in BIM Adoption

Examples from the R&D efforts showed the potentials of the BIM technology, various implementations of state-of-the-art BIM methods, and new technological concepts.

Academic initiatives also addressed the value proposition of BIM methods in various stages of building production processes. A recent survey study by Gilligan and Kunz (2007) of Stanford CIFE analyzed and compared data from the surveys conducted in 2006 and 2007 on the use of Virtual Design and Construction (VDC) and BIM. The data included a wide range of industry participants that use VDC and BIM methods: architects, general contractors, structural engineers, MEP's and facility managers. The data suggested that VDC and BIM use is significant and expanding in momentum. Additionally, respondents to this survey reported more sophisticated use of the methods. More specifically, they reported specific benefits in the areas of improved participant engagement, reduced risk and project contingency, improved latency, and cost and schedule conformance. The study also showed that primary use of the methods was for visualization and prediction in which majority of the sample AEC firms reached this level; however, integration and automation level was only reached by a small group of participant firms. Findings from the study show a clear transformation in the building lifecycle processes, particularly in the early stages of planning and design. Results also illustrate the reported benefits from VDC/BIM use in the different stages of the building lifecycle.

Similar views for current and future trends of BIM adoption are shared by Eastman (2008). He makes a comprehensive review of recent surveys and offers well-reasoned predictions about BIM, both in the near, mid-term and long-term future. He pointed out the process changes, growing demand from the owners, green building needs, and widespread use of BIM and 4D applications in construction sites. Technology trends involve the increasing capabilities of BIM software, development of discipline-specific BIM tools, and growing number of parametric libraries from the vendors.

Recent survey by Gonchar (2006) has suggested that 25% of firms in the U.S. use BIM for production. Using this premise, Eastman (2008) extrapolated that 60-70% of firms in the US will start using BIM by 2012. The most important claim is the dramatic change in the scope of design firm services. According to Eastman, this change will happen in the mid-term with a strong push from the clients. Design firms will extend their scope of services to include detailed energy and environmental analyses, operations analyses within facilities, and value engineering throughout the design process, based on BIM - driven cost estimates. The arguments lead to the domination of BIM based processes in the AEC industry in the long term.

3.6 Issues in BIM Adoption

Although previous sections clearly set the stage for widespread BIM use, researchers like Eastman (2006; 2008) and Kalay (2006) emphasized the issues and limitations of BIM and related methods. Eastman underlined the obstacles as technical barriers, legal and liability issues, regulation, inappropriate business models, resistance to changes in employment patterns, and the need to educate large numbers of professionals. Kalay focused on the culture of the profession. According to Kalay, there is an uneasy relationship between novel computational principles, methods, and tools, and the ancient discipline of architecture. He stated that the use of the new tool is misdirected, or poorly fits the processes that have traditional methods of architectural design and construction. Furthermore, it results in a lack of appreciation for the emerging potentials of technology to change the task to which it is applied. Kalay further explores whether top-down-oriented and "centrally controlled" data management approaches, which follow a single modeling method, really can be a proper platform for comprehensive architectural design data management. Similarly, Eastman (2006) posits that software companies do not clearly distinguish construction domain expertise from software development expertise, and products initially often only poorly meet the requirements of the end users and require iterative extension and modification. On the other hand, he emphasizes the user mentality and adoption perspective very much similar to the Kalay's statements. He argues that even in a case when an advanced-level product is introduced, end users are typically naive and attempt to use the product in an evolutionary way, trying to make it fit older practices. Paraphrasing Eastman, a big gap exists between where users currently are and where they will be in the future. These viewpoints illustrate several fundamental issues in the industry like technological, cultural, and environmental barriers that prevent end-users from utilizing the wide range capabilities of BIM. These observations also hold true for educational use of BIM technology. Existing habits of students and already established design processes, methods, and studio practices are likely to decrease the true value of BIM in architectural education.

Another strong point made by Penttilä (2007) focuses on BIM use in the early phases of design. Using the findings from several in-depth case studies, Penttilä also agrees that BIM is a possible and promising data exchange method that enables wide cross-platform interaction and provides a possibility for life-long project data management. However, he suggests that BIM should not be seen as the one and only design tool in the early phases of a project. He concludes that other methods and tools are needed in addition to BIM in the early project phases, because it cannot solve all required design aspects.

Howard and Björk (2008) discuss the value gain from the deployment of BIM methods and data standards –like IFC – in the AEC industry using a qualitative approach. Unlike the authors of the CIFE survey, Howard and Björk approach this problem from experts' opinion perspective. Their participants include experts from various countries with different professional backgrounds, such as architects, engineers, contractors and IT specialists, about half of whom hold academic positions. Their research participants responded to two groups of questions about BIM methods and the deployment of IFC standards. The experts concurred on the potential benefits and realized value gain from BIM use, but also underlined some challenges for effective adoption. Some of the most significant remarks from the research study are the following:

1. Implementation of BIM models and standards raises questions of who benefits from the extra work done by lead designers.

2. Starting from basic standards to more comprehensive ones seems more feasible where variety of standards relevant to BIM exist.

3. Providing a special role in the project team for an information manager who could coordinate use of models throughout the project may catalyze BIM utilization while developing more advanced methods.

4. Better student education will eventually motivate firms to engage in future adoption of BIM.

5. Development of IFCs still depends on an elite group of experts. Owners are becoming more aware of IAI BuildingSMART initiative and owner response to IFCs has the paramount importance for further utilization. In order to obtain this, building lifecycle processes must be supported by good software implementations with IFCs.

6. To promote BIM and the leading IFC standard as a secret route to competitive advantage could be a more successful approach for motivating owners and the stakeholders in the AEC industry.

3.7 Design Studio, Integrated Education and BIM

The existing practices in architectural education are based on the dominance of the design studio as the knowledge execution environment for developing tacit skills for design. Recent research findings, expert viewpoints and assertions for the transformation in the practice and technology urge a comprehensive discussion about the existing models for studio education. A review of the existing theories on studio education, criticisms, and suggestions is provided for contrasting the traditional studio practices and novel integrated studio approaches.

Salama (1995) provided a comprehensive history of architectural education models since the inception of formal architecture schools and regarding ideologies, curricular structures and studio practices. The well-known model of *École des Beaux-Arts* has it roots in the value system of the 17th century society and the government in France. Akin (1983) stated that the Beaux-Arts model pursued an educational agenda in order to create an architect who was to be the master designer and master renderer largely relying on stylistic mastery. *Bauhaus* education, the only profound alternative to the Beaux Arts was developed in Germany before World War I in response to the changing technological, economic, and social values that originated in the Industrial Revolution. According to Salama, although these two approaches seem different, they are based on the same principles in relation to the society and the needs of the users. Both models emphasize the formal aspects of architecture, fundamentals of style with little concern for socio cultural and economic issues. The American schools have adopted the Beaux-Arts system since the inception of formal architecture schools in US (Anthony 1991). Later Bauhaus School influenced the architectural education due to the immigration movement from Germany.

Some of the most widely cited research studies on modern design studios were conducted by Donald Schön (1985; 1987). Using extensive qualitative methods and observations, he elaborated the pedagogical fundamentals of the design studio and distinctions of architectural education in the context of modern university and practice. According to Schön (1985), the discipline of architecture occupies a marginal place in the contemporary university with its tight connections to an early form of professional knowledge as opposed to the technical rationalities. He asserted that architects are often tempted to adopt an identity within the applied sciences; however, they cannot escape from the core paradigms of professional artistry. Although different disciplines like structural engineering or mechanical engineering contribute to specific design tasks, the general use of science is limited and architectural education embraces the traditions of the design studio. Schön describes the design studio, a traditional example of a *"reflective practicum,"* as a setting designed for simulating architectural practice. This environment approximates a practice world where students learn by conducting manageable design projects . He put an emphasis on the position of practicum as the intermediate space between the *practice-real world* and the "*esoteric world of academia."*

Moreover, Schön (1987) states that direct teaching of design is not possible; students can learn how to design only by doing it. He illustrates this constructive learning process in the design studio facilitated by a Socratic form of "dialog" between the student and the instructor. He further explains the mechanisms of learning in the studio in an epistemological continuum from tacit knowledge to reflection-in-action. According to Schön, the existence of general design problems is doubtful; as a matter of fact all design problems are uncertain and unique – a universe of one – and the designer creates his/her own methods and notions within the given design problem. The designer must deal with the problem by extensive usage of improvisation and invention. Schön calls this the essence, 'the artistry' of design practice. He used knowing-in-action as tacit form of knowledge which is revealed during the performance of a task or action. On top of this, reflection-in-action contains the unexpected and intuitive behavior of the designer sourced from her tacit understanding of the design problem.

Schön's description of architectural design studio urges the student to design before knowing how to design. In this case, the student educates herself by experiencing a contract with the studio instructor by putting herself into a mode of operative attention where she listens, observes and imitates the descriptions and demonstrations of the studio instructor. Schön identifies the design domains for this communication scheme, which involves the essential language elements of architectural design (Table 3.3).

Table 3.3: Normative/Descriptive design domains in the design studio (Adapted from Schön, 1985)

DOMAIN	DEFINITION
Program/Use	Function of buildings, components; uses of building or site, specification for use
Siting	Features, elements, relations of the building site
Building Elements	Component of the buildings
Organization of Space	Kinds of spaces and relations of spaces to one another
Form	Shape of the building or component Geometry Markings of organization space Experienced felt path of movement through spaces
Structure/Technology	Structures, technologies and processes used in the building
Scale	Magnitudes of building and elements in relation
Cost	Cost of construction
Building Character	Kind of building, as sign of style or mode of building
Precedent	Reference to other kind of buildings, styles or architectural modes
Representation	Languages and notations by which elements of other domains are represented
Explanation	Context of interactions between designer and others

Schön's theoretical suggestions are valid for the modern design studio. His observations suggest that artistry and the style of the design artifact are given utmost importance, and performance, physical behavior, and downstream issues have low priority or are often omitted from design-related communication. Based on descriptive design model, communication in the studio processes is carried out through visual representations as the dominant information source.

Salama (1995) reviewed different design studio model proposals by focusing on their pedagogical intents, design processes, and teaching styles. He states that these models have been developed in response to the systematic approaches in design and design methodology movement in late 1960's. According to the content analysis of his study, previously mentioned studio models share common procedures like analysis and synthesis stages where the analysis part is considerably more defined, rational and structured, and the synthesis part depends on highly intuitive and creative processes. The models reviewed in the study and their details are shown in the Table 3.4.

Table 3.4: Studio models and pedagogical contents based on the Studies of Salama (1995)

Studio Model	**Explanation**	**Design Process**	**Teaching Style**
The Case Problem Model (Symes 1985)	Emphasis on professional architecture culture by focusing on design methods, design negotiations and new roles for the architects.	Creation of a range of design approaches, design of alternatives using precedents from the real projects, development of the appropriate alternative, evaluations based on spatial organization, semantic rating, insulation, natural lighting, wind patterns, noise control, construction resources and economic analysis	Small project groups, each groups is involved in a project stage to stage. Defining work of each stage are undertaken by the individuals. Contribution from all students is required for the development of the design.
The Analogical Model (Simmons 1978)	Based on analogy as a rich source for creative ideas. Model asserts that novelty and originality are misdirected and futile. Design knowledge is obtained inductively through observations and accumulation of sense data. Emphasis on eclectic design approaches	Selection of a famous architect or a building technical system, literature review and case study examinations for building technology and formal vocabularies. Using an exiting program building design proposals take shape referring to the work of the selected architect or the technical system.	Individual processes based on 3 pedagogical objectives: providing an understanding of different types of knowledge in architecture, theories and building techniques; developing students' abilities to use these knowledge; use of abstractions of generic ideas from the work of the others.
The Participatory Model (Sanoff 1981)	Emphasis on the impact of design decisions on the clients and users. Design studio based on the examination of architecture through the understanding of people who inhabit those environments.	Learning to develop and apply techniques for involving clients/users in the process of making design decisions; systematically articulate methods of transforming behavioral information into building form; directly experience a design project from inception trough programming, encountering users and environmental constraints.	Design games with direct group experience. Collective search for alternatives in carefully designed workshops with high levels of participant interaction.
The Hidden Curriculum Model (Dutton 1987)	Emphasis on the social, political, cultural and economic relations of the society	Inception of process with students' subjective evaluations and attitudes towards the urban life. Individual program development with social context of their design problem. Group dynamics for consensus decision making. Peer and instructor evaluation and the development of schematic design alternative.	Competitive, heavily dialogue involved to promote the belief of unique design ideas, individually nurtured design decisions and prevent stealing.
The Pattern Language Model (Alexander 1977; Davis 1982)	Based on Alexander's Pattern Language design methodology. Emphasis on the *patterns* as physical relations and set of rules that make the design language for a particular design problem.	Process starts with site visits and identification of *patterns* for the formulation of the pattern language and design intentions. Students investigate patterns in order to create design proposals and the final design.	Students work in groups. Group discussions are the vehicle to reach consensus. Each student is encouraged to participate in the dialog and make judgments about the peers. Desk-crits involve students groups for design evaluations.

Table 3.4 Continued

The Concept-Test Model (Ledewitz 1985)	Emphasis on the conceptual idea generation for architectural design. The model conceives the design process inductively pursued from early principles to refined solutions.	Schematic design alternatives are developed by using gathered information and created concepts. Developed alternatives and concepts are evaluated thoroughly tested according to the information. Final design proposals are developed from the selected conceptual alternatives with formal experiments.	Individual learning through architectural thinking. The studio encourages student to recognize the different between external knowledge and their own interpretations. A reflective approach based on Socratic dialogue and self evaluation.
The Double Layered Model (Goldschmidt 1983)	A hybrid model on inductive/intuitive and rationally/deductive processes. These design procedures both happen at once. These tasks help students to translate data into design decisions.	Information gathering about the design problem in synchrony to the definition of the design imperatives. Design subjectively interprets the information during the programming stage. Final proposals later developed in accordance to the devised program and the gathered information.	The model relies on desk-crits and group discussions. Encourages original and individual interpretations and subjective evaluations.
The Energy Conscious Model (Cole 1980)	Emphasis on energy issues related to the building form and the site. Combination of a seminar class on energy conservation and a design studio. The main pedagogical objective is to translate theories on energy conservation into building design.	Design process starts with the provided generic knowledge about the energy issues. Schematic alternatives with graphic representations are developed before the provision of detailed knowledge. Final proposals are developed in detail and presented with physical models.	Based on Socratic dialog between the student and the instructor. Knowledge is provided to the students in a carefully devised framework in order to prevent information overload.
The Exploratory Model (Robinson and Weeks 1983)	Emphasis on improving the students' understanding of information relevant to design problems during the actual design process.	Design process starts with verbal and formal concepts which involve preconceptions and ideas. Analysis of the concepts is conducted for every selected design aspect through a structured process. Each analysis process includes a set of exercises for helping students to come up with a sound design proposal.	Individual learning based on verbal and visual abilities of the students. Students are required to explore the design problem with its various dimensions by being in the process themselves.
The Interactional Model (Gerlenter 1988)	The model conceives the design problem from two stages conjecture and analysis. The conjecture stage involves intuitive and reflective design processes. Analysis stage involves rational and scientific thinking for understanding the impacts of the new design idea.	The design problem identified and tackled with the cycles of conjecture and analysis stages for conceptual design proposals. The design ideas are evaluated and tested for the development of the final design.	Design problems should be assimilated by students' cognitive schemata in order to accommodate the new knowledge from the design process.

Ideologies and content of the studio models in Salama's study address the major issues of architectural design in the late 20th century with its professional environment, building technology, technological infrastructure, design media, design intents, and socio-economic context. The study does not provide information whether these models were recognized by the academics and architectural schools or not.

More recent studio models like Virtual Design Studios (VDS) were developed in response to the rapid advancements in information and communication technologies with a focus on digital representation, electronic design media, CAD, and virtual environments. Researchers in this domain provided substantial amount of research work, methods, strategies, and case studies for leveraging digital technologies and CAD in the design studio (McCullough and Mitchell 1994; Maher et al. 1999; Proctor 2000; Kvan 2001; Celani 2002; Kalay 2004).

3.7.1 Criticisms towards the Modern Design Studio

Although the conventional studio process has a long and successful tradition, it also has a number of institutionalized limitations and liabilities. It can be criticized in terms of innovativeness and the long-time practiced radical form of learning. Theory and praxis of traditional education emphasize form making and description of the form as the primary skill for the design student. The individual nature of studio processes combined with constraints of production time and representation conventions often obstruct the exploration of wide-range alternatives for the design problem. Studio settings motivate students to pursue inductive procedures, truncating both the breadth and depth of design explorations at the conceptual stage and deferring the addition of content to late stages of the process. Studio projects consume too much time, examine too few alternatives, and explore performance at a superficial level. This also avoids complexity and ignores the downstream aspects of architectural design by causing an *applicability gap* between in-class courses and the design studio (Anthony 1991; Weber 1994; Salama 1995). Weber (1994) argued the conventional design studio approaches as a valid and adequate pedagogical vehicle for preparing students for professional practice, which is significantly different from the Beaux-Arts era. Beinart (1981) discussed the segregated learning and application processes in Beaux-Arts and Bauhaus education models and the resulting disconnect between scientific-technical content of the classes and the stylistic approach of the design studio. The several decades of experience in architectural education collectively held by the researchers have established for us that the architectural design studio is characterized by a personal, project-based learning method that is largely a Socratic dialog between the instructor and the student. Here, it can be argued that the conventional studio employs and promulgates a contemplative, rather leisurely process that depends upon tacit knowledge gained through years of repetitive work under the tutelage of a master designer. It is attuned to a social context in which architecture did not need to reach high levels of technical performance due to long business cycles, cheap energy, and authoritarian forms of leadership.

The National Architectural Accreditation Board (NAAB) and the American Institute of Architecture Students (AIAS) have commented in the past few years on the educational quality and content offered in the schools of architecture. The accreditation standards establish benchmarks for assessing the ability of a curriculum, faculty, and infrastructure to deliver the basic and essential knowledge necessary to practice architecture. The AIAS, particularly in its study of studio culture, has offered criticism of the patterns of architectural education and has suggested remedies.

The *NAAB accreditation guidelines* and *The Redesign of Studio Culture* (a report of the AIAS Studio Culture Task Force about the future of studio culture) provide strong arguments about the future of architectural education (2004). NAAB accreditation guidelines provide a framework for the assessment of the architectural education while establishing important criteria for vision, initiatives, pedagogical key points, infrastructure, and student and faculty characteristics of established educational programs in architecture. On the other hand, the AIAS report particularly focuses on the current practice in the studio environments, educational problems, challenges, changes in global culture and socio-economic life, built environments, and the practice of architecture. The report puts forward suggestions about creating a new vision for the studio culture of the future (AIAS 2002).

From the point of view of the future studio culture, the transformation of the current studio environment is bound to many factors. AIAS Studio Culture Task Force Report involves critical thoughts on the transformation of the studio based on different components and underlying ideologies of design. Although these views reflect a strong emphasis on tactical issues and problems in the ongoing educational approach, there are important viewpoints based on the contextual and conceptual change in studio education. The most important argument made in the report is the lack of change in studio courses over time while maintaining several teaching traditions that are in opposition to the rapid transformation of socio-economic life, technology, and culture. Current perceptions of the studio have significant impact on student life by consuming all available resources. Time and resources are highlighted as main problems and unhealthy work habits are pointed out as a part of the competitive studio culture. The fact that product based thinking puts barriers to form process-focused studio settings is also identified as problematic.

Thomas Fisher (2004) of University of Minnesota School of Architecture voices hard criticisms of the design studio, stressing the seeds of the design studio culture: the long hours, the intense competition, the schematic design focus, the absence of users, the relative disregard for how things get built, and the emphasis on the development of prototypical solutions. Likewise, Anthony (1991) comments on the influence of intensively competitive design studio model with the image of the designer as an individual artist that has reigned supreme. She states that the increasingly complex nature of professional world that is reliant on design teams, joint development efforts, and more complex design projects makes obsolete the designer who is trained as a solo artist engaging in competitive and individual pursuits.

Hamilton and Watkins (2009) discuss the current educational practices in architecture schools. Similar to other educators, they state that despite the fact of changing realities of the practice, architectural education has not changed significantly. The model based on the 19th century Ecole des Beaux-Arts prepares students for an invalid form of practice. Arguments include the absence of cost constraints, technical competence, interdisciplinary teamwork skills, comprehensive knowledge of social and behavioral sciences, and lack of scientific perspective for evidence evaluation. According to Hamilton and Watkins, integrated teaching models offer the possibility of preparing future architects for integrated collaborative practice. They propose evidence-based design approach to pair up the teaching of green design and sustainability. They further stress that the changing directions of the profession urge educational institutions to engage in a thorough analysis of current state of architectural education with a projection of the future state of architectural practice. This effort should lead to well-reasoned suggestions for curriculum revisions and restructuring of the design studio model.

3.7.2 BIM and IPD in Architectural Education

Referring to previous sections, it is evident that the practice of architecture is being transformed under the influence of technological, environmental, social, and financial challenges. BIM and IPD are the innovative responses that are expected to provide the high ground for the AEC industry. Eastman (2008) emphasizes the importance of creating knowledgeable and technology-savvy professionals for the transformation of the AEC industry. Similarly, Smith and Tardif (2009) defines education as the largest and often hidden investment for the cultural shift. He further claims that the education will enable the profession to change its business culture and consequently achieve greater value than can be achieved by simply automating existing processes. Elvin (2007) also highlights the potential benefits of BIM and Integrated practice in education with parameterization of design information with hi-end BIM technologies. Like Eastman, Smith and Tardif, Elvin also points out the importance of BIM-ready professionals as a current challenge in the practice world. Putting architectural education in the focus of changing socio-economic dynamics, foundations of the integrated education lies on the uneasy relationship between aesthetic values of architecture and scientific/technical rationalities of the built environment. This raises significant questions which are critical for outlining a pedagogical framework for the integrated studio.

Based on this perspective Cheng (2006) reviews the architectural education curriculum, integrated practice, and possible implementation of BIM in the architectural education (). She elaborates the role of BIM in architectural education and its appropriate place in the curriculum. She depicts the current trend in the contemporary design studio as the seduction of new forms or reinterpretation of established formal compositional principles. She further criticizes the students' studio process for putting too much emphasis on the generation of form. Additionally, she states that possibilities raised by new production methods are largely unexplored and the underlying logic of the technology is poorly understood. Cheng asserts that the hypothetical model for the integrated practice will be the most interdisciplinary knowledge demanding approach in the early stages of design and current domination of formal emphases will be one of the least urgent factors in the design process.

Cheng hypothesizes the most positive effect of BIM on the curriculum as de-emphasizing formal manipulation. However, she brings legitimate criticisms to such implementation of BIM in architectural education without drawing attention to the essence of design education. She approaches BIM integration and architectural education from the widely elaborated concepts of design process: design thinking or reflection in action versus. design as problem solving. According to Cheng, industry-centric and answer-driven conception of BIM may reduce architectural design to a simple matter of problem solving. From a designer point of view, she asserts that construction can be achieved through problem solving, while architecture requires design thinking. She further stresses the importance of design thinking and potential problems of BIM implementation without acknowledging the considerable liabilities of design thinking.

Barrow (2004) directs very sharp criticisms to the existing status of architectural practice and the education of the modern architect. Barrow asserts that architects are often educated in a culture of individualism and subjective aestheticism, which often obscures broader inclusive issues of mass society. According to Barrow, choosing the *designer* role may eventually frame the profession to a very limited niche in the society along with fashion and product designers. He highlights the changes in the practice sourced from integration of building production processes. Barrow points out information technology as driver for inclusiveness and collaboration for knowledge integration and a disrupter for established notion of architectural practice. As questions rose about the roles and responsibilities of the modern architect, Barrow discusses the emergence of a new-age master builder and proposed the concept of *cybernetic architect* as the main component of a *dynamic knowledge network* of collaborative contributors that offers the ultimate expression of technology, adaptability, craft, and creativity.

Clayton (2006) discusses the influence of aforementioned factors in the architectural education curriculum. He criticizes the existing practices of architectural education which have roots in the 1950’s social, technological, and professional environment. He argues the validity and effectiveness of the Bauhaus-Beaux Arts ideologies which put significant emphasis on traditional drafting skills; teaching of nearly obsolete technological concepts of structural engineering and environmental control systems; and arguably biased content of architecture history courses. In this context, he stressed the inevitable influence of the post petroleum-era, globalization, and the information age on the 21st century curriculum. He asserts that BIM represents a profound change in how architecture is created and documented. BIM has potential to influence the curriculum with its virtual environment, where a variety of design/engineering activities can be tested and evaluated by students without tedious processes of formula driven calculations. His examples included specific topics in structural engineering, finite element analysis, computational fluid dynamics, 4D CAD, walk-through animations, and human behavior simulation. Based on these warrants, he makes a definite suggestion that BIM should be the way of teaching the craft of building and documenting the design.

After the University of Minnesota BIM symposium, Khemlani (2006) summarized the views on BIM and education. The main questions she poses are how best to educate students for a professional future in which BIM will play an important role. How much of BIM should be taught in schools? According to the report, participants agreed on the potential changes and transformations in the profession occurring due to BIM use. Furthermore, concerns and criticism are raised based on the widespread use of CAD and its shortcomings in the design studio. Khemlani emphasizes that even with CAD there was always the fear of "students getting lost in the computer," which made many studio instructors prohibit their students to use CAD in their projects. With a skeptical tone, discussions focused on the possibility of the same trajectory with BIM or BIM as being fundamentally different from CAD that it could prove of tremendous value in core architectural education, in helping students understand how a building goes together. Khemlani does not arrive at any definite conclusions and suggests waiting for architecture schools to start experimenting with incorporating BIM in their curriculum.

In Cranbrook 2007 Studio Instructors Conference on integrated education, Friedman provides insights and suggestions about studio education within the context of integrated practice and the BIM enabled AEC industry (Friedman 2007). He asserts that fully engaged critical analysis and experimentation of integrated practice as an instrument of design inquiry is missing from the current design studio education. He points out the growing interest in the industry for BIM and integrated practice models. Furthermore, he affirms that all students of architecture will routinely explore schematic design in data-rich four dimensional virtual building environments in the near future by accessing measurable correlations among design, construction, and performance earlier in their education.

Similar to these viewpoints, Ambrose (2007) discusses the changing dynamics of architectural design practice and its reflections on design education. His paper based on the critical question of how the academy might prepare students of architecture for a digital practice, focuses on the virtual building model and database management. He emphasizes that BIM and *Integrated Practice* can be provocateurs of design education, which may provide great potential for critical analysis of how architectural design is taught. According to his views, applying new tools and processes to old pedagogical and educational paradigms will not be sufficient. He suggests that educators seek out new methodologies for exploring architecture that reflect the pedagogical shift represented in BIM by developing teaching methods that reprioritize ways of seeing, thinking and making in the design process. The paper sees BIM as more than a tool; rather, it defines BIM as a sound and comprehensive way of thinking about design. The paper underlines the importance of design studio for reflecting on new ways of teaching and addressing

BIM methods and processes, and critically evaluating their effects on and possibilities for architectural production.

3.7.3 Potentials of BIM in the Integrated Studio

BIM may improve the quality dimensions of the current education and alter the studio culture as a facilitator in the process of integrating different aspects of architectural design education. Current software solutions and uses include surface modeling, drafting, and visualization. However, the profession specific nature of BIM is more likely to provide more than the existing solutions while connecting all of IT needs in terms of design, construction, and life cycle processes in a knowledge-based and well-integrated system structure. This can be assumed as a *simulation environment* for different teaching and learning purposes.

More specifically, BIM methods may enhance the quality of education in order to meet the criteria mentioned in NAAB (2004) accreditation guidelines:

1. BIM provides 3D parametric models and automated documentation capabilities that may prompt students to think and design in multiple dimensions (criteria 3 and 5).

2. BIM may also enhance the formation process of fundamental design skills and basic architectural principles by providing a specific digital medium for

design collaboration among students, instructors and consultants (criteria 6 and 7).

3. BIM may play a crucial role in teaching of sustainability issues. Students will have the opportunity to access immediate sustainability information from the virtual building model such as energy consumption, natural lighting, mechanical systems etc. (criteria 15).

4. BIM may enhance the understanding of building systems layers by using particular software components for the each system, such as structures, environmental systems, building envelope systems, service systems, and materials. In addition, BIM provides tools for integration of these systems in a precise and responsive virtual building model (criteria 18 to 24).

5. BIM provides a broad database for specific queries, creating schedules and cost analysis of the building project. This may help students to understand the financial impact of design decisions on their studio projects (criteria 25).

6. BIM may play a crucial role in architectural education by supporting the educational activities used for creating capable architects who possess well-developed comprehensive architectural design skills (criteria 28).

3.7.4 Previous Works and Experiments in the Design Studio

Many researchers have contributed to the understanding of integration of computer applications into architectural design education to achieve efficient pedagogical strategies. Early works include the integration of knowledge-based CAD systems and expert systems (Gero 1989) into architectural education. Research efforts focused on the usage of digital media for effective representation, teaching with digital media, as well as form generation and expression. Use of CAAD systems in these research studies was mainly based on non-integrated, plug-in modules for conventional CAD or knowledge-based/expert systems for very specific tasks in the architectural design Current status of CAD integration in architectural education is predominantly based on achieving graphic representation of design artifacts (both in 2D and 3D). This has a direct impact on the effectiveness of communication during the design process and delivery, and the support for students' design thinking in a flexible medium. There is also an increased interest in the utilization of generative systems for achieving complex forms and fabrication through parametric surface models. Although the use of CAD and surface modelers provide students with increased capabilities for form manipulation, visualization, and documentation, the content of the data and embedded knowledge on these digital artifacts lack of supporting performance based design activities and collaborative processes (Achten 1996; Ataman 1999; Cheng 2001; Flemming et al. 2002; Mark et al.2003; Kalay 2004).

Research on BIM and integration in the design studio is relatively new domain and is increasingly receiving attention. For example, in their study Plume and Mitchell (2007) review the efficiency of building information modeling technology in a multi-disciplinary design studio context. A predesigned IFC building model is employed in order to facilitate a collaborative design process in a teaching environment. Students performed post-design audits and developed process models for the different analyses of the building such as occupancy, cost, thermal, and acoustics. This study shows that IFC based models are successfully used by students with a wide range set of BIM and analysis tools even with the specific technical challenges in geometric representation and integrity of the building model. Research findings from the studio indicate several key issues for the BIM use in the teaching process:

a) Importance of creating a building model that is suitable to support collaborative design;
b) Model management for maintaining the semantic integrity of the model during course timeline; and
c) Inclusion of notion of attaching ‘‘intentions’’ to elements in the project model for collaborative decision-making.

However, the research approaches the problem from a technical efficiency level and does not provide insights about the learning efficiency, improvement of knowledge, and student response.

Oxman (2008) introduces parametric models, complex generative surfaces, and performance simulators as components of a design studio experiment. Student work demonstrates a comprehensive level of understating beyond expressive forms with the aspects of materiality and performance measures. The research oriented context of the studio and utilized technologies shows the potential of technology to transform learning and design thinking processes. Focusing on the parametric models, Guidera (2006) proposes a reductionist approach to teaching undergraduate design students particular system layers of the building with parametric modeling in the design studio. In brief, the main idea of the study is to decompose the BIM software into its functional pieces and limit the software use to parametric modeling module with in-built components. With a heavy emphasis on conventional studio processes, students were required to create specific system components with parametric objects. Later these parametric components and the devised systems were articulated with the studio projects with sufficient visual output. Reported case studies demonstrate the effectiveness of parametric modeling and the supportive role of BIM for understanding building systems with examples. The proposed approach can be assumed to be an efficient method for teaching undergraduate students who lack an adequate level of BIM literacy. Referring to the potentials of BIM discussed by other scholars, the study may be criticized for the limited perceptiveness of BIM integration into the design studio with novel studio practices for leveraging all the capabilities of BIM.

Yan and Liu (2007) present a process framework for a BIM enabled interactive gaming environment for enhancing architectural design and education for sustainability and proposed pedagogical strategies and objectives. They provide a structured system architecture consisting of BIM models, gaming environment, and add-on components for the gaming mode. Preliminary results show the bi-directional connectivity of BIM models to interactive game environment through an API interface. The most appealing aspect of the research study is the approach to the decision process in sustainable design within a highly interactive media where students can evaluate broad range of alternatives and make rapid iterations.

3.8 Summary

The extensive literature review presented in this chapter illustrates the interrelations between BIM, integrated project processes, and the integrated design studio. In brief, literature shows a strong emphasis on BIM as the kernel of integrated design processes and the catalyst of novel practice models. With its capabilities of integration, automation, and simulation, BIM has the potential to support integrated sustainable design and lean construction. Parametric modeling and hi-end simulation methods are altering the architects' way of designing. Within this paradigm shift, BIM and IPD address the challenges of 21st century architectural problems which demand swift and interdisciplinary responses.

From the educational perspective, implementation of BIM and IPD raises significant questions and concerns. In the last two decades, researchers and educators have brought sharp criticisms to conventional studio approaches and clearly demonstrated the need for substantial revisions to the uses of Beaux-Arts ad Bauhaus models in the modern design studio. The incompatible teaching and learning environments which are connected to form and style-centric paradigms may not be effective for engaging the emergent aspects of architectural design like sustainability, mass customization, use of advanced IT, and building economics. In addition, recent studies clearly show the growing demand for capable, well-rounded, and BIM savvy professionals for IPD. Very similar to the CAD paradigm, architecture schools may give quick and straightforward responses by offering one or two BIM classes in graduate and undergraduate curriculums. However, the effectiveness of these classes may be arguable unless BIM and IPD are introduced in a studio context. Integrated studio approaches are more likely to contribute to the restructuring of the design studio. Continuous learning and creative thinking in an interdisciplinary design team is the key point for the formation of future architects. BIM and IPD possess distinct potential to facilitate an integrated studio environment for engaging the different aspects of performance-based design. Taken together, there is clear and increasing recognition that design education methods should be reformed to leverage advanced IT methods like BIM and prepare students for the integrated practice. On the other hand, there are potential challenges and barriers for effective introduction BIM and IPD in the design studio. Limitations of the software capabilities, counter-intuitive and complex interfaces, interoperability problems, and production-focused software development approaches need to be addressed with effective pedagogical strategies for avoiding any obstructions in design learning and architectural thinking. In addition, IPD processes demand decent degree of knowledge and expertise for interpreting wide range explicit information in order to create adequate design solutions. Major qualitative aspects like conceptual depth, aesthetics, contextual relevance, and social performance always apply for any studio model. This dramatic increase in the studio scope may be overwhelming, which will demand more input from consultants and studio instructors.

As a conclusion of the literature review, cited viewpoints and criticisms justify the need for further exploration of BIM and IPD with empirical studies, as suggested in the present study. BIM utilization strategies and the interoperability approach in this study refer to state of the art examples and best practices.

This literature review also identifies certain concepts which are further used in later stages in the research study for content analysis and interpretation of research findings. Based on the three sections of the literature review, extracted concepts are given in Table 3.5. Relationships between the concepts in relation to the research study are synthesized in a concept map (Figure 3.11).

Table 3.5: Extracted concepts from the literature review

Technology	Practice	Architectural Education
Interoperability	Integration/IPD	Integration of the Curriculum
Shared BIM Models	Technology Adoption	Integrated Studio
Performance Simulation	Interdisciplinary Collaboration	Studio Pedagogies
Parametric modeling/adaptability	Socio-economic Factors	Studio Models
Component Propagation	Technology Enabled Workforce	Tacit Knowledge
Data Standards	Changes in Business Models	Explicit Knowledge
	Sustainability	Design Methods
	Sustainable Architecture	
	Building Costs	
	Energy Performance	
	High-performance Buildings	
	Green Building	
	Certification Systems	

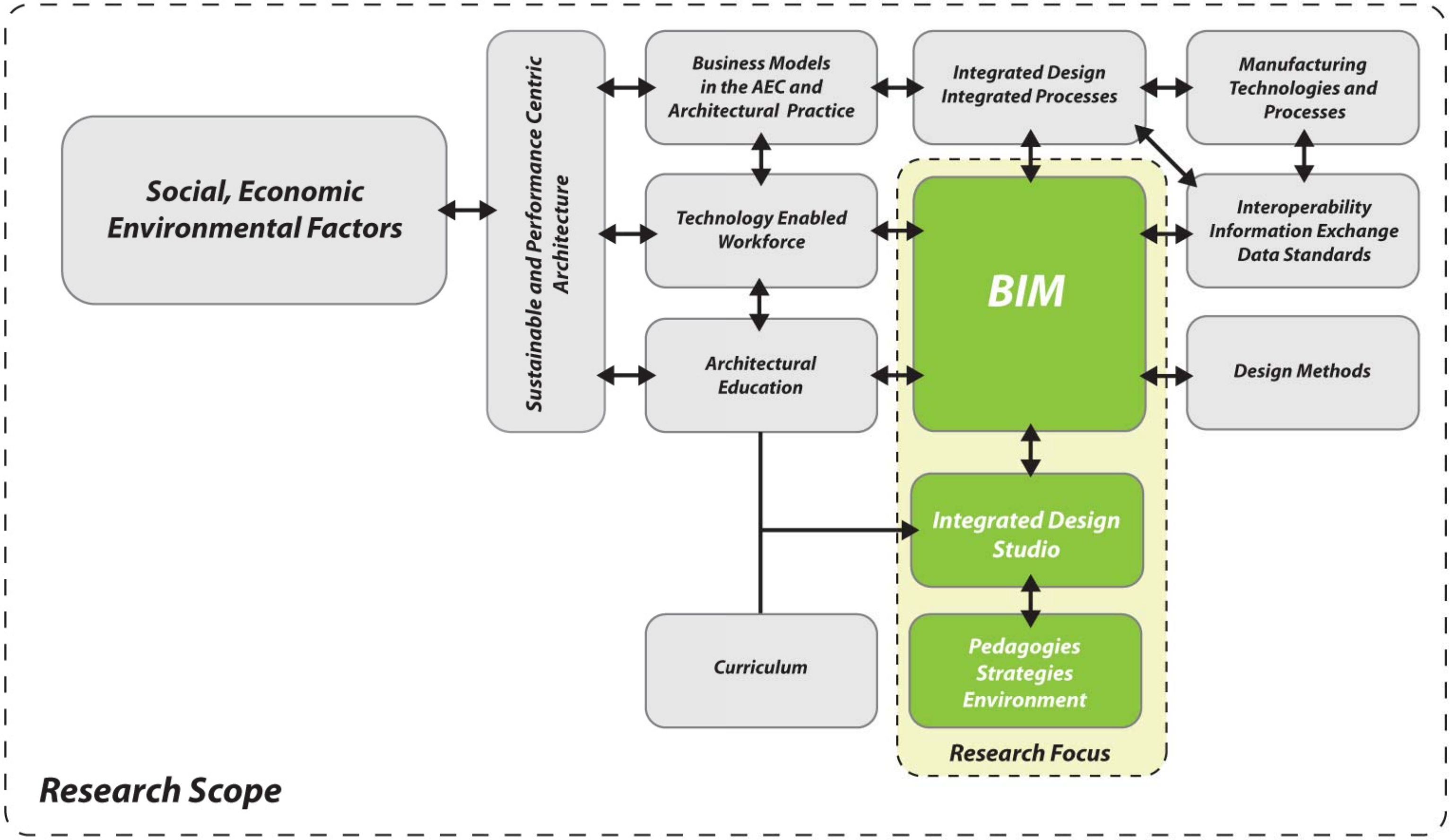


Figure 3.11: Concept map of the research study extracted from the critical literature review

CHAPTER IV

DEVELOPMENT OF THE PEDAGOGICAL FRAMEWORK

This chapter presents the results of the focus group studies, several case study examples from the practice domain, an analytical performance model for BIM and IPD, a pilot study and the proposed pedagogical framework for the integrated studio.

Findings from the focus groups clearly highlighted the potentials of BIM in relation to the levels of integration and interdisciplinary collaboration and revealed the differences between practice and education in terms of responses to social and economic challenges, utilization of advanced technology, organizational change and professional approaches. Participant opinions and feedback provided sound insights about changing design processes and delivery methods related to performance-based design, IPD and BIM.

Pilot study revealed the potentials of BIM use in the studio, improvements in the process, and the studio results. Findings strongly suggested that value from BIM in a conventional studio process is likely to be limited and that further experiments demand integrated pedagogical frameworks and strategies.

The prototypical pedagogical framework was formulated in the light of theoretical bases from the literature review, qualitative evidence from the focus groups and the findings from the pilot study. The fundamentals of the pedagogical framework are thoroughly explained using warrants, comparisons and targeted objectives for the integrated studio and BIM.

4.1 Focus Groups Overview

Four focus groups were conducted over a seven month time frame in 2007-2008. A diverse participant group actively contributed to the research effort. One focus group consisted of faculty members who have a common interest in BIM and integrated practice but diverse expertise in architectural education, studio teaching, information technology, design, construction, legal and practice issues, engineering, and other fields. Student focus group consisted of M.Arch. students from Texas A&M University who had at least two semesters of studio experience in the graduate program.

Two focus groups were composed of AEC/FM industry professionals who volunteered to meet for a half-day workshop. The participants from industry were purposely selected from firms that were known to the researchers to have had significant experience with BIM for implementing building design and construction projects. This group included representatives from large architecture firms, mid-sized architecture firms, structural engineering firms, contractors, MEP designers, and FM professionals, as well as design/build companies. These firms also provided comprehensive case study examples.

The agenda for the faculty and industry focus groups focused on different dimensions regarding BIM adoption and IPD. In the first phase participants were asked to provide insight about BIM adoption, use strategies, challenges, value gain and potential transformations in the AEC industry. The second phase involved questions about education and preparing students for the new models of architectural design practice like IPD.

Student focus group agenda included questions about students' perception about studio education, BIM and CAD tools, scope of the projects and their vision about the future of architectural design practice.

The focus group discussions have led to several theoretical models that can clarify the opportunities of BIM and how best to take advantage of them. From the focus groups, a terminology was devised for three strategies of implementing BIM that gives a framework for understanding the impact of BIM in the near future of architectural design practice and architectural education.

4.2 Data Analysis

All focus group discussions were transcribed and coded using a predefined conceptual framework regarding the research study. Coding process was conducted simultaneously with the interpretation of the transcribed text. As a result the final coding schemes provided the variable groups, patterns, frequency of the concepts, and identification of the opinions referring the research scope and intent. Two layers of identification tags are used for the coding of the transcribed text. The first layer included the general categories like understandings; positive or negative comments; suggestions; and questions. Second layer consisted of the content codes which were derived from the existing literature on BIM and IPD. During the interpretation procedure transcribed texts were tagged with the most appropriate content code regarding its content.

4.3 A Theoretical Model for the BIM Adoption and Performance

The content analysis from focus group transcripts suggested the existence of a significant transformation in the AEC industry passing through three levels of adoption:

a) In the low-end adoption level, which is termed BIM-A, BIM methods and technology are used internally to accelerate existing tasks and operations. Being a superset of CAD, BIM provides better tools for design visualization, documentation and the improvement of various tasks in the design process. Although this level of adoption is relatively simple and simplistic, our focus group participants reported high profit margins when they executed projects with 100% BIM utilization beginning at schematics and proceeding throughout production drawings.

b) The second level—referred as BIM-B—assumes BIM methods as the catalyst for the transforming the business model of a firm through integrated processes and collaborative design and production. In this level BIM models are used by the design team as the repository of cross-disciplinary information. Models are shared through an interoperable building model according to capabilities of the given task group. A wide range of simulations and analyses are derived from the common model. BIM-B is closely aligned with an Integrated Project Delivery (IPD) model for contractual relationships.

c) The third level, which is called BIM-I, posits adoption of interoperable building information across entire industry networks of designers, consultants, contractors, suppliers, and operators. It is more visionary than practical but was clearly understood by focus groups participants as the long-term goal because of potentially very high value and increase in productivity.

Findings from the industry focus group discussions suggest that internal adoption of BIM-A methods and tools significantly improved bottom line measures of design and structural engineering firms such as project production time, accuracy and value. Although there are some technology related challenges, such as interface and software usability, the internal adoption appears to be a well-established trend that is likely to spread swiftly throughout the industry. The level of current technology appears adequate to justify a decision to adopt and is likely to improve rapidly to support required activities in design and engineering workgroups. Profitability of BIM-A implementations was generally very significant and convinced decision-makers to move rapidly toward universal adoption within their firms. Likewise faculty and student focus groups stressed the advantages of BIM tools over conventional CAD tools in studio and other courses. Faculty observations and student opinions confirmed that introduction of BIM tools in studio and other courses has positive impact on project production time, quality of visual representation and detailing.

BIM-B is often linked to a design/build or integrated practice approach to project delivery. These firms are pushing the envelope of the technology and the business forms within the industry towards fully integrated practice. From the perspective of current technology, the “BIM B” level can be realized with current BIM tools and approaches; however, there are technological and cultural challenges that must be addressed for achieving success with this strategy. When compared to BIM A, BIM-B requires more effort, investment and expertise to handle the streamlining of information within various tasks and across interdisciplinary boundaries. Firms that have reached this mid-level of BIM adoption demonstrated cutting edge case studies with substantial evidence of value increase. Examples included large projects with strict sustainability goals, complex engineering applications and compound constructability requirements. Both industry representatives and faculty emphasized the importance of interdisciplinary collaboration for effective BIM deployment and the education of BIM savvy professionals who can master this new model of practice. BIM-B level use and strategies emerged as an achievable goal for educational initiatives particularly architecture schools by altering the curriculum structure and content of studio courses. As it will be explained in upcoming sections, BIM-B level adoption formed the cornerstone of the proposed pedagogical framework and teaching strategies. Following statements highlight the importance of BIM use for integration and collaboration.

> *I think that's another debate but I think BIM, you need to have all the bases loaded in a grand slam; it's the same thing and you know, architecture, MEP, and structure, that's all the bases loaded if you're just looking at the design portion.*
>
> ***Practitioner, Focus Group Participant***

> *So there's a lot of this talk about integration and I think some of that's a byproduct of this, the people having the realization that having the bases loaded with BIM would help us derive even greater value from this. Just doing a silo of design or an engineering practice, we need to all be contributing to this.*
>
> ***Technology Director, Focus Group Participant***

> *We are continuing to develop new strategies each day to leverage more valuable data from the architectural model, improving our analysis of our designs to help our designers and clients make better design decisions. We are able to study the design by using DOE2 energy model software, as well as natural day lighting simulation for glazing solutions on the perimeter offices for distribution of light on the interior spaces, and Building Envelope Option studies with include payback analysis for design options such as improved glass types, which help our*

> *clients and designers better understand design variables and the impact on the life cycle cost of a building.*
>
> ***Project Administrator, Focus Group Participant***

Many of the research participants expressed an expectation that in time all designers, consultants, contractors, sub-contractors, and suppliers would be able to accept and deliver information models among project participants. Thus, BIM-I is an ideal or a future stage in BIM adoption. The models would be used at the design stage, the construction stage and the operations stage. However, the research participants reported no cases that were able to employ extensive BIM-based, automated data exchange.

> *The goal of everyone in the industry should be better, faster, more capable project delivery created by fully integrated collaborative teams. Therefore the goal is to streamline the project delivery process from schematic design through construction, by assembling a design-build team capable of utilizing available BIM tools to better design, coordinate, document and construct.*
>
> ***Practitioner, Focus Group Participant***

4.4 Value from BIM Adoption

Figure 4.1 illustrates an adoption model for BIM in accordance with proposed theoretical adoption levels. According to Rogers, different social groups exist in the market in terms of their innovativeness and technology adoption (Rogers 2003). These groups are: 1) innovators, 2) early adopters, 3) early majority, 4) late majority, and 5) laggards. Briefly, innovators seek out new technologies and implement them to their business models by accepting the associated risks. Early Adopters benefit from the pioneering efforts of the Innovators. They may accept the new technology when the business case is uncertain or marginal, but they are well-positioned to gain benefits. Early Majority adopters accept the technology once it is mature and proven. Early Majority follows the opinion leaders, creating a tipping point beyond which the rate of adoption rapidly increases. Late Majority adoption occurs because of a contextual pressure and where adoption becomes business vitality. Laggards avoid or ignore the technology and adoption trend. They may be either isolated or already out of the market. Based on the collected data and this theoretical basis, it can be expected that the universal adoption of BIM-A will be achieved relatively quickly as the technology seems to be reaching the tipping point of Early Majority adoption. The adoption of BIM-B can proceed once a threshold of adopters have accepted BIM-A. BIM-I strategies require very widespread penetration of BIM-A as well as significant levels of adoption of BIM-B. BIM-I thus can be expected to become a significant and attractive strategy only after the other strategies have diffused widely across the AEC industry (Figure 4.1).

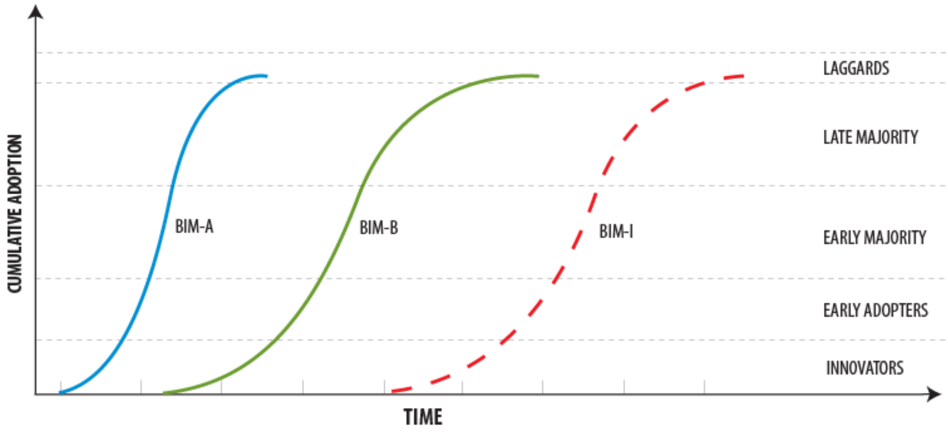


Figure 4.1: Adoption strategies and relationships to social groups and time

Using the findings from the data analysis and existing theories on technology adoption, the graph in Figure 4.2 is devised as a description of a performance model for the different strategies of BIM adoption and their interrelationships through time. These adoption strategies imply different value propositions. The upper left edge represents the concept of the maximum value that can be obtained by a BIM strategy. It advances at a rate determined by the improvement of the technology through time, and the improvement of a firms' familiarity and use of the technology through time. It can be argued that the value of BIM-B will rise at a steeper rate than BIM-A and BIM-I will rise at a steeper rate than BIM-B.

> *For us culturally it made a lot of sense and it's not just an integrated model, this idea of taking an idea forward into construction, I think it's a good fit because we had built up this reliance on 3D tools already and we got to a point where we said 'we're driving a lot of value from design explorations in 3D, why not take*

> *that further and have all that also be kind of bundled with our documentation process and not have things so segregated?*
>
> ***Project Administrator, Focus Group Participant***

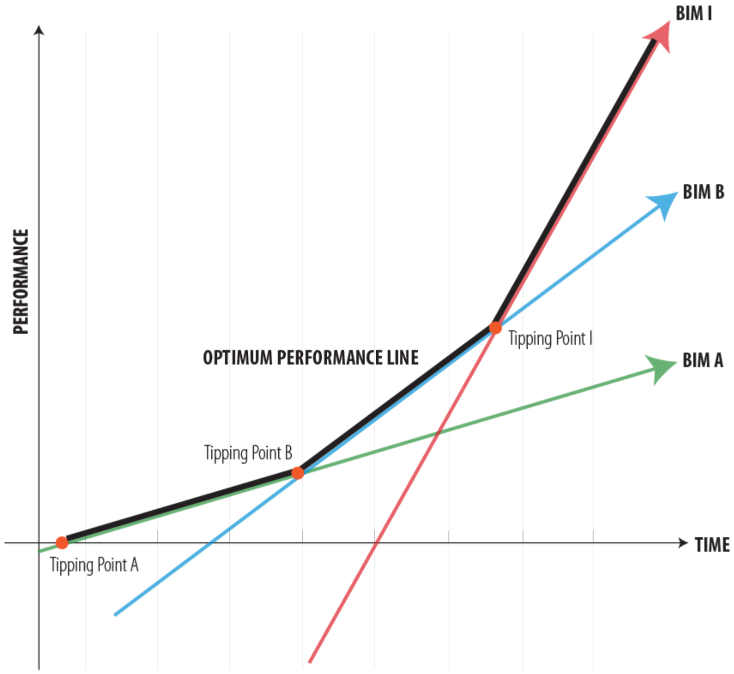


Figure 4.2: Adoption strategies and performance relationships

The reasoning behind the differences in steepness of these curves is drawn from past history of other disruptive technologies. BIM-A, BIM-B, and BIM-I are consistent with value curves related to network effects. The network effect is a characteristic of a technology such that the value of a good or service to a potential customer depends upon the number of other customers who own the good or are users of the service (Farrell and

Klemperer 2006). BIM-A is least susceptible to network effects because the technology is used internally. There are relatively few interactions and exchanges of information, although in large firms and integrated firms the number of exchanges may be significant. Large firms and integrated firms have the most to gain from BIM-A adoption. In BIM-B and BIM-I the value of the technology is dependent upon how many industry members have adopted the technology. BIM-B significantly reduces the cost of communications among designers, consultants, and prime contractors, increase the scope of the project and adds value. BIM-I should dramatically reduce the cost of communication among these same project participants and also suppliers, sub-contractors, trade workers, owners, and facility managers. As the number of participants who have adopted the strategy increases linearly, the value of the adoption increases exponentially. Because the value of BIM-B and BIM-I is susceptible to network effects, the technology achieves the status of being a disruptive technology. The curve of maximum value shows discontinuities at points where the more advanced strategy of BIM technology overtakes a simpler strategy. These tipping points indicate degrees of adoption where critical mass for the different strategy is achieved within the AEC industry. According to this model, the demand for BIM-B and BIM-I capable professionals especially architects may increase rapidly in each tipping point as the industry accepts the paradigm shift in delivery methods and design processes.

Recognizing that the adoption of BIM into practice is having disruptive impacts that change assumptions of design processes, delivery methods, scope of projects, industry demands, contractual relations, and even industry productivity, the responsibility of the educators emerges as to reexamine the pedagogical methods to adapt them for this new model of practice. Using this value model for BIM implementation in education, the question becomes clearer about the strategies and approach to BIM. As given in the model there are several possible trajectories like staying in tool/technology limits to support existing pedagogical practices and educational content or creating novel strategies in response to the BIM enabled delivery methods and design processes. In this study , the proposed theoretical model is used as the cornerstone to formulate the pedagogical framework, goals and objectives. Here, BIM-A level corresponds to a tool utilization level that is relatively easy to implement in a conventional studio. BIM-B level requires schemes and collaboration structures to provide sound basis for experimental studies in the design studio.

4.5 Challenges for BIM Adoption and IPD

The challenges that prevent an answer to the questions raised by BIM adoption or discredit the premise may be examined to help educational initiatives to craft strategies and tactics for adopting BIM technology and addressing them in education.

Focus group participants provided many insights about challenges and obstacles. Aligning the results with the core educational intent of this research study, their insights can be grouped into six major categories:

1. Integration
2. Interoperability
3. Information use
4. Data management
5. Culture
6. Education

4.5.1 Integration

Focus group participants recognized that much of the promise of BIM derives from its potential to integrate diverse processes of design, construction and operations. BIM can facilitate reuse of information across multiple processes or even feed tools that automate processes. However, participants identified several challenges to fulfilling the promise of integrated processes:

a) BIM tools do not yet have all of the capabilities that are need to support integrated design, construction and operations.

b) Processes of design and construction are not standardized so integration of those processes using BIM is difficult. Project team members are often reluctant to attempt integration of processes because they perceive that information and format are too different between disciplines, businesses, and lifecycle phases to permit success.

c) Integration downstream is particularly difficult as conventional processes are largely discontinuous across major phases. Although a design team is accustomed to working together and can conceive of integration across design processes, traditions enforce constriction of information between design and construction. Likewise, another constriction point occurs between construction and commissioning. Delivering the information of the design intent to the construction field or facility management field is a particular problem.

4.5.2 Interoperability

A major technological problem for BIM adoption remains the level of interoperability of software, or the challenges that occur when importing data into another application and exporting data for use in other, sometimes unknown, applications. All participating firms concurred that a solution to this problem is critical for achieving a more integrated business environment, particularly design tasks where interdisciplinary collaboration is needed to assess building performance. There appeared widespread understanding of the Industry Foundation Classes (IFC's) and their theoretical value in supporting exchange of data across software platforms from different vendors. However IFC's were perceived to have only modest effectiveness. Participating firms reported that:

a) Usage of one brand BIM tool may not maximize the benefits from BIM. At present, various tools have differing capabilities. It is more efficient to use a large set of tools so that they can address multiple purposes. This may lead to problems of data exchange and interoperability across platforms.

b) Participating firms reported that the global IFC format underperformed in their projects. They feel more comfortable with interface software (NavisWorks or Innovaya) that can provide data exchange between BIM and estimating software or Web-based collaboration software.

4.5.3 Information Use

When information is not consumed by other project participants, the production of the information appears to be wasteful. Participants from design firms stated that BIM expanded the scope and quantity of project information that they delivered. Yet they are anxious whether the information will be used or whether they will reap benefits from their effort.

The success of BIM-B adoption is dependent upon cooperation by interdisciplinary teams outside the team that originates the information. All teams must incorporate the information into their processes. If they do not do so, there may be no added value for the project and the effort of the designer who has used BIM will appear to be wasted. This issue strictly applies for the BIM use in education. Use of BIM for individual project processes or particular tasks may degrade the educational value of BIM adoption and it may obstruct BIM utilization for integrated education.

4.5.4 Data Management

Managing the large datasets of a BIM can be very difficult. Updating information stored in the BIM model and reintegrating the information with other models can be a major challenge and demands a level of expertise and understanding that is currently uncommon. This is often a problem when a model passes from one team to another team. Development of a schedule may be a significant effort each time an architectural model is delivered to a contractor. The contractor likely must add a significant amount of information about composing entities into work packages and declaring schedule information. Version management and the persistence of information and identity across multiple files remain a challenge.

Too much data remains a danger, even though hardware and software capacity has increased by many factors. Overly large models can slow even very powerful computers. The challenge of managing a huge amount of building related data may prevent firms from leveraging BIM methods and technology. The optimum amount of information is directly affected by the project scope, project team, and technological infrastructure. Too much data can reduce value rather than increase it.

The quality of BIM models is also of concern. Expert level ability with the software is rare due to the relative youth of the software. Also, expert design ability is rare among BIM users, as many of BIM users are new graduates with little project experience. Poorly constructed models can greatly reduce the reusability of data. Materials suppliers are beginning to deliver BIM-compatible models of building components, but the quality of the models is often low.

The assumptions behind a particular BIM system and the way the models are implemented may create inaccuracies or challenges at other stages of a project. A BIM component may not account for all of the materials and quantities of materials that are needed to assemble the real object. Models produced for design by designers may not be reliable for supporting constructability analysis and estimation, and likewise models produced by other parties may be less than optimal for designers. When approached from the education and studio environment point of view, dealing with huge amount of data and heavy BIM models may obstruct the learning process and reduce the efficiency of BIM for teaching purposes.

4.5.5 Culture

According to focus group participants, the business culture or long traditions of educational practices may also be a source of major challenges to BIM adoption. Not all firms are prepared or adapted to use BIM successfully also many architecture schools do not possess capabilities for teaching BIM and BIM enabled design education.

There are substantial differences in technology infrastructure among the AEC industry. Human resources, level of computer skill among principles, managers, and specialists, and sophistication with BIM are all important factors. Companies that employ experienced information technology officers may have a significant advantage in achieving successful BIM adoption due to their ability and willingness to champion the technology. Likewise there are significant differences between architecture schools in terms of technological resources, teaching priorities, faculty expertise, organizational structure and studio cultures.

Industry and faculty participants highlighted that skepticism towards new techniques and tools is not uncommon. Many in the industry and academia are inherently very conservative about their tools and processes. Accuracy, efficiency, or suitability for creative activity may be concerns.

4.5.6 Education

Education is a major concern for BIM adoption. Focus groups revealed multiple dimensions of BIM use in architectural education like curriculum transformation, BIM literacy, content of design studios and pedagogical practices.

Because BIM can compress the production stage of a project and create wide-range information about the different performance levels of a building, a designer who uses BIM may require especially high levels of both software skill and building technology knowledge. Entry level professionals may have relatively high levels of software skills but may lack comprehensive knowledge of building design and construction. Faculty and industry participants reported that some architecture schools are currently producing graduates with knowledge of BIM software use but are less successful in equipping graduates with the requisite knowledge of design and construction to allow them to be highly effective BIM experts.

> *So we want a model with a foundation, we want a model with the beams, all of that stuff. We want to model the building as its going to be built. And that's where they get lost, actually having to model it and build it in the way it's intended to be built. Where I think the construction, a lot of students they don't know how to put together a building.*
> ***Technology Director, Focus Group Participant***

> *(Regarding the comment above)*
> *It's one of those things where every school takes a very different tack, or tract on how to actually run a design curriculum and I think it's one of those things where the knowledge set that you're using, and I know that we see a shortage in is how the building goes together because it's so critical to the BIM process*
> ***Faculty/Practitioner, Focus Group Participant***

> *(Regarding the comments above)*
> *It's like you said, give me a week and I got them trained in our BIM process but it takes, and even though it's quicker in BIM, and I've experienced that too, it's*

> *just, it takes a lot longer to get that kind of knowledge of a building's way of working than it does to train how to use a tool.*
>
> ***Practitioner, Focus Group Participant***

It is strictly stressed that possible incorporation of BIM in architectural education is not a simple technology implementation problem. Integration and information use imply new design processes and changes in the content of the curriculum, studio practices and use of design media. Educational dimensions of IPD and BIM also lead to cognitive aspects of architectural design in terms of enabling students to think and make decisions with explicit information. Following statements show the concerns about the content of current pedagogical practices and contradictions with the BIM and IPD approaches.

> *Well, I'm here with 2 hats on so if I put on my 'worried about education hat' I think that universities should be educating the students that understand what we're talking about and use BIM at the very beginning of the education and be used as a foundation for how they work through their college career.*
>
> ***Faculty/Practitioner, Focus Group Participant***

> *I think what we're talking about here is that a kind of monumental change I mean, not only for BIM maybe something beyond. A new prospect that will alter the way we design and build our environment. But some school has to be first and I think if any of you could come up with what you think the ideas would be*

> *on that first school that does it. Maybe it's time to change our curriculum drastically. I believe that that's necessary, or will very soon be.*
>
> ***Faculty, Focus Group Participant***

> *Actually, it is possible to do simulation with CAD based data but students don't do or can not do it. Why? …Simply it takes too much time. Now the new technology enables students to this frequently and easily in studio projects. So students will develop those skills and intuition to use this information in terms of sustainability, performance and so on…*
>
> ***Faculty, Focus Group Participant***

The following conversation between faculty participants highlights the utilization of BIM as a design media integrator and arising questions from the potentials of BIM.

> *Best studio projects I have seen recent years have been the ones where students make something and use all possible digital and tactile media in complementary fashion…*
>
> ***Faculty, Focus Group Participant***

> *Absolutely…Well the good designers are the ones who develop the facility to move back and forth between various types of media because they developed an inherent sense of what sort of media to use for what they want to achieve. Here,*

> *BIM with its automation and simulation capabilities adds multiple layers…I mean very complex layers to this and we need to address it in architectural education.*
>
> ***Faculty/Practitioner, Focus Group Participant***

Student opinions confirm the existence of an interest towards BIM tools. Awareness comes from the industry demand for BIM savvy architects and extended capabilities of off-shelf BIM tools for 3D modeling, documentation and visualization. Students reported that use of BIM ncouraged them to consider building components and their relationships by giving immediate visual feedback about different systems of the design artifact. However, students stressed the problems about capabilities of BIM tools in terms of flexibility in conceptual stages where design information is fuzzy yet BIM tools require explicit input. Students did not report any examples of BIM use for performance simulations or exporting information to external software other than 3D renderers. Use of parametric components is very limited and it is perceived as a complex task which is not required for typical studio projects. Taken together, students' approach to BIM somewhat falls into BIM-A tool use level that includes modeling, automated documentation and visualization.

> *And here is my concern; I use Revit for my studio projects last two semesters. Well, it is a great tool when it comes to do things quick, add details and create nice renders easily...But I know I can do more with it. All the BIM blogs and web*

> *sites are full of interesting applications, particularly in sustainability studies... Now, I realize that BIM is something more than I do. But my studio projects do not require any of those new stuff. Even I can't imagine designing with all of them…*
>
> ***Focus Group Participant, M.Arch. Student 1st year***

> *BIM is great when it comes to middle stages of my studio project. Because I know much about my project and I can enter required information. I prefer more flexibility and ambiguity for conceptual design and later refine it for the final project. I know there are some BIM tools for unconventional forms but it is hard for me to use all that parametric components without a working design and experience*
>
> ***Focus Group Participant, M.Arch. Student 1st year***

4.6 Pilot Study

In order to have a preliminary assessment of the potentials of BIM applications in the design studio, a pilot study was conducted in one first year Master of Architecture design studio. Students were encouraged to employ mixed media with an emphasis on BIM applications. The main objective was to test different research methods and instruments to illustrate the potentials of BIM applications in the studio processes.

4.6.1 Pilot Study Setup

The master design studio consisted of 15 first year students, 1 faculty and two assistants. The second TA was assigned to act as a consultant for CAAD and BIM tools. A start-up exercise required students to design an interior partition to an existing building to support children's "thinkering processes". The main design topic was K2-12 educational facilities. The studio was structured around four major graded phases: Programming; Schematic Design; Design Development; and Design Presentation/Defense. All exercises were individual student efforts.

As a pedagogical choice of the instructor, students were required to present all design ideas using 3D representation. Mediums of representation were left open. Students were allowed and motivated to choose multiple media forms (physical models, virtual models, sketches, etc.) in different phases of the studio. Students were also required to present two "mini reviews" where architectural concepts, design solutions, and media alternatives were discussed.

4.6.2 Data Collection

To gather data from the design studio process, a multi-layered online-database system was designed and implemented as a data-driven Web site using the Microsoft ASPX with a connection to a multi-table MS Access database. The monitoring system included different report screens for students and the observer as well as user management module. Utilization of this system also provided more consistency for monitoring students’ learning curve and design process during the studio.

Several instruments were fielded. Pre-studio surveys established demographic data and the level of students’ CAAD literacy and familiarity with BIM. Task/Time Sheets were used to collect data to monitor individual student’s design process. Inspection of computer files allowed the researchers to assess the complexity of models and the sophistication of the modelers, determining the student’s proficiency in CAAD and BIM tools. Observation sheets for each student provided for qualitative assessments on a periodic basis. Task sheets, included multiple parts in order to gather data about project phase, design task, duration, BIM usage and used BIM modules. Observation sheet for each project designed to number of alternatives, major developments in the design project, BIM proficiency, process quality, problems, strengths and general observations for the BIM-design process relationship. Multiple data sources for each student project provided triangulation in order to increase the reliability of the findings and evaluation of the studio process from the student and the observer perspective.

4.6.3 Pedagogical Approach

A passive instructional approach based on *knowledge acquisition during knowledge application with instruction was adopted* for BIM (Akin 1986). It was also agreed that skill based software training was to be avoided in studio. The BIM tool used was Autodesk Revit Architecture, which has a complex interface and advanced modules for particular operations. The challenge of learning to use this software was the main potential for interference with the real objectives of the studio. However, teaching assistants provided students active support in identifying solutions for specific problems in their particular design propositions. A low LOD modeling approach also proposed in order to prevent students from using detailed BIM procedures and unnecessary operations.

4.6.4 Survey Results

Results from the pre-studio survey showed that students typically use conventional drafting tools and surface modeling software for three phases of their design projects:

1. Design Development
2. Representation
3. Communication

Majority of the students responded that they use software mainly to support drafting and basic 3D modeling as opposed to design development and design assessment. 2D and 3D tools are not tightly connected. Students reported frequent reworking and redundant modeling to support different processes or requirements in the studio. Responses to questions about support of CAD tools in different phases of previous design studios are given in Table 4.1.

Table 4.1: Design stages in the studio and CAD support

CAD Support	*1-Not at all*	*2-A little bit*	*3-Moderately*	*4-Somewhat*	*5-Quite a lot*
Conceptual Design	**6**	**3**	**5**	**1**	
Design Development		**3**	**6**	**4**	**2**
3D Communication		**1**	**4**	**6**	**4**
Design Detailing			**7**	**7**	**1**
Final Presentation			**7**	**8**	
Cost Analysis	**N/A***				
Energy Analysis	**N/A***				

From this section of the survey 3 groups of students emerged.

1. First group had low interest in existing CAD tools and often experienced difficulties while design studio proceeds. This group had a tendency to use traditional and analog methods and used digital media only when required.

2. Second group could be labeled as “neutral” and use mixed media in the design studio. Students in this group had intermediate skills in digital tools as well as knowledge about the expected benefits of digital tool use.

3. Third group consisted of a few students who had sufficient knowledge about CAD and other digital tools to enable them to determine and solve technical problems during the studio. These students reported use of a variety of media and software to maximize the quality of the studio project.

The second part of the pre-studio survey was dedicated to assessing the familiarity of the students with BIM (Table 4.2).

Table 4.2: BIM use frequencies

	# of Students	*Level*	*Use Frequency*	*Average Experience*
BIM Tools	15	10 Beginner 5 Non-users	1 Often 2 Sometimes 7 Rarely	Approximately 1 year

Students' attitudes towards BIM use before the design studio are shown as the following table with pre-determined variables: learning, usability, flexibility, time management and support (Table 4.3).

Table 4.3: Attitudes towards BIM

	1-Strongly Disagree	*2-Disagree*	*3-Neither agree or disagree*	*4-Agree*	*5-Strongly Agree*
It is not easy to learn a new software in a reasonable time	**1**	**3**	**5**	**5**	**1**
BIM tools seem so complex for using in my studio projects	**2**	**7**	**3**	**2**	**1**
It may take too much time to create BIM models	**1**	**8**	**2**	**3**	**1**
It may take too much time to modify/change BIM models	**1**	**7**	**5**	**2**	
Teaching/Support is not enough to use BIM tools for my studio projects	**1**	**3**	**3**	**6**	**2**

Responses to BIM related section also confirmed the tendencies of the aforementioned groups. The first group had a perception of complexity in BIM tools with the anticipation of difficulties in the learning process. The majority of the students in the second group were aware of the potential benefits and had modest experience with the BIM tools. Students in these two groups were skeptical about further usage due to lack of continuous support during the design studio. The third group of students was already using BIM tools for design development and 3D visualization of studio projects.

Open-ended questions in the survey permitted students to share their thoughts about digital tools and design studio experiences. The following statements are extracted from the students' responses.

a) First experiments of BIM tools in the previous studios increased the flexibility to think both interiors and exterior components in the design development phase.

b) One of the main concerns of the students is simultaneous software learning and designing process. This created such problems while reflecting the design intents during the previous studios. Every new issue while learning decreases the effective use of the dedicated studio time.

c) Students emphasized the importance of active support while learning tool use to deal with frequent issues with the design software. As a result, elimination of software related issues during the instructor-student communication may need extra effort from both sides.

d) Students indicated that software tutorials do not help much when specific problems occur in the studio project.

e) According to majority of the students, complex designs need complementary use of different software. Students reported problems in dealing with high-end interoperability issues during the studio time span. All of the students highlighted interoperability as a main concern.

f) Students tend not to use CAD or BIM tools for conceptual design. Students reported that low level knowledge in software create many problems when flexibility is a real concern in conceptual design. Students also indicated that information requirements and preset notions in BIM tools decrease the flexibility.

4.6.5 Results from the Pilot Study

Observations and the analysis of task/time sheets returned information about BIM usage patterns in the studio and their relationship to time. Over 127 work sessions are monitored with task sheets. Session duration varied between 2-8 hours. An average of 93 sessions involved the BIM usage. Distribution of study sessions with BIM is given in Figure 4.3.

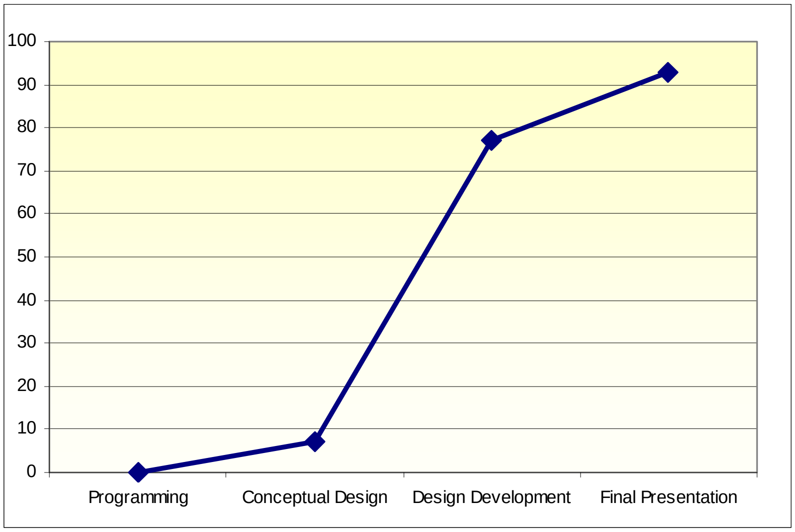


Figure 4.3 Distribution of BIM use during the pilot study

Content analysis of the task sheets and observations suggested certain learning thresholds and usage patterns. Learning thresholds are derived from intrinsic concepts of the BIM approach. Students inevitably faced these thresholds through the development of design projects. The main thresholds revealed in the studio time-line are:

a) Interoperability and mixed use of BIM with other digital tools and analog media.
b) Surface/Solid modeling vs. Parametric Modeling approach
c) Hierarchical structure for building components and behaviors
d) Extraction and processing of the data from the building model for external use

According to these results, further thresholds may be expected in accordance with studio-topic, setting and setup.

Programming : No CAAD or BIM tools were used by students in the programming phase in the pilot study. Although no use was observed in the studio, BIM tools are capable of supporting such exercises. This raises important and controversial questions that need to be addressed from an architectural education perspective.

Conceptual Design: Students reported difficulties in the integration of different tools and modules for creating a BIM model in the conceptual design phase. Data standards and operational issues were the main problems. These findings were aligned with the findings in the pre-studio survey.

Additional effort was necessary to assist each student in creation of specific building components for their design as well as teaching them the data structure of existing components for modification. Students' response to support and instruction did not excessively interfere with the studio process focusing too much on the software training.

The mass modeling process mainly involved surface modelers and hand sketching. Students reported that the main design decisions were dramatically changed or enhanced after 2nd or 3rd session as they switched to using BIM software.

Students reported that they were able to utilize the information generated from the BIM models after making critical decisions about spatial configuration and mass modeling. BIM based information was mainly used to control building programmatic consistency, sun-light analysis and data for LEED exercises. Students also reported their approach to spatial configuration was highly influenced from the information feedback of the virtual building.

Due to use of BIM based information in the students’ models, discussions and critiques became detailed and building oriented. With the help of 3D BIM models, it became easier to discuss different systems of the building and concepts such as constructability, structural system, and tectonic components, and horizontal and vertical layout or configuration. Transition between different applications and modules within given applications did not affect the students. They appeared to be able to manage the data exchanges without complaint.

Presentation: Visualization outputs from BIM software were acceptable for reviews. Students had the advantage of focusing on the building rather than drafting and visualizations outputs. Figure M shows a final result from the first stage of the design studio. In this example the student used hand sketching, surface modeling and BIM tool to develop the project. BIM tool served as the main media for the synthesis of the final form and space solution. The student chose not to deliver any conventional printed 2D documents like plans, sections or elevations. In the final jury, the BIM model was used in real-time to create needed visual information, complemented by a previously created animation that had preset camera points and behaviors.

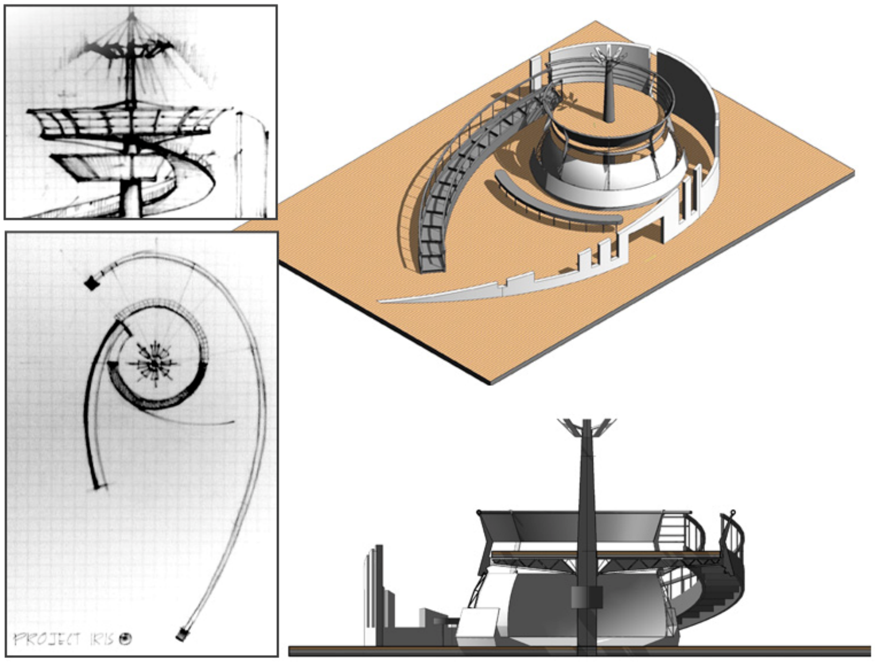


Figure 4.4 Use of analog process with BIM, examples from the student sketchbook and the BIM based Interactive 3D

Observer notes and student statements concluded that the main reason for creating an interactive final model was a reflection of the student's design process with the combination of tools available. Considering the time limit for the start-up project, the student used BIM tool (Revit) and surface modelers (Sketch-Up) to develop a BIM model that would allow the interactive evaluation for function-space-form relationships, indoor lighting analysis, visual perception tests, structural base as well as basic understanding of constructability. Figure 4.4 shows an example from the studio process. The student provided in-depth 3D representations along with area usage plans, quantity take-offs and schedules of main building components. All of the information and documentation are extracted from the BIM model.

As the semester progressed and the required operations became more complex, session durations using BIM actually decreased or remained constant. However the anticipations for decreasing the efforts for final documentation were not realized. Students reported very long sessions for final documentation process using the BIM software. It is important to note that educational design studio presentations are a different kind of graphic and textual documentation that is not well supported in existing AEC industry oriented BIM software.

Majority of the students reported that they made refinements or changes during finalization phase. This result suggests that one use for the BIM technology is through “process oriented” studios that provide the student increased design time and flexibility for modifications in every phase of the project.

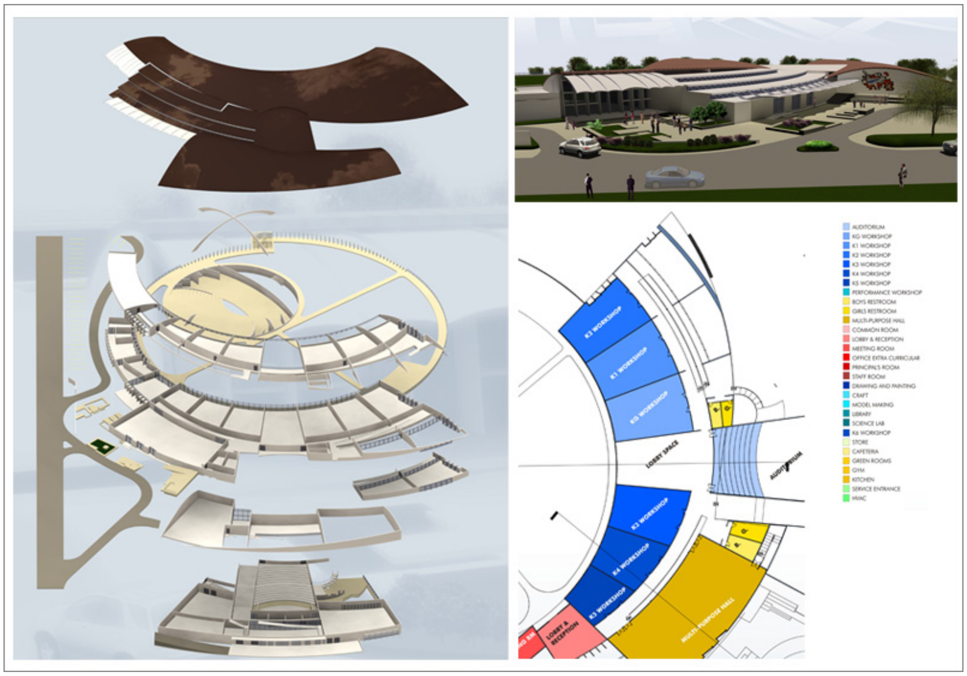


Figure 4.5 Student Work Examples

4.6.6 Findings from the Pilot Study

This preliminary pilot study produced valuable data to further improve case studies for BIM integration. Findings of the study showed the effectiveness of a proactive approach from the instruction side in order to overcome the issues of BIM use; possibility of further expanding studio frameworks with the use of BIM models and extracted information; issues, problems, learning curves and results that may be applicable in similar educational settings. Survey results showed that students pursue conventional and inductive project processes using software tools mainly for visualization and documentation. This trend was also occurred as the same during the pilot study. The studio results demonstrated high levels of comprehension about form, function and required spatial performance according to the given design problem. It was clear that

BIM tool helped students to understand different layers of the building, structures, and materiality also provided flexibility for the evaluation of building envelope connected to interior settings with immediate 3D feedback. Documentations and visualizations were rapid and rich in visual content.

However the results can be considered as inconclusive from an interoperable and collaborative design point of view. Generally, findings converged to the technical aspects of BIM use in the design studio and experimentation of software capabilities during project stages. Results did not suggest the incorporation of BIM as a method of designing. Referring to the devised theoretical model for BIM adoption, the occurred use schemes stayed in BIM-A level. BIM use increased in middle and late stages of the project which confirmed that students preferred to get the benefits of extended visualization and documentation capabilities. Distinct advantages of BIM over CAD systems in an IPD setting were not explored. The missing aspects are:

1. Studio setting and setup in conformance with integrated project processes;
2. Frontloading of the project with required performance indicators as defined by the IPD;
3. Deployment of an integrated set of BIM tools for modeling, simulation and computations;

4. Required use of BIM in a collaborative project setting where students create share and modify BIM models;
5. Creation of parametric elements and leveraging parametric adaptability for building form and system components;
6. Absence of performance indicators like detailed cost, energy use, daylighting throughout the all studio process;
7. Derivation of explicit information from the BIM models and simulations for decision making;
8. Active participation of interdisciplinary experts and consultants for design decision assessment during all phases of the process.

4.7 BIM, IPD and Design Methods

Focus group studies and the pilot study suggested a different dimension of BIM in design process. As seen in case studies and comments from the focus group participants, BIM enables architecture and engineering teams to create, use and share consistent and computable information about the building process. Opinions and arguments from the focus groups imply that the use of BIM enhances the roles and responsibilities of project participants in an IPD process setting and alters the way of design process. From this perspective, BIM posits an information-rich design method that ignites a deeper discussion regarding its relationship to established design method theories. Understanding of BIM and IPD from this perspective strictly relates to the prototypical pedagogical framework, architectural thinking in IPD, learning objectives and design processes.

Design theory literature includes scholarly work focused on understanding the design activity from the cognitive mechanisms of the designer and relationships between designer, information and design problem. Rittel and Weber's (1973) definition of "wicked problem" highlights the importance of design methods and their expected functions. According to Rittel and Weber, the information needed to *understand* the problem depends upon one's idea for *solving* it. In other words, formulation of a wicked design problem in sufficient detail urges designer to develop a solution space consisting of conceivable *solutions* ahead of time. These particular solutions are created though set of actions processes and methods. Nigel Cross (2008) described "design methods" as procedures, techniques, aids or 'tools' for designing. These methods represent a number of distinct kinds of activities that the designer might use and combine into an overall design process like the research elements of this study: BIM and IPD.

In his widely cited work, Jones (1992) provided a deeper understanding of traditional and new generation design methods. In order to classify the methods and their use, Jones devised a disintegration model for the design process composed of three stages divergence, transformation and convergence. *Divergence* stage refers to the act of extending the boundaries of a design situation to form a search space for solution development. Preliminary thinking of design and exploration of solutions falls into this stage when the status of design is unclear and tentative. Second stage is *transformation* for the establishment of a precise framework for narrowing down the alternatives in the solution space to permit convergence to the single design. Being a middle stage in the process, the objective, the brief, and the problem boundaries are fixed due to clear determination of constraints, judgments and opportunities. Third stage *convergence* reduces the uncertainties, and final design is refined in every detail. When approached from the amount of information and tasks point, Jones model for design and related methods are cumulative and inductive. Major tasks and effort happen in middle and late stages.

Divergent design methods focus on exploring design situations and information gathering about the particular design problem. Method examples are given briefly in Table 4.4:

Table 4.4: Divergent design methods (produced from Jones, 1992)

Method	**Aim**
Stating objectives	*To identify external conditions*
Literature searching	*To find published information for influencing the designers' output*
Searching for visual inconsistencies	*To find directions for searching design improvements*
Interviewing users	*To gather users' preferences demands*
Questionnaires	*To collect usable and valid information from a large population*
Investigating user behavior	*To investigate behavior patterns*
Systemic testing	*To identify actions for bringing desired changes in situations that are too complicated to understand*
Selecting scales of measurement	*To relate measurements and calculations*
Data logging and reduction	*To infer patterns of behavior for the critical design decisions*

Divergent / transformative methods focus on the thinking process of design and creation of solutions in fuzzy and unclear state. Here, Jones reviewed the assertions of creativity theorists and provided an understanding that the mental process of the designer that can be seen as *black boxes*. According to Jones, there is no limit for the speculations for the brain functions and interoperation of information therefore it is better strategy to focus on design methods to support creativity. He further asserted that the output of the designer's black box is governed by the inputs received from the design problem and the inputs from the previous experiences. Capacity of the output production is dependent on the time to assimilate and manipulate information. Intelligent control over the feeding mechanism of the *black box* is likely to increase the quality and the chances of outputs relevant to the design problem. This process is open to sudden solutions when complicated problems are simplified by creative insight. Jones described two major creative methods for searching design ideas: *Brainstorming* and *Synectics* (Figure 4.6). In brainstorming method, a group of designers share design ideas with conversations without criticisms. Synectics refers to another group activity design sessions where diverse participants use analogies to stimulate designers' thinking process. Synectics differs from brainstorming in that the group engages collectively towards a particular solution, rather than generating a large number of ideas. These two methods have some resemblance to the preliminary stages of IPD process. However IPD engages the full lifecycle of the building, all required tasks and it involves specific expertise, utilization of technology and complex design problems.

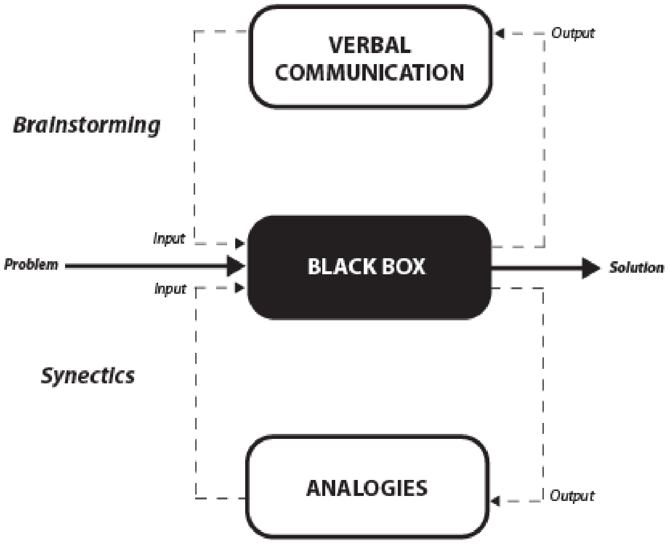


Figure 4.6: Black Box model of designing with brainstorming and synectics method (adopted from Jones 1992).

Referring BIM as the core essence of the research study, Jones (1992, 73) envisioned the role of computational approaches in design and explained the potential value of human-computer interaction by stating:

> *The ideal picture of a man-machine symbiosis is . . .one in which machine and human intelligences are linked into a quickly responding network that permits rapid access to all published information . . .The nett (sic) effect is expected to be one of mutual stimulation in which open minded people and programmers nudge each other into unpredictable, novel but realistic explorations . . .*

Nigel Cross (2008) proposed an 8 stage rational design process and related methods. The objective of his design process model is to define and clarify the overall design problem with its sub-problems and to create the overall solution with its sub-solutions. He described the model as an integrator of procedural aspects of design with its structural aspects of the design problem. Cross suggested different methods each design stage illustrated in the Table 4.5. However he pointed out that the importance of unconventional thinking. According to Cross, it is highly important to put effort to follow the methods with rigor and interpret the outcomes in an imaginative fashion. He further suggested that use of ant design method require strategic thinking about the process. Although many designers operate without an explicit design strategy and still follow a *random search* for novel design situations, Cross stressed the importance of explicit strategies for design problems for specific requirements. Pushing the envelopes of methods for tailoring strategic design frameworks is crucial to achieve better and more efficient processes.

Table 4.5: Design stages in Cross's model, methods and aims (adapted from Cross, 2008)

Stage	**Method**	**Aim**
Indentifying opportunities	User scenarios	*to identify and define an opportunity for a new or improved design.*
Clarifying objectives	Objectives tree	*to clarify design objectives and sub-objectives, and the relationships between them.*
Establishing functions	Function analysis	*to establish the functions required, and the system boundary, of a new design.*
Setting requirements	Performance specification	*to make an accurate specification of the performance required of a design solution.*
Determining characteristics	Quality function deployment	*to set targets to be achieved for the engineering characteristics of a design artifact, such that they satisfy customer requirements.*
Generating alternatives	Morphological chart	*to generate the complete range of alternative design solutions for a design artifact, and hence to widen the search for potential new solutions.*
Evaluating alternatives	Weighted objectives	*to compare the utility values of alternative design proposals, on the basis of performance against differentially weighted objectives.*
Improving details	Value engineering	*to increase or maintain the value of a design artifact to its purchaser whilst reducing its cost.*

Different from the process based design methods, Christopher Alexander (1977) proposed a rational design method by decomposing the design problem into its components. In his model components of the design artifact form *patterns* and combinations of the patterns form a design language. In Alexander's method, the design problem decomposed into physical components that adequately identify the design artifact and its environment. After this stage, solution space is defined by a relational matrix for the search process for design. Designers can identify the scope by picking points in the matrix and initiate a language forming sequence going through the patterns. Alexander asserted that a systematic search by grouping the patterns will result sound design templates.

Alexander's method seems effective for solidly defined design problems but flexibility and creativity can be listed as concerns to this model for design. The reductionist approach to design may be useful but creating design solutions in a solution space with an indefinite and infinite number of components, constraints and performance measures is a big challenges for the designer. Nevertheless, the notion of a solution space -whether it is definite or indefinite- necessitates intelligent, flexible and effective approaches for finding the optimum solutions that satisfies a set of design criteria.

Within the view of decomposition of design, Peña and Parshall (2001) introduced *Problem Seeking* method to define the design problem prior to the actual designing -- or synthesis -- process. They simply divided the process into two stages: Analysis and

Synthesis. Peña and Parshall approached the whole process as the relationship between defining the "ill-defined" design problem and solving the problem. Within the view of problem-solving paradigms, they proposed a flexible framework for defining the design problem, structuring the search process and determining the aspects of the solution space. 5 steps for the programming stage are introduced: (1) establish goals, (2) collect and analyze facts, (3) uncover and test concepts, (4) determine needs, and (5) state the problem. They decomposed the design into its aspects as *form, function, economy and time*. The model based on the relationships of these 4 aspects with the all 5 steps in the programming stage. The *Problem Seeking* approach attempts to provide designer the knowledge of all parameters influencing the building projects prior to the design process. From this perspective the method involves frontloading of actual designing stages as in IPD.

Having tight connections to technical rationalities, the rational models for the design activity were criticized by Schön (1987). He asserted that unique design problems should not be framed into standard approaches. Schön's model for design is based on the interactions of the designer with the design artifact. The experiences carried from the previous experiments and the intuitive and *"reflective"* reaction of the designer to the design problem result new and unique design solutions. Schön's assertions have been widely cited to explain the expert designer behavior under conditions of uncertain design knowledge.

More recently, Hamilton and Watkins (2009) proposed a rigorous and *research based* approach for architectural design process. Referring to evidence based medicine; they stressed the importance of *evidence* in design. In addition to conventional evidence sources they asserted that there are emerging sources of evidence which necessitate a novel design process model. According to Hamilton and Watkins, innovations, technological advances and resulting cultural shifts imply significant changes in buildings – form, space and performance – and the way architects approach to the high-technology design problems under the influences of IT, new trends in education, ecology of natural systems and energy consumption. They stated that the transformation of the practice and architectural education is a necessity by incorporating research in to design and described evidence based design as (Hamilton and Watkins 2009, 9):

> *…a process for the conscientious, explicit, and judicious use of best current evidence from research and practice in making critical decisions, together with an informed client, about the design of each individual an unique project.*

Unlike the other reviewed process models and methods, Hamilton and Watkins did not provide clear cut steps, stages and design methods. Instead they introduced novel concepts to devise evidence-based design processes. They suggested that it is crucial to structure a broad and robust *"database of buildings"* for the research tasks on design-related information. They discussed different approaches to specialization as single specialty field or generalist model both suit for the evidence based design. Concepts also included economic aspects as client-driven response, promotional market model and strategic business models.

According to Hamilton and Watkins, practitioners should commit to applied and design related research by employing rigorous and scientific research methods as a vital part of their designing activity. Hamilton illustrated the levels of evidence-based practitioner evolution in relation to his/her responsibilities.

Although the core idea of Schön's reflective approach and rational approaches have significant differences, the common existence of a design search process imply a logical mental activity that can be stimulated by new generation of tools and technologies. Cross (2008) suggested that both creative and rational methods are complementary aspects of a systematic approach to design. Despite the skepticism towards rational methods as obstructers of the creative activity they may help designer, especially the student designer, to keep afloat. Whether it is creative or rational, the purpose of the design methods is summarized as: to define the design problem, to understand the process and to devise a strategic framework for achieving the objectives. From this review, it can be claimed that the design methods literature does not provide comprehensive insights about the use of advanced IT, computational methods and processing of design knowledge with electronic form of information.

Approaching the research elements of the study from the design methods perspective, there are significant similarities between IPD approaches and reviewed design processes, methods and tasks. IPD involves clear stages and tasks which form a pragmatic and applicable design process for complex design problems. IPD addresses many challenges and existing inefficiencies within the AEC industry. Briefly IPD connects the all members of the project and frontload the process with preliminary information and defines the design problem with its all aspects regarding its lifecycle. All stages are collaborative, integrated and interoperable. Recent literature documents the projected benefits and values that very are appealing from the business and practice point. However potential educational benefits of IPD and BIM can be examined in the context of design methods. From this perspective, a BIM-enabled and integrated method finds it justifications in the necessities to cope with emerging rationalities and mandates of the society. Challenges aroused from the environmental and economic factors urge designers to approach design problems under the constraints of energy use, cost and other performance measures which are making the any given design problem further “wicked” when combined with the qualitative factors like aesthetics, social performance, and contextual relevance. Here, question may asked as: If aforementioned aspects of performance are inevitable, how one can leverage technology to reduce the complexity of design problems and support the creative activity?

In this regard, utilization of BIM in an IPD setting is more likely to connect the link between quantitative and qualitative aspects by parameterization of performance variables connected to the designer's process of designing. From a process standpoint, BIM passes the required expertise and overwhelming analyses tasks to the expert software through a design interface. Here, BIM can be perceived as a novel design method where designers' mental activity is stimulated by wide-range explicit information and the blind search for alternatives is replaced by an intelligent, BIM-enabled search that uses both external inputs and subjective evaluation. During this process, outputs from the designer is pushed to the virtual model, stored and further processed with simulators. BIM technology also acts as the common design medium between designers and consultants. It can be hypothesized that the use of BIM provides the designer enough room and flexibility for creative activities by increasing intelligent feedback, reducing complexity of information, and achieving continuous control over the performance constraints.

Based on the theoretical premises, application examples and preliminary findings from the focus groups, the steps of application of the BIM-enabled design method can be proposed as the following:

a) Definition of the design search space with aspects of the design artifact like aesthetics, performance variables, technology, materials and components;
b) Determination of reference points in the search space process by frontloading of information;

c) Modeling of design alternatives with BIM and creation of information through simulations;
d) Formation a collaborative network by sharing BIM models, embedded information and design ideas;
e) Use of shared information to feed the design search mechanism of all team members;
f) Establishment of an iterative and rapid cycles of evaluation for all phases of the project;
g) Narrowing down in the search space, and refining the design alternatives with detailed meta BIM models.

These steps also provide basis for the pedagogical strategies and the process flows in the integrated design studio.

4.8 Pedagogical Framework for the Integrated Studio

Based on the findings from the focus groups, case study examples and the pilot study, the model for design studio courses is devised to leverage BIM in the level of BIM-B adoption level. The model incorporates BIM as an intrinsic process for design teaching and integrated studio.

Rather than focusing on solely tacit knowledge, the model drastically extends the scope of “modern design studio” described by Schön (1985),and accepts a warrant for design decisions that embraces the emerging theory of "evidence-based design" and requires a comprehensive decision process based upon explicit knowledge (Hamilton and Watkins 2009). This commitment led to an integrated studio model with expanded tasks and deliverables that make explicit the rationale for design decisions. Achieving the objectives of integrated studio is predicated upon the confluence of a rapid, collaborative, evidence-based process of design with BIM-ready tools. In the model, a collaborative design process employs consultants who actively participate in the process similar to IPD, transforming the dialog to a multi-channeled form of communication for collective learning. The process in the model is derived from "Circle Integration" theoretical model of integrated design that suggests that aesthetics and high performance are both achievable through iterative cycles of multidisciplinary collaboration supported by electronic information exchange (Fischer and Kunz, 1993). This collaborative process of design is greatly aided by advanced information technology. BIM can serve as a common design medium –an integrator of design specific information- for collaboration among students, consultants and instructors, enabling them to produce quantitative and qualitative information that is needed for a wide variety of technical and engineering analyses of performance.

Because utilization of BIM in the context of design studio has more pedagogical dimensions than merely the teaching of technology or software use, the prototypical framework designed to include content from design methods research, emerging models of practice such as IPD, and theory of design pedagogy, as well as training in software tool use. The courses are the implementation of pedagogy to teach students this new way to design and equip them with skills that involve creation, exchange, assessment and reuse of the design-centric information in all forms.

The critique of the conventional design studio model can be illustrated by contrasting it with a new integrated model of design. Table 4.6 compares the conventional studio process to an integrated studio process. Using the findings from the literature survey and the focus groups the following set of qualitative indicators were determined with a group of experts consist of studio instructors, licensed architects and graduate students. These qualitative indicators put into sharp relief the contrasting assumptions and solutions of the devised method.

Table 4.6: Comparison of traditional and the proposed integrated studio

	CONVENTIONAL	**INTEGRATED**
Roles	*Instructor, Student*	*Instructor, Student Teams, Consultants*
Communication	*Verbal dialogue and graphics*	*Multi-channeled and digital*
Learning	*Individual*	*Collaborative*
Production	*Individual*	*Teamwork*
Representations	*Graphic and abstract*	*Virtual and simulated*
Process	*Discrete, Sequential, Unstructured*	*Continuous, Cyclic, Structured*
Assessment Duration	*Weeks*	*Hours*
Media	*Primarily analog*	*Primarily digital*
Knowledge Type	*Tacit*	*Primarily explicit*
Approach	*Form/Function-Centric*	*Performance-Centric*

The proposed framework comprises the major issues for BIM and IPD derived from the focus group studies. The pedagogical intent is to provide sufficient theoretical knowledge about interoperability, integrated design process, sustainability and constructability. In order to overcome the data management issues the prototype framework adopts the just-in-time instruction and technical support.

According to the findings from the content analysis of the focus groups, one of BIM's advantages is the use of advanced software technology and interoperable information to resolve conflicts in collaboration and coordination. In professional settings these conflicts are typically caused by different technical requirements and particular solutions between project teams. As explained in previous sections, typical studio settings do not involve these challenges as intense as in the real world practice since design studio processes are more individual with a limited focus on upstream design aspects (Anthony 1991). The features of real world design settings involve comprehensive assessment of parallel design alternatives, construction restrictions, time and cost limitations, value engineering, structural and mechanical systems integration. From the design education point, design studios provide the educational environment for preparing students for the practice by testing the potentials of advanced IT technology and IPD. Introduction of comprehensive design problems with the participation of interdisciplinary consultants are more likely to increase the design challenges and conflicts sourced from integrated design processes. Use of BIM in the studio has potentials to teach students different strategies and methods to engage particular design problems, resolve conflicts and assessment of design solutions. The core idea for the integrated studio is to shift the emphases on form and function to an emphasis on total building performance by frontloading the studio process with explicit interdisciplinary knowledge of topics such as sustainability, structures, lighting, cost, construction schedule, and spatial requirements, as well as visual performance. The design teams cycle rapidly through the synthesis of a candidate solution and the assessment of the performance of that solution, and repeating. The strategy has been to adopt two core interventions into the studio process: establishment of project teams that include architects and consultants that parallels the use of IPD, and imposition of multiple BIM tools for supporting a wide variety of design and analysis capabilities. The prototype framework is devised in flexible fashion to allow the incorporation of new aspects and application of any knowledge or method in case of needs during the design process.

CHAPTER V

CASE STUDIES

This chapter presents the process, procedures and the findings from the design course case studies that addressed BIM-B level of adoption.

Findings from the literature search, focus groups studies and the results of the BIM-A level pilot study provided sufficient evidence to devise instrumental case studies in order to explore BIM-B level studio approaches. Adoption of BIM for the design studio necessitated integrated processes, collaborative learning environments and performance-centric approaches to the design process. The pedagogical framework and available resources were synthesized into a flexible case study structure. The structure was organized around a compact design problem with comprehensive performance requirements.

The case studies were conducted during 2008-2009 academic year as special topics courses in the Master of Architecture programs of Texas A&M University and Prairie View A&M University. The chapter provides the pre-survey results about the student demographics, attitudes and preferences prior to case studies; describes the case study setting and the setup; presents in-depth observations in a systematic outline with the concepts related to the integrated studio; documents the changes in attitudes and knowledge levels with the post-study survey results; and provides the results from the focus group review with studio instructors and the final evaluation survey.

5.1. Pre-study Surveys

Students' demographics, experiences, knowledge, and attitudes were documented using a comprehensive and sequential survey set. This specific survey set included pre-test survey proceeded with weekly progress surveys and finally a posttest survey for comparisons. Variables and open-ended questions for the survey were based on the findings from literature review and focus groups.

The pre-study surveys measured the overall skills and literacy on BIM, as well as education level and existing attitudes towards conventional studio processes. Survey included both matrix of choice questions also open-ended questions for validation and eliciting further remarks from the students. Determination of the background and the skill set of the students were the part of the research strategy in the research study. Pre-survey tests were given in all three case studies and results suggested significant similarities in attitudes and preferences that corresponded to the skill level.

5.1.1 Background of the Study Participants

A total of 27 students participated in the three case studies. These instrumental case studies involved students and consultants from various disciplines and expertise groups. Degree information of participants is shown in the Table 5.1. During the case studies

M.Arch students formed design teams, which collaborated with consultant teams made of M.S. Arch, MSCM and Ph.D. students.

Table 5.1: Degree information of the case study participants

Current Seeking Degree	Number of Participants
M. Arch.	19
M.S. Arch.	1
MSCM	4
Ph.D.	3
Total	**27**

Majority of the students had four-year undergraduate education like B.Sc. in architecture or B.E.D. 9 of the students had five-year bachelor degrees from international universities. Ph.D. students had either M.Arch. or M.S. degrees from the universities in the U.S (Table 5.2).

Table 5.2: Education information of the case study participants

Education History	Number of Participants
4 Year-B.Sc or BED or equivalent	16
5 Year-B.Arch or equivalent	9
M.Arch	1
M.S. in Architecture	1
Total	**27**

Majority of the study participants had at least one-year work experience and had internships in the U.S., India and Gulf Region. Two students had LEED accreditation, while four others were in the accreditation process. Students indicated different focus areas during their internship experiences varying from residential design, healthcare architecture, educational buildings, sports facilities and hospitality buildings. One of the

Ph.D. students was a registered architect and acted as a consultant in all three case studies (Table 5.3).

Table 5.3: Work experience of the case study participants

Work Experience	Number of Participants
None	6
1 Year	9
2-5 Years	12
5+ Years	0
Total	**27**

5.1.2 Software Literacy and Design Media

Software literacy of the students illustrated that majority of the students had intermediate or expert skills in CAD software, image-processing tools, and surface modelers. Responses to the questions demonstrate an internal consistency and suggest that students are using software tools in order to support incremental design processes and project documentation. Figures 5.1, 5.2 and 5.3 show the usage distributions according to the level of knowledge. According to student responses, the influence of software tools in the early phases of studio projects is considerably limited, but several students also reported extensive use of digital tools for conceptual design, particularly for form making. As seen in Figure 5.4, the usage frequency of software tools increases in accordance with the detail level of the studio project as a general trend.

The BIM literacy was mainly based on knowledge of and familiarity with particular software brands. Students responded that the research and teaching activities in both universities motivates them to use BIM tools. Students use BIM, especially the Autodesk Revit Suite for its extended capabilities in 3D modeling, visualization and documentation after a self-teaching process. This has significant resemblance to the BIM-A level use for the improvement of the bottom line measures of the design production. Conversely, the vast majority of the students do not typically utilize common off-the-shelf BIM and simulation tools. Therefore, a BIM-B level use and collaborative processes thorough BIM do not exist. Responses show that students had very limited experience in using BIM in an interoperable fashion for performance simulations, cost analyses, and other design specific tasks.

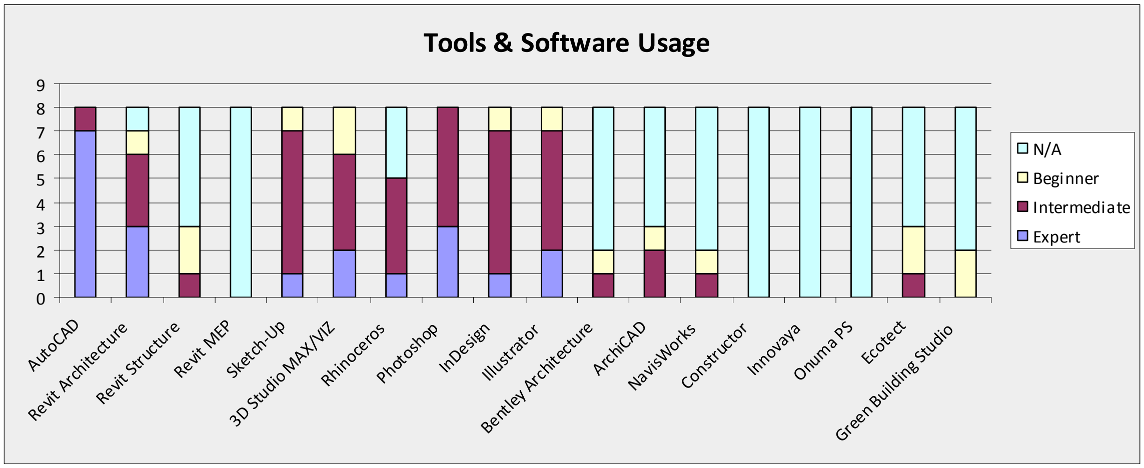


Figure 5.1: Tool and software usage of the case study 1 participants

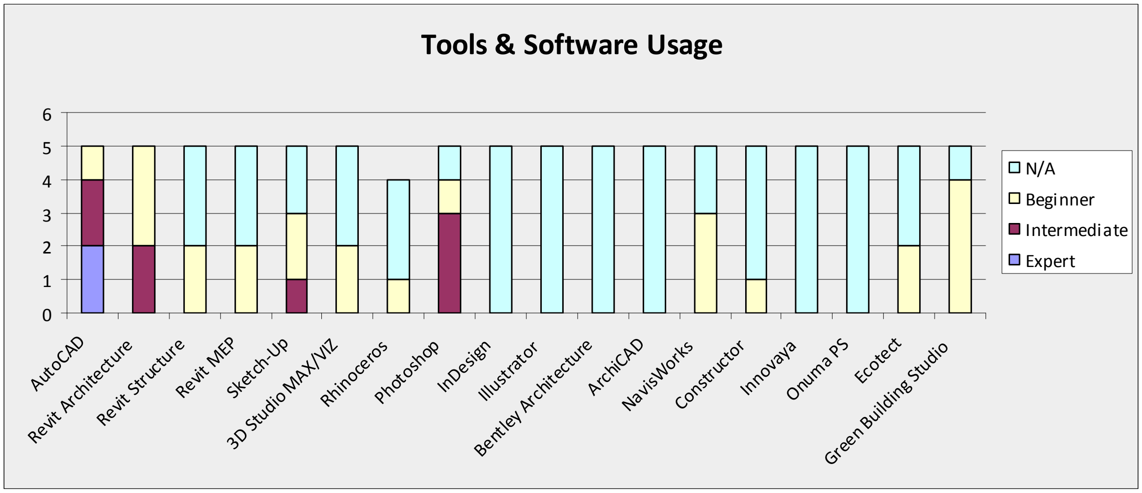


Figure 5.2: Tool and software usage of the case study 2 participants

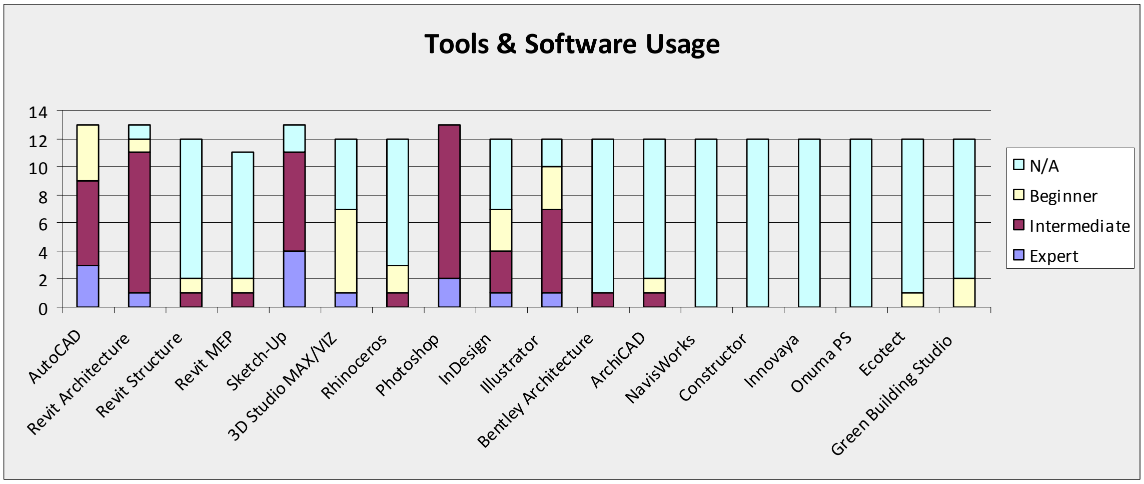


Figure 5.3: Tool and software usage of the case study 3 participants

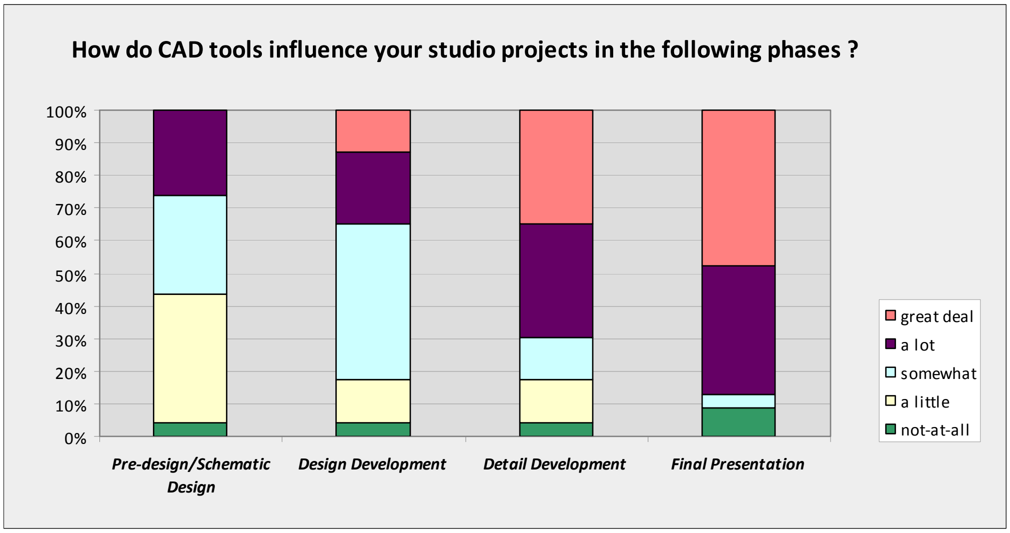


Figure 5.4: Influence of CAD tools on the studio projects of the case study participants

File types and standards in use by the participants indicated the complementary use of conventional CAD and BIM models and 3D visuals (Figure 5.5). IFC usage is extremely limited and specific to small experiments. Other XML based exchange formats were not recognized by the majority of the students. In the open-ended part of the question students stressed the interoperability issues and the difficulties of the file conversion and transfer between platforms.

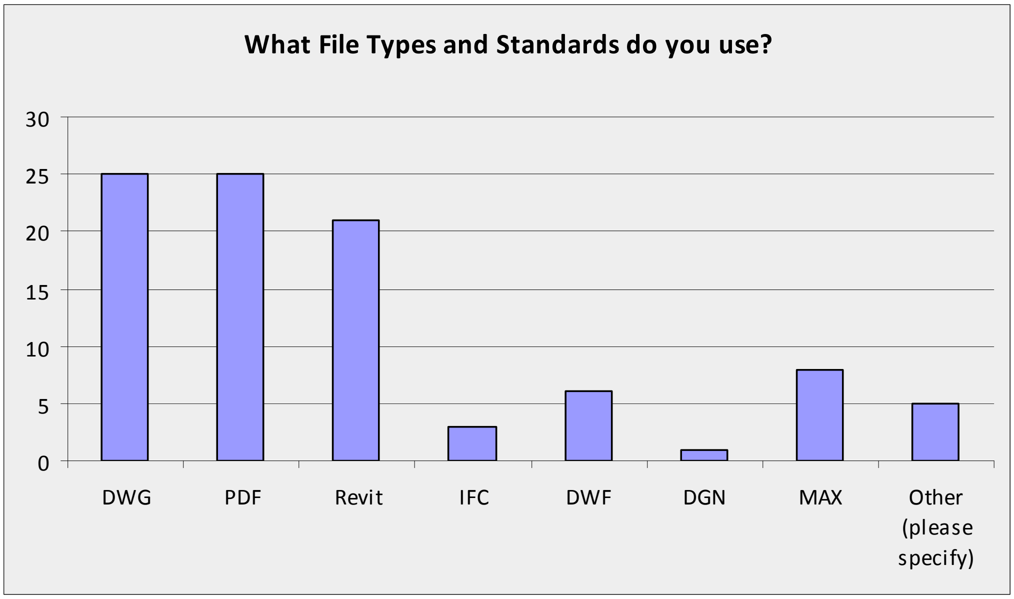


Figure 5.5: Used data formats in the previous studios

Responses to the design media question showed that students use both analog and digital media. It is also evident that students have personal preferences for their own design media and IT environment. Nevertheless, it is doubtful that these preferences are resulted from a collective and interrelated use strategy or systemic to design thinking and decision making processes. Figure 5.6 shows the frequency of used media during a typical studio process. Here it can be claimed that students have a very pragmatic approach to media use in conformance with the conventional studio processes and pick the most appropriate tool set for the required task and deliverables.

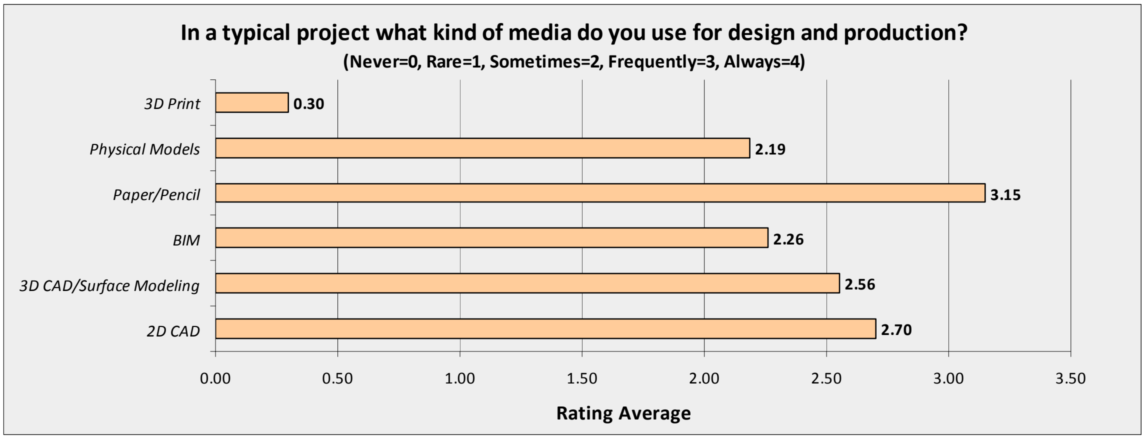


Figure 5.6: Design media and usage frequency

5.1.3 Project Process

The third part of the survey included questions about the studio process. Prior to the surveying stage, a set of performance and quality variables were identified from the literature review, the pilot study and expert group opinions. These upstream and downstream variables include Schön's (1985) *normative and descriptive design domains* and Rush's (1986) *building performance mandates* for collecting data and interpreting various aspects of the integrated design process.

Responses show the existence of a focus upon form and function with an emphasis on upstream issues of architectural design. In addition, current developments in social and environmental factors urge students to incorporate energy and environmental variables to their design decisions. Other downstream factors, such as construction cost, constructability or facility operations, typically are not included in the scope of the design studio.

The following figures illustrate the frequency of design aspects, confidence levels and the timing of design decisions during the students' studio processes. As seen in Figure 5.7 upstream issues like form/aesthetics (Avg.=3.48/4), spatial layout (Avg.=3.70/4) and visual performance (Avg.=3.35/4) have significant values falling into high frequency zone. Students also reported that they consider these aspects early in the design process and achieve a high level of confidence in their decisions. Energy and environmental factors were reported to be issues of interest in the studio projects but students responded with moderate confidence level (Avg.=2.17/4) indicating that they were not proficient in performance based design.

Responses to downstream factors suggested the late consideration of cost, constructability, mechanical systems and operations. Students often omit these design features within the scope of the studio work (Figure 5.8). Values for confidence of the downstream features stay in the low-weak levels (Figure 5.9).

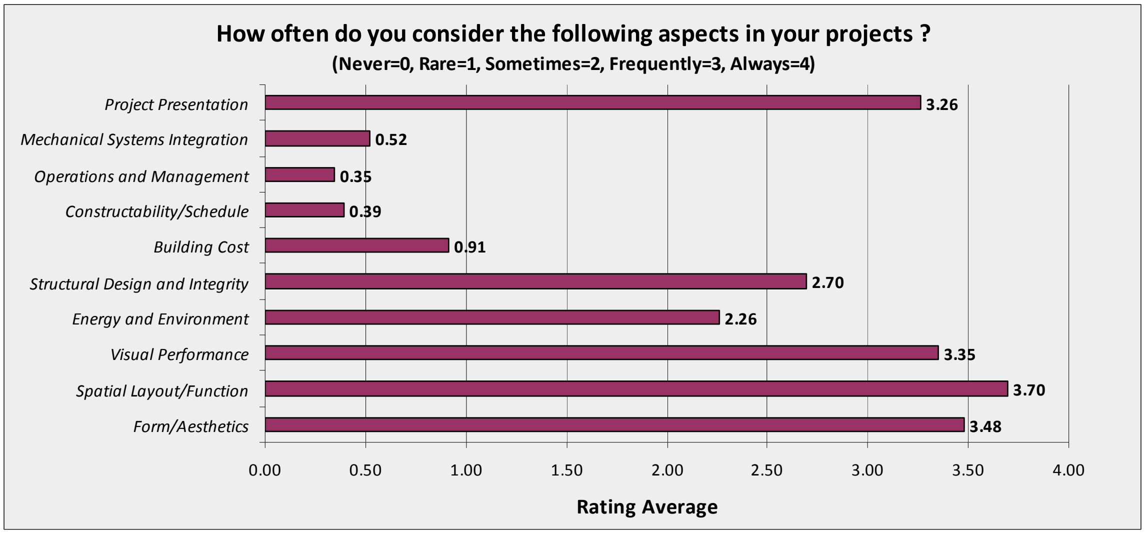


Figure 5.7: Design considerations according to the pre-defined performance variables

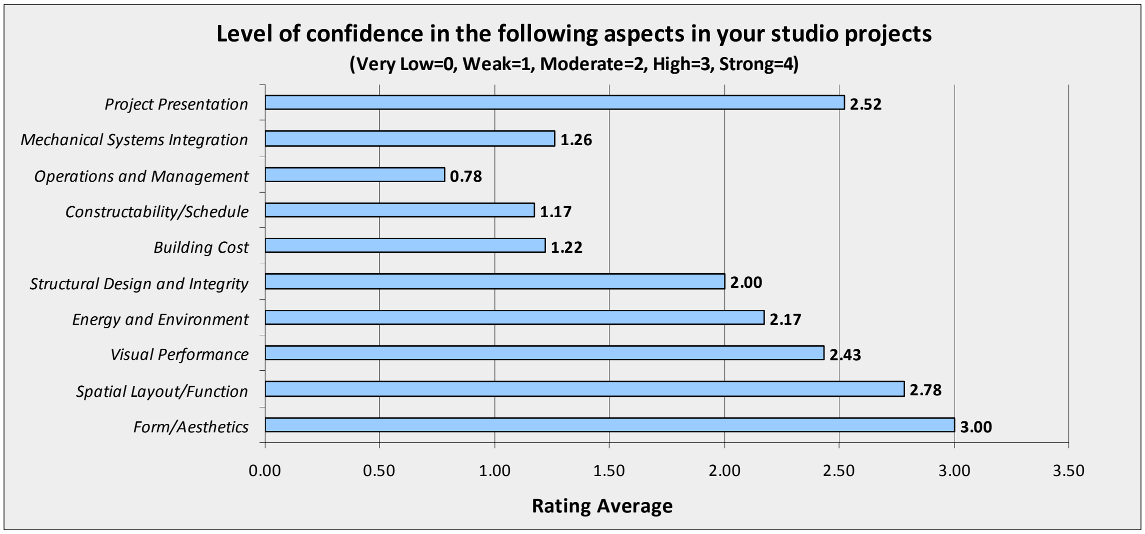


Figure 5.8: Confidence levels regarding the pre-defined performance variables

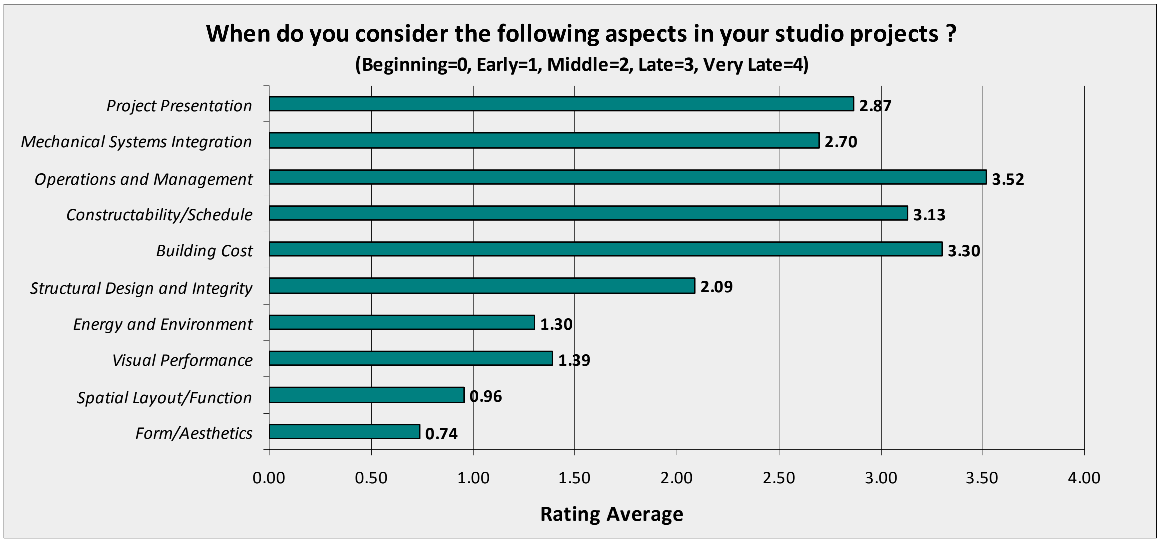


Figure 5.9: Timing of design decisions according to the pre-defined performance variables

Approximately 2/3 of the study participants responded that the active participation of the consultants and experts to the whole studio process is extremely rare, and they occasionally consult experts and professors in person for specific problems in their design projects (Figure 5.10). The issues were reported as design criteria for specific building types, structural integrity, energy use, and material selection. A significant portion of study participants reported that they develop their projects individually without consultant and expert feedback.

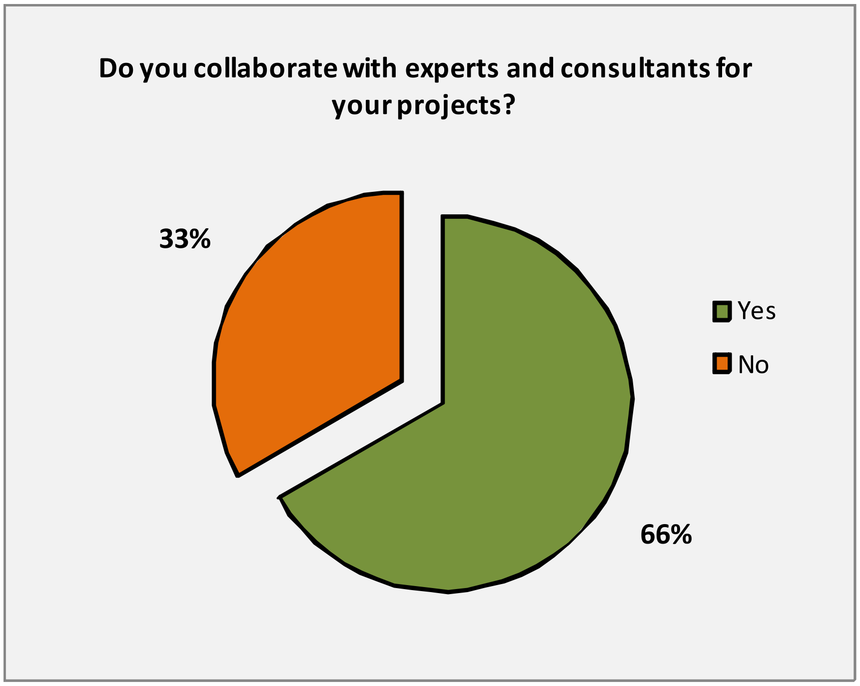


Figure 5.10: Student preferences for consultant and expert support

5.1.4 Open Ended Questions

Students were asked to be more specific on the effects of tools and design media in the following aspects:

Interdisciplinary Collaboration: Students' responses showed that used tools have limited effect on collaboration and communication during the design process. The content of information from the digital models is not sufficient to facilitate interdisciplinary collaboration when time constraints of the studio project are considered. According to one of the participants in the study:

> *They do not help much for collaboration any it is more convenient to share drawings or 3D surface models between people where it is necessary. But there is not much interdisciplinary interaction in a typical studio.*
>
> ***Study participant, Master of Architecture program 2nd year***

Design Learning: Existing tools and methods like CAD and surface modelers provide students extended flexibility to create both conventional and complex forms. Testing tasks for their visual and spatial performance are very rapid with visualization tools. Capable surface modelers were given as assets for 3D understanding of design artifacts.

> *In case of design learning, I just use Sketch-Up as the main tool for schematic design phase because it is easy to make a 3D model such as mass study or specific shape. I create alternatives and evaluate exteriors and interiors rapidly.*
>
> ***Study participant, Master of Architecture program 1st year***

Communication /Information Exchange/Documentation: Student responses demonstrate that students heavily rely on the individual use of employed tools. Communication among the studio participants is carried out with 2D and 3D visuals. In a typical studio process, exchange of information-rich building models or sharing of derived information is very uncommon.

> *It takes some time to exchange information between software especially 3D data. Sometimes problems do not let me to do what I intended. For documentation everything merges mainly into 2D after design is completed this takes substantial time. That's why I switched to use Revit last 1 year.*
>
> ***Study participant, Master of Architecture program 2nd year***

Decision Assessment: Used tools mainly provide visual and spatial feedback about the design. Assessment of the design alternatives using specific domain information regarding sustainability features, structural integrity, and other downstream aspects is rare. The main information sources for decision assessment were reported as desk-crits and pin-up session comments.

> *In decision Making or design evaluation, I just use professor's comment in studio. Current technology provide representational material for getting more clear feedback*
>
> ***Study participant, Master of Architecture program 2nd year***

> *CAD and 3D modelers give only representational feedback for form, spatial layout and visual assessment of the project. By using 3D modelers I sometimes try for sunlight analyses.*
>
> ***Study participant, Master of Architecture program 1st year***

> *As a design develops to the last stages, it is possible to evaluate decisions quickly and efficiently, but initial ideas and decisions are made outside of BIM tools.*
>
> ***Study participant, Master of Architecture program 2nd year***

Project Scope: Students did not report significant influence of tools and media on the scope of studio projects. According to the responses the scope is heavily dependent on the project brief and required deliverables. In agreement with answers to other questions, tool use supports the typical project requirements of form development, spatial configuration, and visual performance.

> *Scope of my project is defined by the given design brief, most of the time requirements are very similar between studios. For me only the design problem change....form, spatial layout, structural system, siting and so on…deliverables are like sufficient 3D images for describing my design, interior perspectives, plans, sections and elevations, sometimes details. All I use CAD and Photoshop…only one studio project required cost information at the very end of the project.*
>
> ***Study participant, Master of Architecture program 2nd year***

> *I try to finish my design according to design problem and the instructor's critics, the tools I use are very straightforward like Revit, AutoCAD and Illustrator...They let me to create my documents faster and more appealing...*
>
> ***Study participant, Master of Architecture program 1st year***

5.1.5 Typical Studio Processes

Students reported their most recent studio prior to the study. Open ended questions returned insights, preferences and decision making processes. Responses support the arguments and assertions from the literature review. According to study participants, the typical studio depends upon highly individual processes and inductive design methods directed toward a form-centric design problem. The primary objective of the students is the achievement of a consistent and plausible form and space layout. Students reported that they start with initial form ideas, refine the form iteratively and modify them to satisfy given criteria such as sustainability and structural integrity to an adequate level.

The following statements are selected from the student responses:

> Question: ***Please describe your most recent design studio or project process***
>
> *I started with designing a space on paper then I created the model in BIM, the second alterations were made on the BIM model, so as to visually understand the differences in design options. Later I transferred the design to a 3D rendering*

software for final renderings. I made 2 options on the BIM model, later in the design I adopted a combination of the two options.

Study participant, Master of Architecture program 2^nd^ year

I create the form using my experience and design preferences, instructor feedback make it clearer. I give form decisions by sketching or modeling. Then I modify my design for structural integrity and other performance requirements in later stages of the studio. Some studios require preliminary decisions about energy, sustainability or construction. These are very beneficial but it stays in the very basic level and I show a broad understating and that meets requirements I never go deep into energy analysis or systems integration with simulating my building

Study participant, Master of Architecture program 2^nd^ year

For me, form is derived from a conceptual basis that has been researched heavily. Environmental and structural factors play a large role in the final out come of the form. Some ideas about the form develop very early, but it evolves a great deal from start to finish. Spatial layout has as much to do with the form as anything else. Changes in layout will ultimately Impact the final form. Spatial arrangement will often be a precursor to the design of the shell. Energy is a very numerical based thing and thus comes late in the project as the form is more

> *established, but environmental factors are address in the design in the very beginning.*
>
> ***Study participant, Master of Architecture program 2nd year***

> *The most recent project was the library of the 21st century where we had to design a library that would be user friendly for the 21st century. I started with research and gathered information; from there I used the information gathered in developing forms for this problem. I then started exploring different options that might be used. By comparing solutions with the information I came up with a design that was initiated and further developed.*
>
> ***Study participant, Master of Architecture program 1st year***

> *I didn't really develop any other alternatives beyond the initial design phase, but the bulk of the schematic design phase was related to evaluating options by functionality and sustainability.*
>
> ***Study participant, Master of Architecture program 1st year***

5.1.6 Theoretical Knowledge of BIM and IPD

Students demonstrated an acceptable level of receptiveness towards BIM and IPD and also a basic level of understanding for collaboration, simulation and building performance. Surveys show that students were exposed to the industry-wide interest and dissemination of information about BIM and IPD and their bottom-line benefits.

However the responses showed a notable level of skepticism about BIM use for studio projects.

> *BIM is a set of representations of a building that has all information about itself, performance, constructability embedded with in itself to increase the flow of information from one stage to the next during design through occupation. BIM responds to the problems in the practice in terms of information needs. Because of these, It is very likely that I will be practicing in a BIM dominated professional environment in the next few years.*
>
> ***Study participant, Master of Architecture program 1st year***

> *I remain extremely skeptical of BIM technology having anything to do with learning to design. BIM is a tool and perhaps a means to an end, but hardly a way to learn design methods and principles. I've never, and doubt seriously, that I will ever use BIM to formulate conceptual designs unless that concept is how closely we can simulate cost and energy savings.*
>
> ***Study participant, Master of Architecture program 2nd year***

5.1.7 Summary of the Pre-study Survey

The pre-study survey provided evidence about the preferences, attitudes, and skill level of students regarding the research focus. Results were aligned with the criticisms of the academic initiatives by suggesting form oriented, individual, and inductive studio processes with conventional use of BIM, CAD and image processing tools. Student responses suggested that the decision-making process rarely includes performance issues like sustainability and energy use. Downstream aspects of design are often obscured in the studio or examined superficially. Current developments in the practice world have influenced students to value BIM skills to some extent but students have not learned to use BIM or incorporate it to achieve process integration or information exchange. Students' comments also provided some justification for implementing an integrated approach to the design studio using BIM.

For research purposes, the survey formed a baseline for testing the effectiveness and the influence of the proposed pedagogical framework on students' skill level, design preferences, and attitudes.

5.2 Analysis of the Case Studies

Data is analyzed by using a predefined concepts framework. As in the pre-study and post study surveys, these conceptual topics are drawn from the established theory and focus group results. These are:

1. Integration and Collaboration
2. Form, Spatial, and Visual aspects
3. Parametric Modeling and Adaptability
4. Sustainability and Energy Performance
5. Scheduling and Use of 4D Models
6. Cost Control

Text, visual and numerical data grouped naturally into these concepts and was interpreted in the context of integrated studio education and BIM. Text data is comprised of the progress reports and assessment sessions logs. Design artifacts are comprised of BIM models, domain models, 3D visualizations, 2D documentation, and presentations materials created during the case studies. Numerical data was derived from the energy simulations, daylighting analyses, scheduling schemes and cost control reports. Analysis of the process observation logs and progress reports was conducted by a search for concepts listed above. Interpretations are corroborated with design artifacts, simple statistics and numerical data.

5.2.1 Case Study Settings and Setups

Although the case studies inherited the project-based learning pedagogy of the architectural design studio, the format was divided into compressed special topics courses with extensive collaborative sessions, comprehensive performance assessments, and discussions about the integrated process. The "boot camp" type of courses were intended to overcome the preconceptions and learned patterns of design process based on the conventional studio model so that they can be replaced with the new model of design process. The learning strategies were the following:

a) To achieve an immersive and concentrated learning setting by compressing the course into 45 hours of contact time;
b) To reduce need for software instruction by prerequisite of moderate levels of skill with BIM tools;

c) To include high levels of expertise and credibility by recruiting and including graduate students and licensed professionals who could take on roles of disciplinary experts in design, construction, costing, energy efficiency, sustainable construction, lighting, and structures;

d) To focus on design methods theory and practice to disrupt students' preconceptions about how to design;

e) To form cross-disciplinary teams requiring multi-channeled communication and coordination among team members;

f) To commit design members to make decisions based on evidence by requiring a base case and frontloading design evaluations;

g) To exploit parametric models to make faster and more precise decisions in conceptual design with evidence from simulations and computations.

The courses had two major stages: a theory stage employing lectures, readings, and discussions, and a practicum based on a compact design project. The lectures focused on IPD, BIM and other advanced digital technology, case studies within the BIM domain, and a strong grounding in design methods theory. They included presentations from practicing architects who have implemented BIM into their integrated design process as well as case studies involving best practices from medium and large firms. The traditional design process and its associated tools and methods were compared and contrasted to an integrated approach with BIM. In order to enhance the understanding of integration and BIM process, adoption strategies of BIM-A, BIM-B and BIM-I were given as a theoretical background.

In the second stage, the students were assigned a compact but realistic design problem. They were required to design a train station in College Station, Texas. The on-campus station projected to have 4000 SF indoor space and 8000 SF covered platform within a $2M budget. In addition, a four month construction time limit was established as a realistic constraint on construction methods to avoid disruption of campus activities (Figure 5.11 and Figure 5.12).

Figure 5.11: Satellite view of the project site and surroundings

Figure 5.12: Photos from the project site

Students were required to provide extensive evidence supporting the expected performance of each design alternative including:

1. Schematic alternatives illustrated with plans, sections, elevations, and perspectives;
2. Preliminary and detailed construction schedule proposals;
3. Construction cost estimate;
4. Structural component selection and design;
5. Operating cost report;
6. Energy consumption report;
7. Mechanical systems integration;
8. Sunlight studies and day lighting performance;
9. Water balance and rain water harvesting strategies;
10. LEED Silver Certification;
11. Conformance with Amtrak design guidelines; and

12. Visual analysis to indicate sensitivity to the campus setting and design aesthetics.

This list of performance criteria that must be explicitly addressed appears overwhelming in the context of a conventional studio. However, it necessitates the adoption not only of BIM but also a classroom version of IPD as a pattern for collaborative design. Students were taught to produce a base case design rapidly and pass it to consultants for feedback, frontloading the design process to incorporate as much information as possible in the initial stages of the design. To provide students with experience in collaborative design, three main design and analysis roles were established:

Core Design: Form, visual performance, spatial layout, details and essential building components by the architectural designers. Each design team created BIM models for pushing and pulling information during integrated design process using Autodesk Revit Architecture and Structure.

Constructability: Cost breakdowns, quantity take offs, schedule outline, conceptual structural design produced by construction and structures consultants. The Revit models were exported to Revit Structure, Autodesk Navisworks and Microsoft Project for producing constructability analyses.

Sustainability: Energy use and environmental analyses. Revit models were exported to Green Building Studio, Ecotect and Radiance for energy simulation and lighting analysis by additional consultants. Some students preferred to use Climate Consultant during the initial phases.

In addition, a BIM assistant established course-wide drawing and modeling standards incorporated into project template files of families to reduce the setup time and avoid fumbling with documentation tasks. Core design teams consisted of Master of Architecture students, while the consultants were each very experienced architects and designers pursuing Ph.D. degrees in the specialization areas of their consulting expertise. The task domains of the case studies and the relationships between them are illustrated in Figure 5.13.

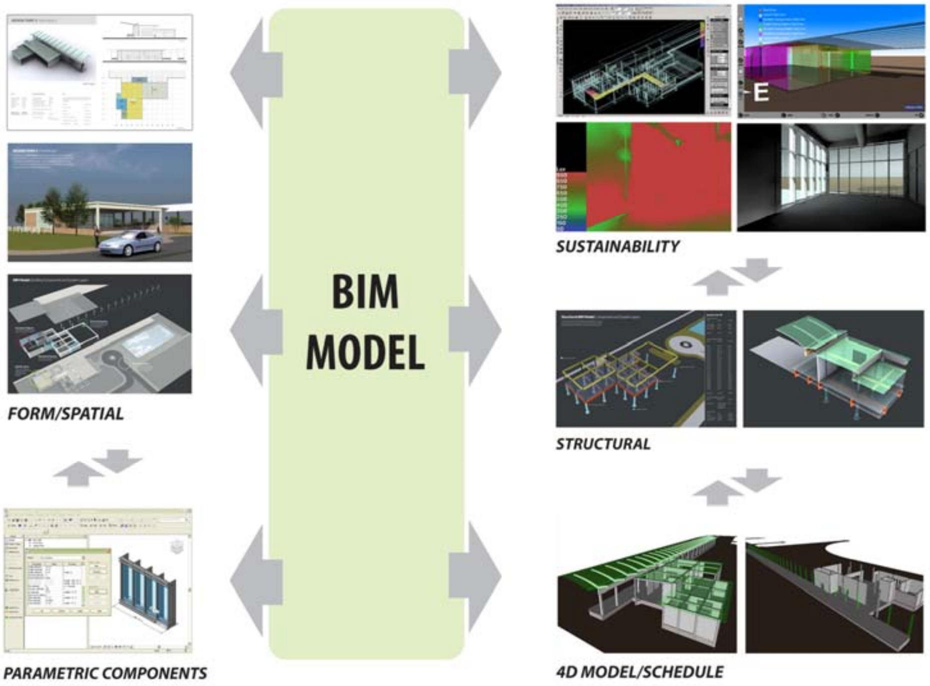


Figure 5.13: Task domains and the results from the study

There were slight differences in the case study setups due to logistics of the offered courses. The course setup structure was also modified in accordance to student skills and expertise level. The second case study had three individual designers as opposed to design teams in the first case study. The third case study setup consisted of collaboration clusters where M.Arch. students were given different roles in their own team. These teams collaborated with external consultants for the design assessment. Case study setups are given in Figure 5.14, Figure 5.15 and Figure 5.16. Shared BIM models were utilized to allow multiple designers to work on the same alternative. The use scheme was not based on a "single meta-BIM model" but information was extracted from the shared BIM model in an appropriate file format for use in the simulation tools. The process involved propagating information to create different domain models for software such as Green Building Studio, Ecotect, and Navisworks for sustainability simulation, daylighting and sunlight studies, and 4D models.

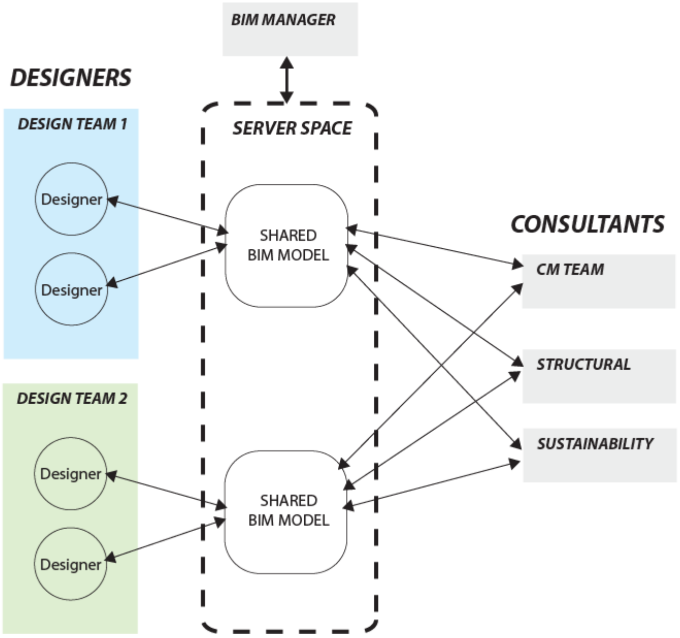


Figure 5.14: Setup diagram of Case Study 1

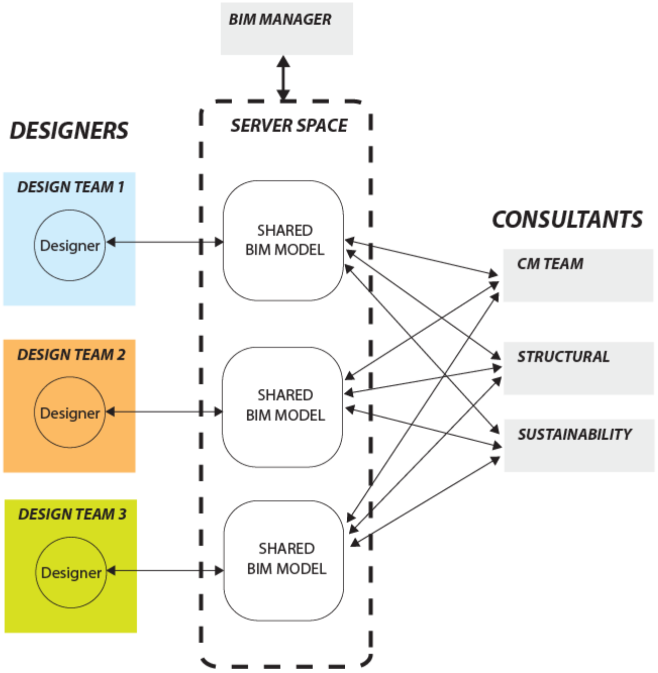


Figure 5.15: Setup diagram of Case Study 2

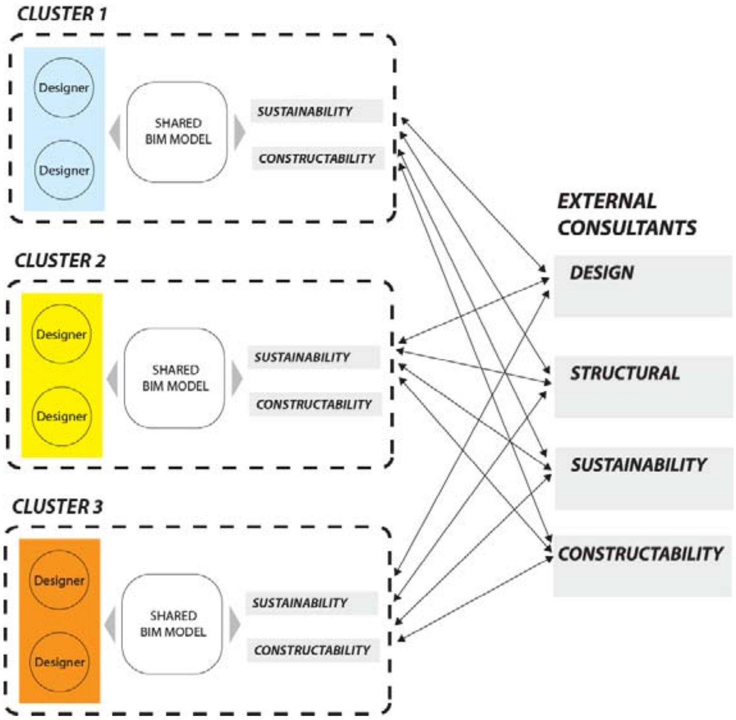


Figure 5.16: Setup diagram of Case Study 3

5.2.2 Learning Environment and Workspace

Case studies were conducted in classroom environments where students worked collaboratively with consultants. Unlike the typical studio environment, groups formed a *club workspace* for increased communication. Every student provided a notebook computer loaded with required software. White boards, projectors and interactive plasma screens were used for communication and design assessment (Figure 5.17).

Figure 5.17: Photos from the collaborative design sessions

An Active Directory based server space was dedicated for sharing the central BIM models and all project-based information during the first two case studies. The third case study utilized an FTP server for sharing the information among design groups. The tree structure for the shared space was designed prior to the study and students were given clear instructions about the use policies and file update procedures.

5.2.3 Integration and Collaboration

Switching from conventional design methods to an integrated approach emerged as a major challenge for all study participants. Although students were very receptive about the instructed concepts of integration and collaboration, inductive design habits disrupted the collaboration process in the first case study. Design teams omitted the environment and performance input and tried to achieve an iconic canopy design with complex parametric elements. Consultants’ contribution stayed at the very minimum level, and two design sessions did not include any simulation or estimation information until the development of the base case was complete.

Base case (Figures 5.18 and 5.19) was introduced in the process with a very heavy emphasis on creating a prototypical architectural solution and performing all analyses on the base case. The base case need not be a carefully considered and elegant design, but merely a quick and obvious reaction to the program which is still translated into architectural form. The base case established the basis for performance comparisons and thus supports evidence-based decisions. The base case helped to frontload the integrated design process and initiated the design cycle to include assessment of the design scheme. Second and third case studies inherited the base case with minor modifications. Referring to Rittel’s (1973) wicked problem concept, the base case design allowed students to comprehend the different performance requirements and define the design problem by creating a prototype design alternative. Preliminary cycle also demonstrated an example of design-simulation-assessment cycle to the students.

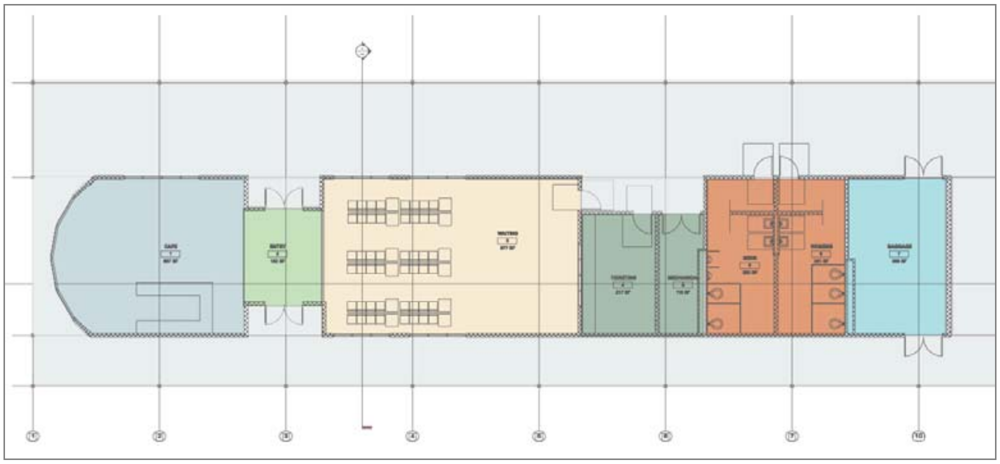


Figure 5.18: Base case floor plan from the first case study

Figure 5.19: Sectional perspective of the base case

The following statement is taken from the process report of a design team member:

> *I was given the project and asked to design it based on my design preferences. Later, my judgments were criticized based on evidence and data derived from the base case. This type of criticism proved very constructive as it was based on*

> *evidence not merely based on someone else's judgment and perception of the design.*
>
> ***Study Participant, M.Arch. 2nd year***

Frontloading emerged as the key concept to drive students to switch from conventional design methods to a highly collaborative one. The performance requirements and the content of design problem required students to collaborate with consultants for with quick but sound alternatives. Frontloading the process with technical and performance-related information added significant amount of complexity and students had to prioritize the performance variables. Except for some minor challenges, frontloading did not obstruct the design process and collaboration. Observations and student reports show that frontloading eliminated the usual procrastination period which occurs in the early stages of typical design studio until the student gets comfortable with the given design problem. In the progress reports, students stressed the importance of project frontloading and leveraging building information. Reponses demonstrate that students gained substantial level of understanding of the early phases of integrated design and the role of BIM as opposed to the typical studio processes.

> *In comparison to the traditional studio we start with the conceptual ideas as oppose to the information driven approach of the exercise. Through the analysis of site and climatic information the project is far more informed. The methodology of simulation of the design and evaluating the project over*

numerous iterations make for a more thought out design. The mutual contribution of working with a group in a "firm-like" atmosphere rather than on an individual basis contributes to the overall success of the process.

As oppose to the traditional studio environment this seminar guides you towards an idea of form follows performance rather than the age old debate of function follows form or form follows function. The seminar also fosters each individual's leadership skills to a point where you have a far more improve approach to the idea of collaboration unlike the efforts made in a typical design studio

Team progress report, Case Study 3

The contrast between the BIM process verses the typical Studio process is that in the BIM process we are more attuned to addressing issues through information that is gathered at the beginning of the process, while in the regular studio format we address issues as they come along in the design process. Also, in the design process we are more focused on creating then resolving instead of resolving then creating like in the BIM – Integrated Project Delivery method. Lastly, in the preliminary phase of BIM – Integrated Project Delivery method one is less inclined to use traditional sketching and drafting approaches to resolving the design issues that arise through research and informational networking

Team progress report, Case Study 2

Responsibilities of the students were reinforced and communications channels became more effective as students went through the collaboration cycles. Developed procedures for integrated process were observed to be similar fashion during all case studies.

Integrated design cycles were initiated by the design teams. The design intent defined by the integrated team was executed by designers. Shared BIM models were created under the influence of performance criteria. This phase was succeeded by broadcasting the model to the consultants for the creation of domain models and simulations. Visual and text output were generated by the consultants and organized for assessment by the entire team. Collaborative assessment sessions involved discussions on the objective achievement of form, visualizations, and spatial configuration as they were connected to energy performance and daylighting; cost and scheduling framework and preliminary construction plans. Extracted design information was summarized and used for further development of the alternatives. These cyclic processes were repeated until the design and performance objectives were fulfilled to an acceptable level. Figure 5.20 illustrates the flow of the observed integrated design cycles with tasks and design content.

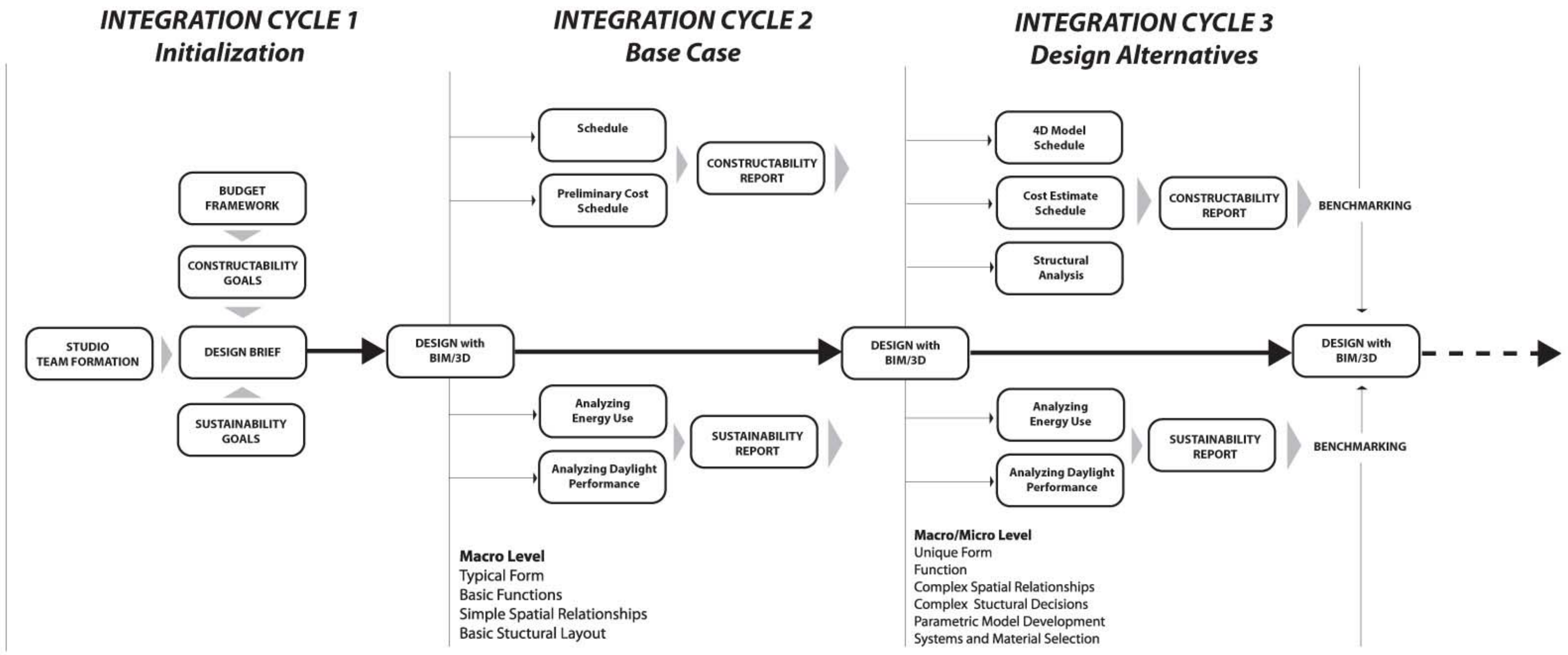


Figure 5.20: Observed process flow during the early stages of the case studies

5.2.4 Formal, Spatial and Visual Content

From a very theoretical point, one of the major pedagogical challenges during the study was the addition of the "reality" dimension to the process in order to transform the typical relationship between the design thinking and the design artifact in a typical studio. As a result, observed processes regarding form, spatial and visual aspects included this mutual relationship between the design decisions, reality factors and the design artifacts.

Since the case studies focused on the investigation of the prototype studio framework performance based approach, well-established qualitative aspects of architectural design were combined with the process and tested against the performance criteria. Architectural representation, design discourse, contextual relevance, proportions, spatial perception, texture, and materiality were the qualitative quality dimensions. For instance, spatial relationships between the canopy and core building, spatial definition of transient spaces like the platform area, and materials for the functional and also perceptional elements were the major design components specific to the given problem.

Students' approach to form and spatial creation was driven by the given spatial program, local built environment of the city and the university campus, but also exploited capabilities of the BIM tools for parametric freeform design. While dealing with performance criteria and budget constraints, students were simultaneously creating form alternatives with an emphasis on a contextual connection to the site and highly connected indoor and outdoor spaces that addressed the local landmarks. In all case studies, students tended to create highly transient and transparent spaces in order to increase social interaction and visual perception. All preliminary mass studies and form alternatives for the actual building and the canopy system were explored with parametric solid models involving freeform exercises. These exercises necessitated the creation of custom families and parametric components rather than the use of generic components delivered with the software. Student occasionally used surface modelers to create mass models or modeling templates along with the BIM tool. Interior spaces and their visual performance were assessed using interior perspectives and composite renderings. BIM tools provided for efficient design development and form generation with the ability to simultaneously check given constraints and performance criteria.

Parametric canopy examples in Figures 5.21 and 5.22 were created in the second week in case study 2 and 3. These early designs were further refined and used in the final design alternatives. As seen in the figures, canopy components were created according to the given form using a simple subdivision equation for component generation. Overall canopy designs involved developable surfaces to ease fabrication and simplify connected structural system components.

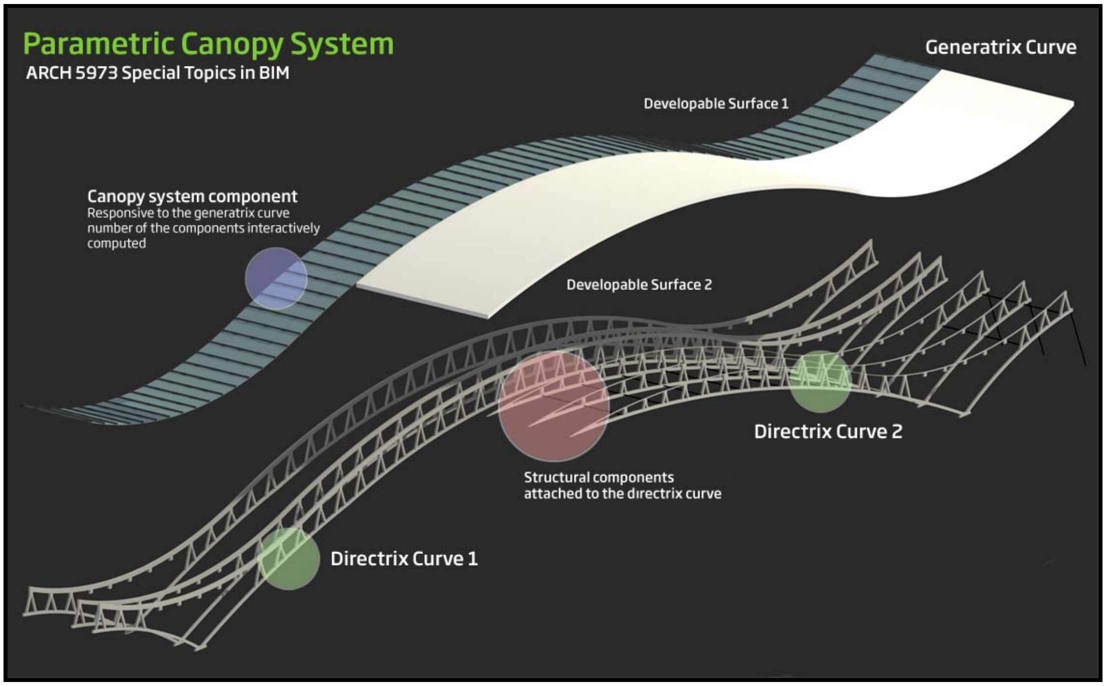


Figure 5.21: Parametric components of the canopy design

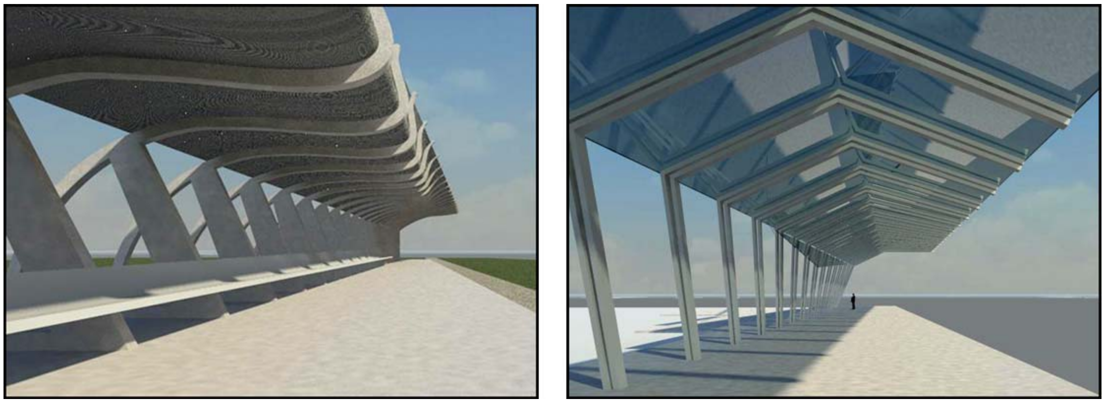


Figure 5.22: Preliminary parametric canopy designs from the case study 2

5.2.5 Interoperability

All of the case studies employed a large collection of software tools. Autodesk Revit Architecture and Structure were used as architectural and structural design software platform. Designs were analyzed in Green Building Studio by exporting a Revit model to gbXML and analyzed in Ecotect/DaySim by exporting to 3DS files. 4D CAD models were developed in NavisWorks using Revit native file format. Cost and schedule information were derived from Revit by exporting tabulated data to external applications like MS Excel and MS Project for cost estimation and scheduling. Two design teams in the third case study used Climate Consultant. Figure 5.23 shows the interoperability framework. Note that dashed icons represent the tools utilized in particular case studies.

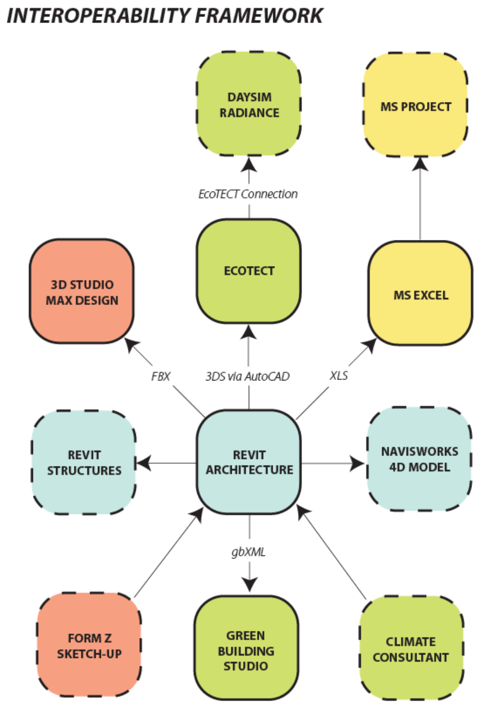


Figure 5.23: Interoperability framework of the study

Interoperability emerged as one of the major issues before and during the design process. The figure 5.23 shows the software and data standards employed in the project. Software interoperability effected the collaboration and communication particularly in the early phases. Students experienced difficulties in file conversion and exchange procedures. Data structure inconsistencies and complex geometric content of the BIM models created conversion problems and simulation tools occasionally returned fatal errors. For instance, the limitations of DOE2 format in GBS simulation engine allowed only particular recto linear forms. Simulation of complex curvilinear elements was achieved after analytical simplification of the model was performed. Further efforts and small pilot tests provided assurance that issues in data integrity data and conversion were minimized. Solutions included the simplification of BIM model content; use of common legacy file types as the interface; and remodification of BIM models in simulation tools. Using these trivial examples, students were given clear instructions about software interoperability to avoid interruptions of integration and collaboration.

5.2.6 Parametric Modeling and Adaptability

Students used parametric BIM components for two different tasks. During the first case study students designed parametric system details that were responsive to the building form and system component. Due to the emphasis on form in second and third case study, students used parametric scripts for the generation of assembly components and freeform canopy alternatives. Use of parametric details like curtain wall systems, shading devices and structural components provided a rapid cycle of design, assessment and modification. Students also harnessed the portability and reusability of parametric models. New forms and components were propagated using parametric objects and nested families.

Examples in Figure 5.24 show parametric building components from the second week of first case study. It took one session (2-3 hours) to create the component sets with support from the BIM assistant and consultants. These components had a nested structure and they were adaptive to the building envelope. Further designs in the first case study included these modules with parameter modifications.

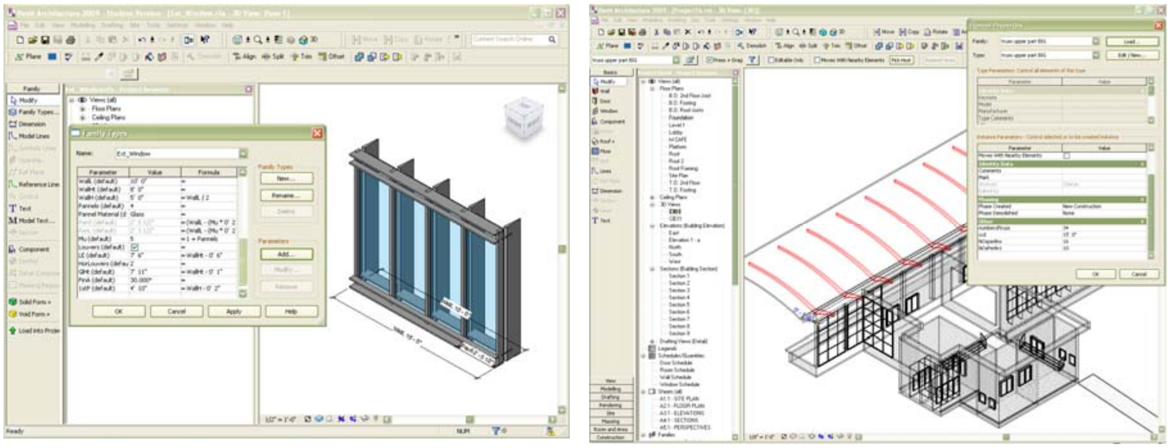


Figure 5.24: Parametric component designs and dialog interface to create alternatives by parameter modification. Models are from the first case study.

One of the observed challenges during case studies is the shifting of students' perception from 3D solid modeling to parametric modeling. Vast majority of the students had the preconception of manual 3D surface modeling for building components and form alternatives. In order to overcome this issue, a just in-time instruction procedure was employed as follows:

a) Selection of a building component or overall form concept;
b) Determination of component properties;
c) Development of parametric equations and constraints;
d) Implementation of equations with the BIM software;
e) Creation of component families;
f) Use of family and assembly of the final model;
g) Test for performance.

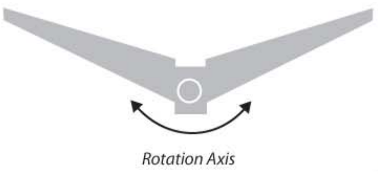
For illustrating the interconnected relationship between design decisions-form-parametric BIM components and performance, the following example is taken from observation logs. Two consecutive integrated design sessions were dedicated to the alternative including the conceptual idea, and implementation and solution suggestions from the consultants. In this particular example, designers created custom shading components that are responsive to the wind directions and sun angles at the given site. Parametric component development was based on rotation angles and main structural system spans. Overall form was defined by the replication of the parametric component across the structural system. Simplified version of the model was analyzed for energy, sunlight and daylighting performance.

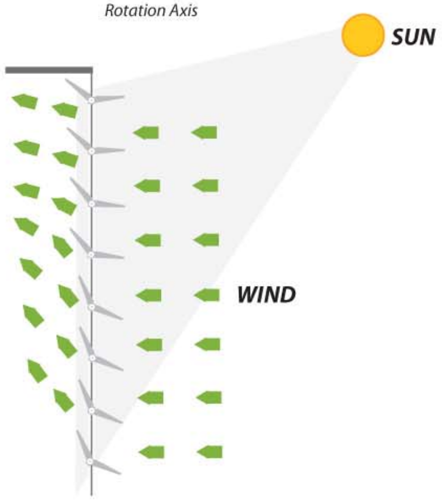
Date: March 4, Wednesday, 2009
Integrated Session 3
Duration: 2 hours 43 minutes

Session agenda

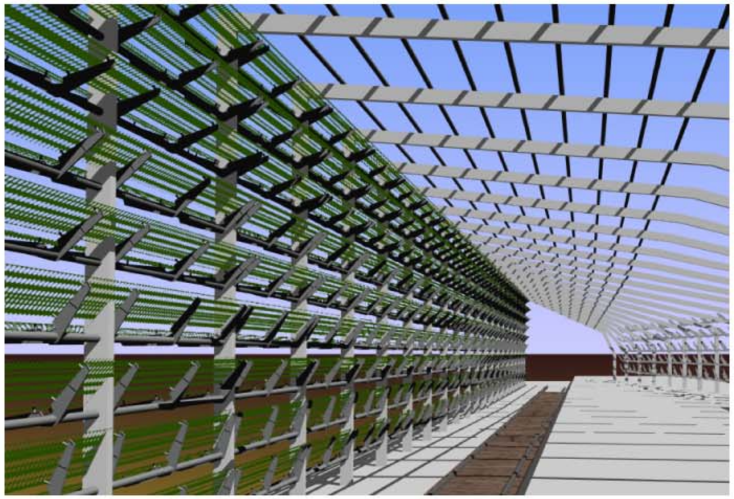
- Parametric modeling applications
- Development of canopy system and components
- Preliminary space layout
- Conceptual cost framework details
- Energy saving strategies

Parametric Surface Element

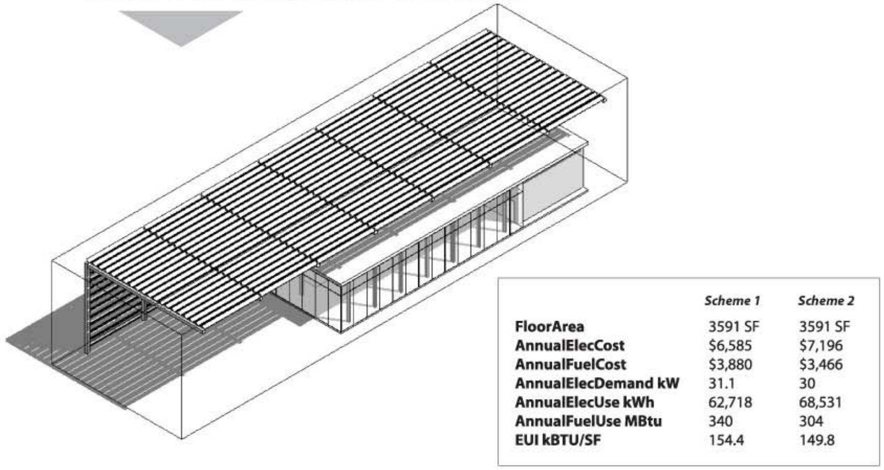




Conceptual idea for sun shading and wind harvesting



Parametric implementation on the canopy system



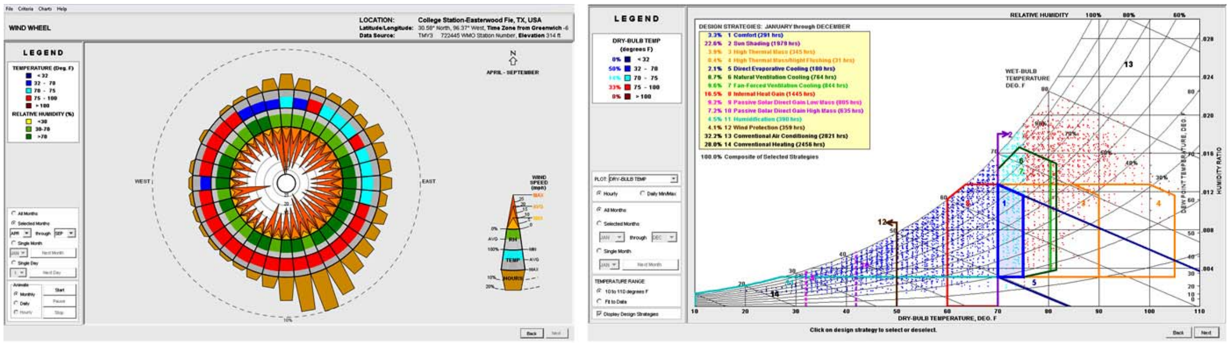
	Scheme 1	*Scheme 2*
FloorArea	3591 SF	3591 SF
AnnualElecCost	$6,585	$7,196
AnnualFuelCost	$3,880	$3,466
AnnualElecDemand kW	31.1	30
AnnualElecUse kWh	62,718	68,531
AnnualFuelUse MBtu	340	304
EUI kBTU/SF	154.4	149.8

Energy Model and Simulation Results

Figure 5.25: An observation log from the second case study

5.2.7 Sustainability and Energy Performance

Building energy use and sustainability features like daylighting were some of the core focus areas in all case studies. After the first design cycle, energy consultants and designers worked closely on the assessment of the alternative in order to meet LEED silver requirements. Use of Green Building Studio and Climate Consultant provided preliminary information for wind directions, sun angles, and the climatic data about the given project site (Figure 5.26).



LOCATION: College Station-Easterwood Fie, TX, USA
Latitude/Longitude: 30.58° North, 96.37° West, Time Zone from Greenwich -6
Data Source: TMY3 722445 WMO Station Number, Elevation 314 ft

DESIGN STRATEGIES: JANUARY through DECEMBER
3.3% 1 Comfort (291 hrs)
22.6% 2 Sun Shading (1979 hrs)
3.9% 3 High Thermal Mass (345 hrs)
0.4% 4 High Thermal Mass/Night Flushing (31 hrs)
2.1% 5 Direct Evaporative Cooling (180 hrs)
8.7% 6 Natural Ventilation Cooling (764 hrs)
9.6% 7 Fan-Forced Ventilation Cooling (844 hrs)
16.5% 8 Internal Heat Gain (1445 hrs)
9.2% 9 Passive Solar Direct Gain Low Mass (805 hrs)
7.2% 10 Passive Solar Direct Gain High Mass (635 hrs)
4.5% 11 Humidification (390 hrs)
4.1% 12 Wind Protection (359 hrs)
32.2% 13 Conventional Air Conditioning (2821 hrs)
28.0% 14 Conventional Heating (2456 hrs)
100.0% Composite of Selected Strategies

Figure 5.26: Environmental properties of the given building site from Climate Consultant

Students revised the shell, spatial layout, and the details of the design alternatives to achieve improved energy performance. All design teams created numerous energy use schemes for the design alternatives. The decision making scheme for the energy efficiency emerged as a rapid cycle as the following:

1. Creation of the analytical performance model (gbXML) for the design alternative;
2. Simulation of the alternative using Autodesk Green Building Studio;

3. Interpretation of the simulation using key performance values such as energy usage intensities (EUI), daylighting factor (DF) and daylight autonomy (DA);
4. Benchmark of the results to base case for energy savings;
5. Modification of the analytical model within the simulator tool;
6. Collection of feedback and assessment from the consultant;
7. Modification of the design alternative and the creation of macro or micro solutions.

It is observed that students put extensive effort for optimizing the energy use and daylighting. Simulation outputs show the variations in performance measures in accordance with modifications of the design alternatives. These modifications included several aspects of the design. In some cases, students preferred substantial revision of the building form or the canopy system. Modification of spatial layout and the space configuration was another alternative solution. Students also opted for developing systems and use of material options for the reduction of the solar heat gain. Following figures show the energy use intensity and annual energy costs charts from each case study. Students created as many gbXML files as needed for performance simulations. The process results indicate that the students' response to energy efficiency was positive and trends for EUI's and energy costs were decreasing except in few cases. Major increase points in the EUI and costs correspond to the substantial changes in the design alternative (Figures 5.27 - 5.29).

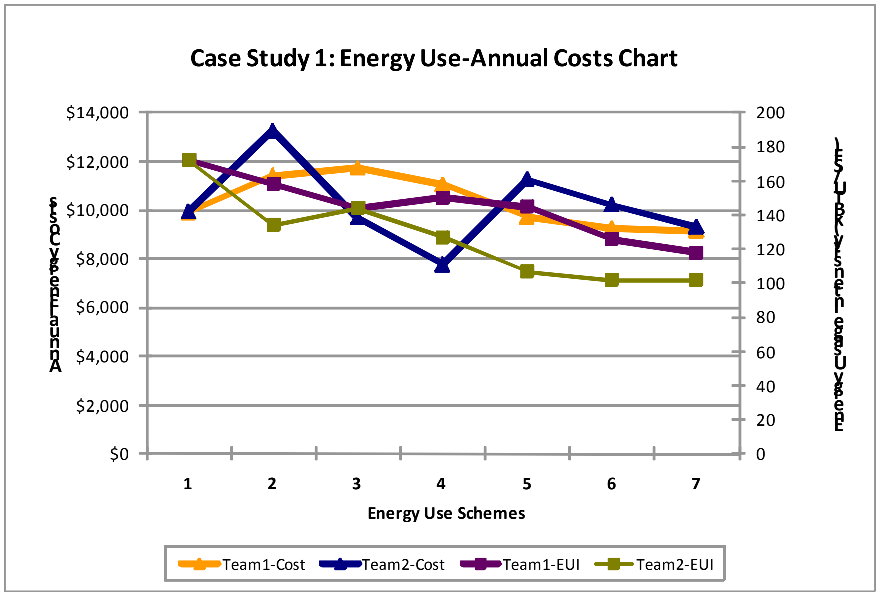


Figure 5.27: Energy usage intensity and annual energy costs chart for the case study 1

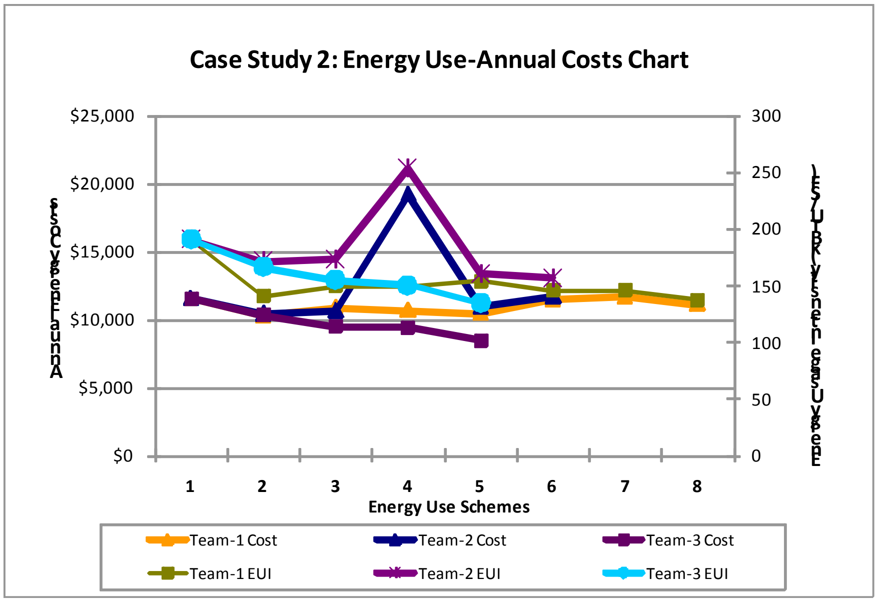


Figure 5.28: Energy usage intensity and annual energy costs chart for the case study 2

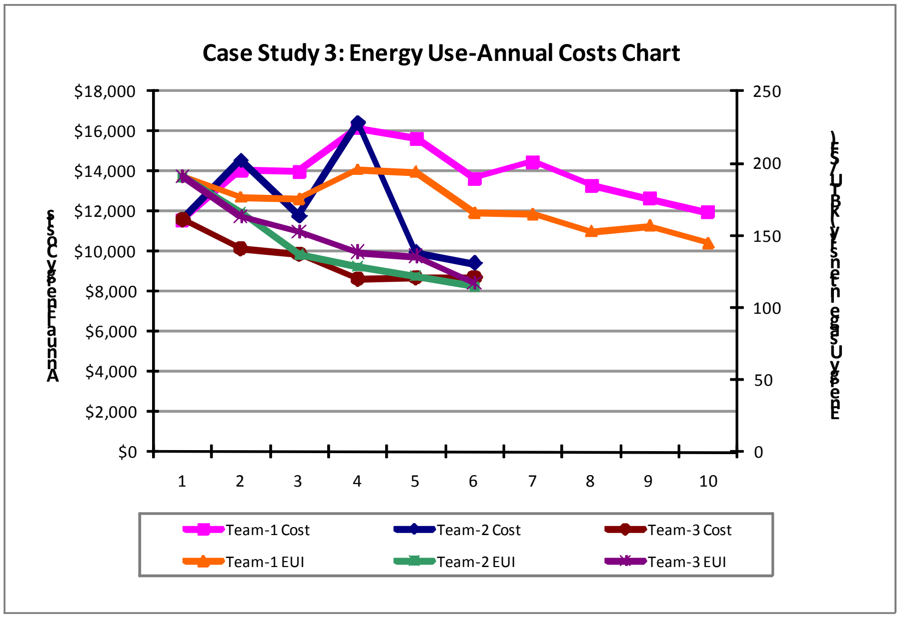


Figure 5.29: Energy usage intensity and annual energy costs chart for the case study 3

Daylighting performance and sunlight studies returned significant feedback, particularly for the components in the building shell and canopy design. The location and the orientation of the site added another complexity as reducing the solar heat gain from the S-SW direction while letting reasonable amount of daylight into social spaces. Daylight level in the museum space was also required stay in certain limits. Sun studies were conducted to test the performance of the canopy design during different seasons and different times of the day.

Figure 5.30 illustrates various design decisions for addressing the heat gain and required natural light levels. As seen in the figure, building envelope and canopy in this example were designed using massive elements to block sunlight and heat gain from South-

Southwest direction. North-Northeast side of the building consisted of transparent building components with shading elements for sufficient daylight for social spaces.

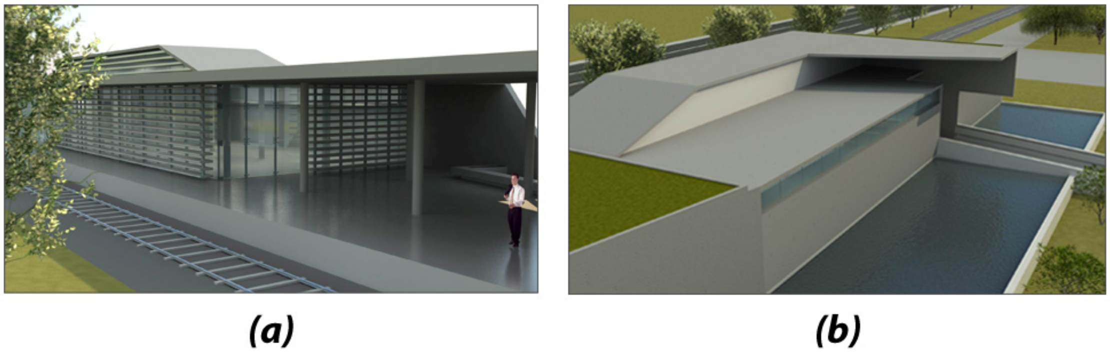


Figure 5.30: Building envelope design in accordance to the site orientations

Sunlight studies were conducted to assess the performance of canopy design during the different times of the year. Simulations demonstrated the shadow progress during Equinox, Winter Solstice and Summer Solstice. Perspective images and animations were used for visualized feedback. Figure 5.31 is a screenshot from the second week of the Case Study 2. Sunlight animation was created using Ecotect. Autodesk Revit also provided quick and effective sunlight analyses and visualizations (Figure 5.32).

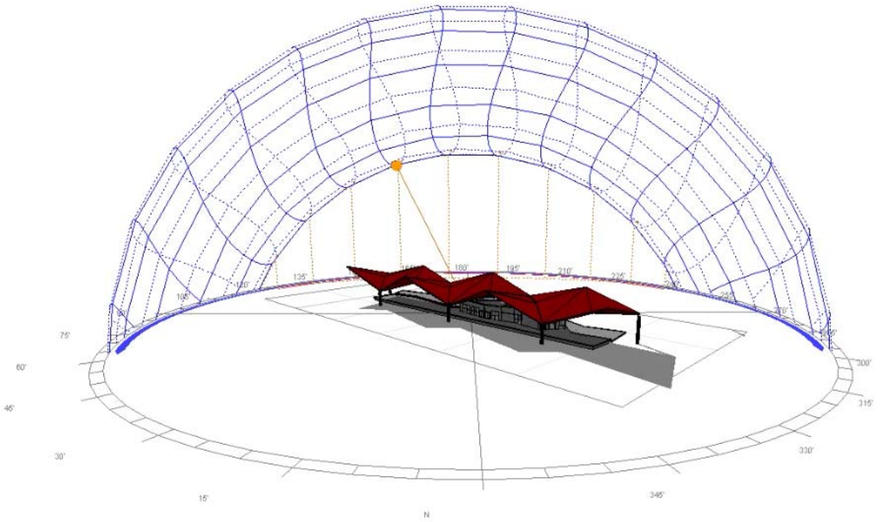


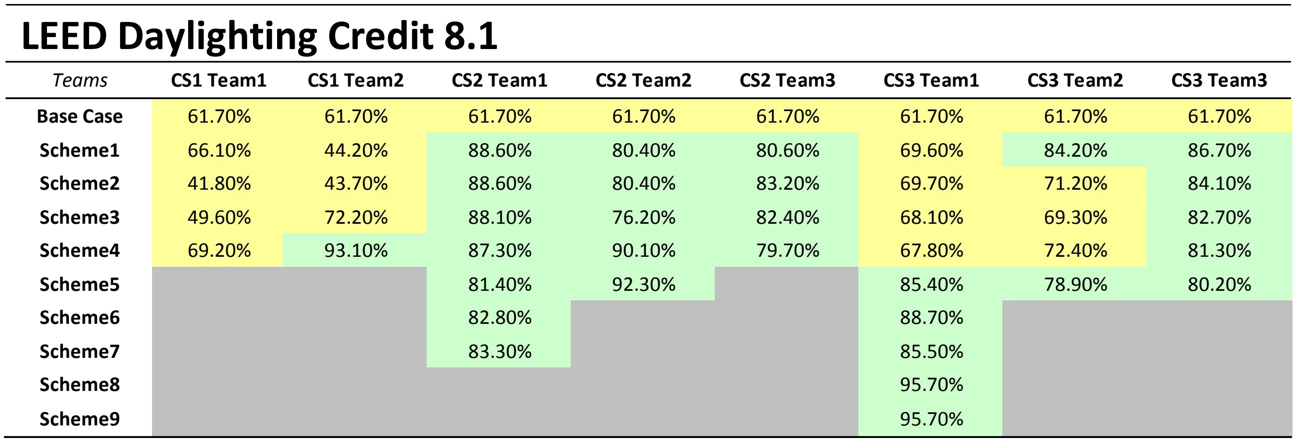
Figure 5.31: Second week sunlight study animation using Ecotect

Figure 5.32: Early stage sunlight studies using Autodesk Revit with rendered perspectives

Details of the daylighting analysis process illustrates the depth of the task connected to the decision making process in the design. The main reason for daylighting analysis during the design process was the early detection of possible problems of glare or lack of daylight in accordance with the LEED Daylighting Credit 8.1. Analysis tasks for daylighting attempted to take advantage of that natural resource for an overall better lighting and to avoid as much as possible the use of artificial lighting for its direct effect for resource consumption and carbon emissions. Daysim software was used to perform an annual simulation of luxes obtained in a grid of sensors in the room at a desk or workspace height. After this analysis, Daylight Autonomy was checked which is the capacity of the designed room or building to provide a minimum amount of 300 luxes (according to the new IES Standards) throughout the year, and for ranges of UDI (Useful Daylight Illuminance), from <100 (lack of daylight), between 100 and 2000 (useful range), and >2000 (possible discomfort glare problems). All of these are also along a year analysis. With these results, projects were assessed for whether the design needed to be improved in order to comply with the requirements for a particular task or function in the project. In addition, Radiance rendering analysis was conducted to check for adjacent surfaces with a brightness contrast over 10 times which may create glare problems. Using false color image, the distribution of light is analyzed for uniformity within the given space.

Students used LEED requirements for the daylight performance assessment. According to LEED guidelines, given project alternative must achieve a minimum Daylight Factor of 2% (excluding all direct sunlight penetration)in 75% of all space occupied for critical visual tasks (USGBC). After a quick check for LEED daylighting credit 8.1, all projects were simulated for certain daylight factor levels with defined virtual sensors in the BIM model. Table 5.4 shows the daylighting schemes and daylighting factor percentages (qualified schemes over 75% are shown). The data suggests that design teams had the tendency to control daylight requirement, by staying either over or close to 75%.

Table 5.4: LEED daylighting credit comparisons of all case study projects



LEED Daylighting Credit 8.1

Teams	CS1 Team1	CS1 Team2	CS2 Team1	CS2 Team2	CS2 Team3	CS3 Team1	CS3 Team2	CS3 Team3
Base Case	61.70%	61.70%	61.70%	61.70%	61.70%	61.70%	61.70%	61.70%
Scheme1	66.10%	44.20%	88.60%	80.40%	80.60%	69.60%	84.20%	86.70%
Scheme2	41.80%	43.70%	88.60%	80.40%	83.20%	69.70%	71.20%	84.10%
Scheme3	49.60%	72.20%	88.10%	76.20%	82.40%	68.10%	69.30%	82.70%
Scheme4	69.20%	93.10%	87.30%	90.10%	79.70%	67.80%	72.40%	81.30%
Scheme5			81.40%	92.30%		85.40%	78.90%	80.20%
Scheme6			82.80%			88.70%		
Scheme7			83.30%			85.50%		
Scheme8						95.70%		
Scheme9						95.70%		

Examples provided by students in the following figure show the depth and comprehensiveness of the daylighting simulations conducted during the design process (Figure 5.33).

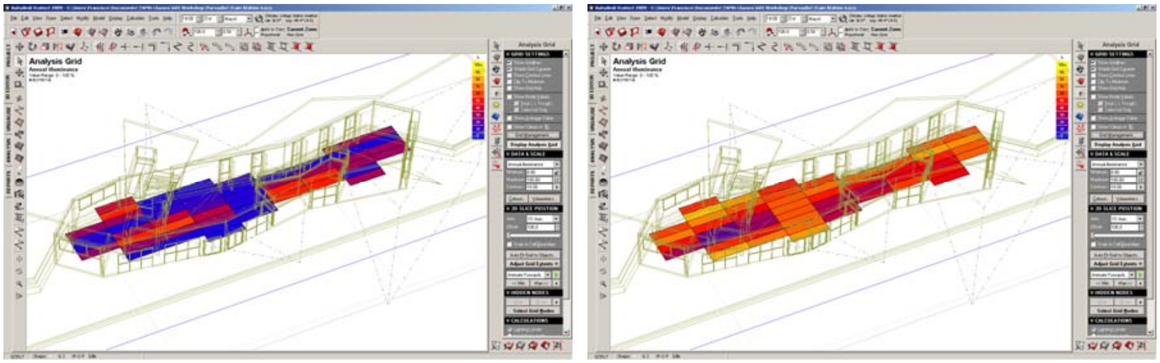


Figure 5.33: Daylighting simulation results of the design alternative for UDI 100lux and UDI 100-2000 lux

Figure 5.34 shows the connection between daylighting analysis and design revision for maintaining the desired level of daylight in the exhibition space. Radiance simulations returned accurate daylight values. Designed louvers during the second week of the case study decreased the direct light and balanced the indirect daylight in the exhibition space.

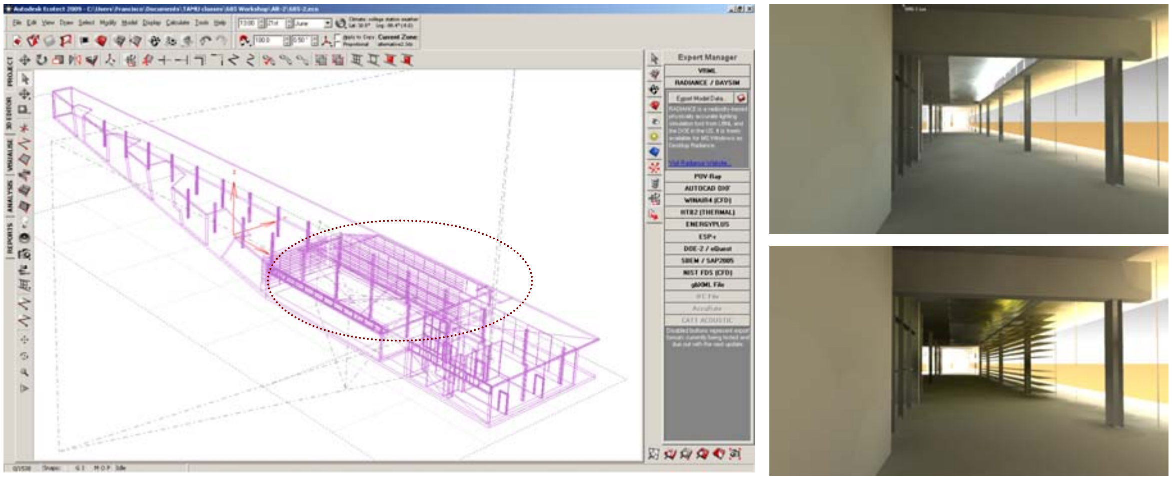


Figure 5.34: BIM model and human sensitivity-daylighting simulation results. The model and simulations were created during the second week of the case study 2

> *Using BIM we were able to share data with the other consultants relatively easily, whose responses and analysis led to various changes or implementation of criteria. One instance led to the major rearrangement of the plan, location of louver for decreasing the direct sunlight in the museum area, and use of a large canopy over the entry based on lighting analysis in relation to the location of programmatic elements.*
>
> ***Team progress report, Case Study 2***

Students also studied water balance and renewable potentials of their designs by using the results from the GBS simulations. Students implemented solar panels in final designs using the PV potential calculations from the simulations. These inputs were not the top priority, but they provided another layer of knowledge for future reference.

5.2.8 Scheduling and Use of 4D Models

Typically, 4D models are created and employed after the completion of design development and construction documentation phases. However, 4D BIM models provide a wide spectrum of information that can be leveraged for design development during the early stages of design. Evaluation of different building system options, systems integration and form/material/construction relationships can be further studied with 4D BIM models.

In the first and second case study, 4D BIM models were used as a common coordination medium in order to establish efficient communications between designers and construction management students. During the process, overall forms, building system options and scheduling of the design alternatives were evaluated using 4D models and dynamic spreadsheets. For every design alternative 4D Autodesk NavisWorks models were developed to visualize the relationship of selected building components and the behaviors of preliminary building systems during the presumed construction process. Students responded very rapidly to the use of 4D BIM models for understanding their designs from a systemic point of view. The 4D BIM model became a valuable source of information for design decision-making. Students were able to evaluate the impact of design decisions on construction schedule and make design alterations to meet given scheduling criteria of the required four month construction timeframe.

Figure 5.35 shows the construction sequence of a design alternative from the second case study. The model of the alternative was quickly transformed to a 4D model with its different components and possible construction schedule. Potential problems and construction details were examined with the 4D model during the conceptual design phase.

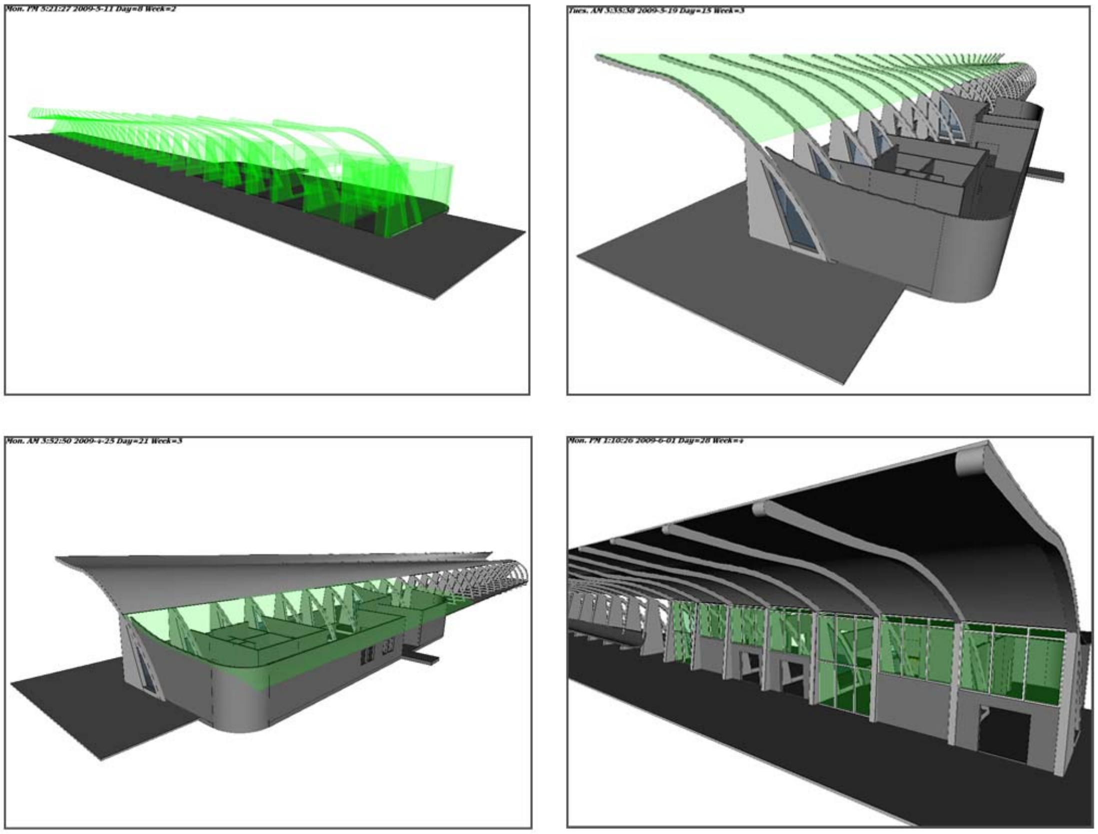


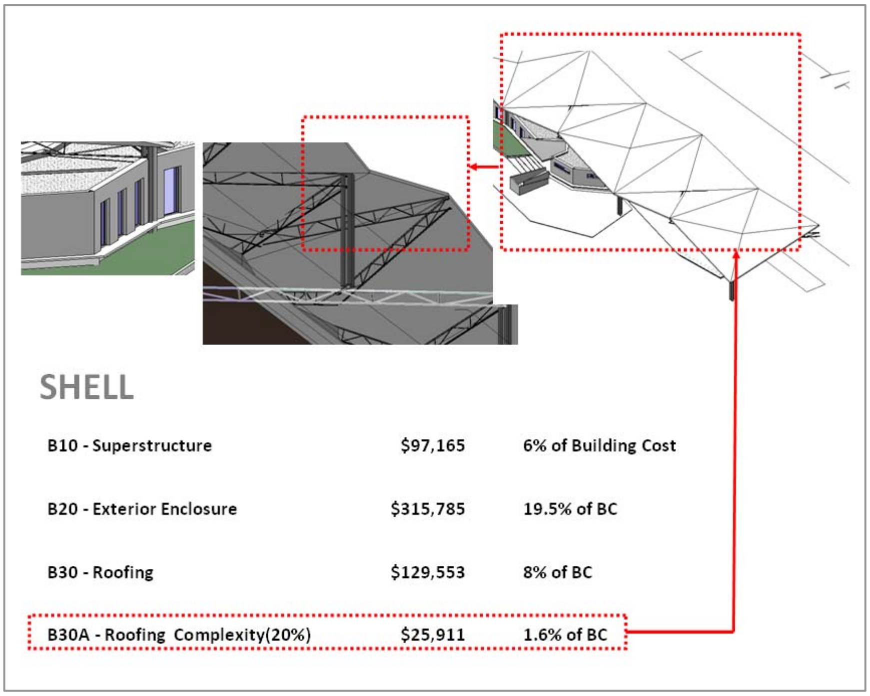
Figure 5.35: 4D Model of a design alternative from the second case study. The model belongs to the third week integrated sessions

Results suggest that creation and utilization of 4D BIM models were convenient and valuable as proactive methods for solving the problems of construction and procurement processes during the early stages of design. Use of 4D BIM models and 4D visualizations helped frontload the project processes with reliable information, and increased the depth and efficacy of communication between architectural design and construction management students in the early stages of an integrated design process.

5.2.9 Building Cost Control

One of the emerged issues with the cost control was the problem of quantity take-off during the conceptual development process. Although the models possessed an extensive amount of building components based on generic models, it was hard for the construction management team to pick the appropriate component from the RS Means cost data. In order to solve the problem floor area based cost framework was introduced. The simplicity of the framework with predefined Excel spreadsheets streamlined the process and provided reasonable feedback for cost control. Nevertheless construction management teams experienced slight difficulties in grasping the content of conceptual design alternatives for the creation of reasonable cost estimations. Observation logs show that at least two collective assessment sessions had addressed the major problems in the cost estimation results.

Another issue in cost estimation procedure was the incorporation of design complexity into the cost framework. Area based cost calculations provided an overall scheme for estimation; however, various design alternatives included complex canopy forms and non-generic building components that are not accurately estimated using the floor area approach. With feedback from the instructors, CM teams devised quick solutions by examining design decisions and putting additional items into the cost estimation framework. Figure 5.36 shows an example for custom designed roofing panels and the proposed structural system and the addition to the overall cost estimation.



SHELL

B10 - Superstructure	$97,165	6% of Building Cost
B20 - Exterior Enclosure	$315,785	19.5% of BC
B30 - Roofing	$129,553	8% of BC
B30A - Roofing Complexity(20%)	$25,911	1.6% of BC

Figure 5.36: Example for cost estimation according to the complexity level of the canopy system

The cost estimation data suggests that students had different approaches to control the cost. Contrasting approaches were to be very conservative during the process or use a flexible cost framework and attempt to optimize in later stages. Following charts from the case studies illustrate the designed indoor and outdoor area amounts and conceptual cost estimations. Results show that design teams were able to control the cost within the acceptable ranges. More detailed designs led to increases in the estimated building costs. Although the contingency portions were decreased in the final stages, design refinements inevitably added cost for specific design features, particularly with the customized components in the building envelope. Nevertheless the exercise showed the possible incorporation of the cost dimension for decision making in the studio using the information from the shared BIM models (Figures 5.37 - 5.39).

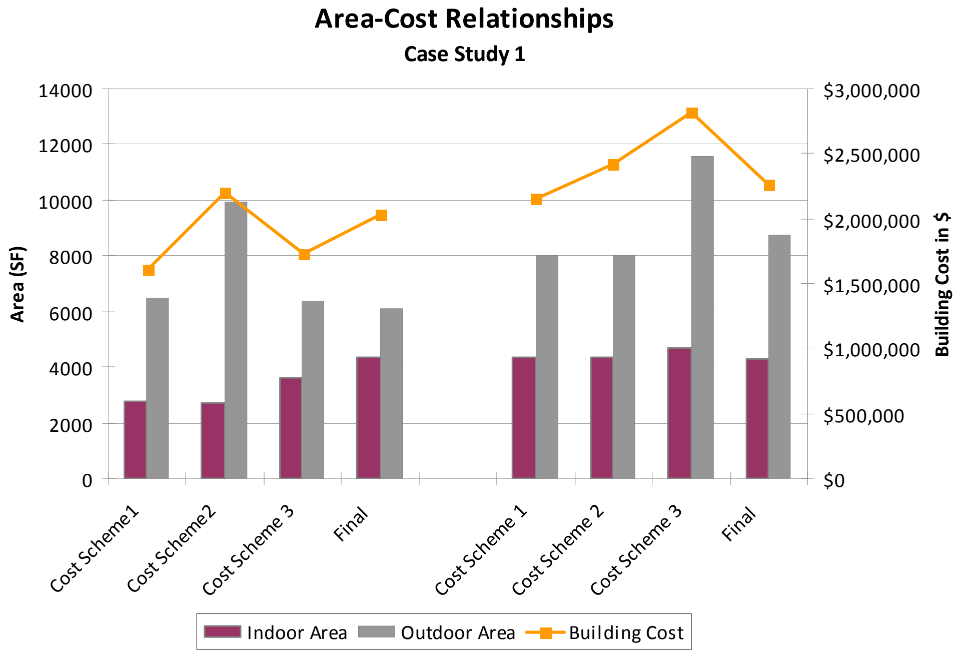


Figure 5.37: Area and cost relationships, Case Study 1

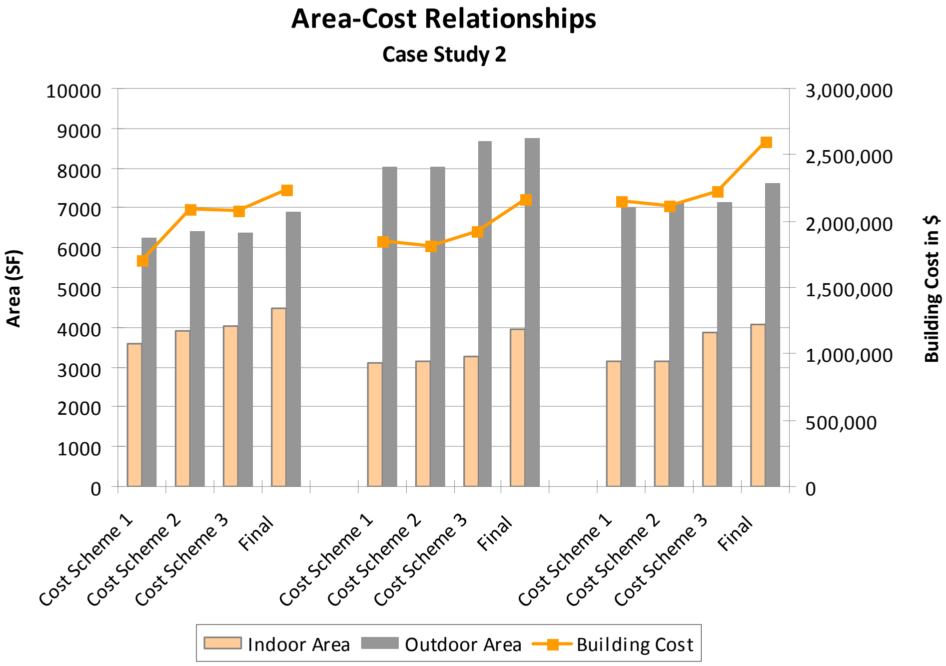


Figure 5.38: Area and cost relationships, Case Study 2

Figure 5.39: Area and cost relationships, Case Study 3

5.2.10 Structural Systems and Integrity

Through the use of the BIM the structural systems were designed on micro and macro levels. A structural system concept was discussed and immediately created as a BIM model. Designers could make macro level structural decisions, such as cast in place concrete vs. steel frame structure, and get immediate visual and spatial feedback. The feedback loop produced more detailed information, such as plausible footing designs, exact member sizes for desired spans, bracing requirements, and identification of areas that might require special attention or detailing. Designers were then able to assimilate this information and make micro level design decisions. This process afforded the designers an opportunity to see how micro and macro level decisions affect each other, i.e., how the selection of a certain structural system necessitated certain details that may or may not be desirable for the given design solution. Several instances included the design of the structural system using parametric components. These examples showed that use of BIM tools with quick component creation enabled students to merge their form design approach with structural design intent. Figure 5.40 shows the structural BIM model and details with parametric structural components.

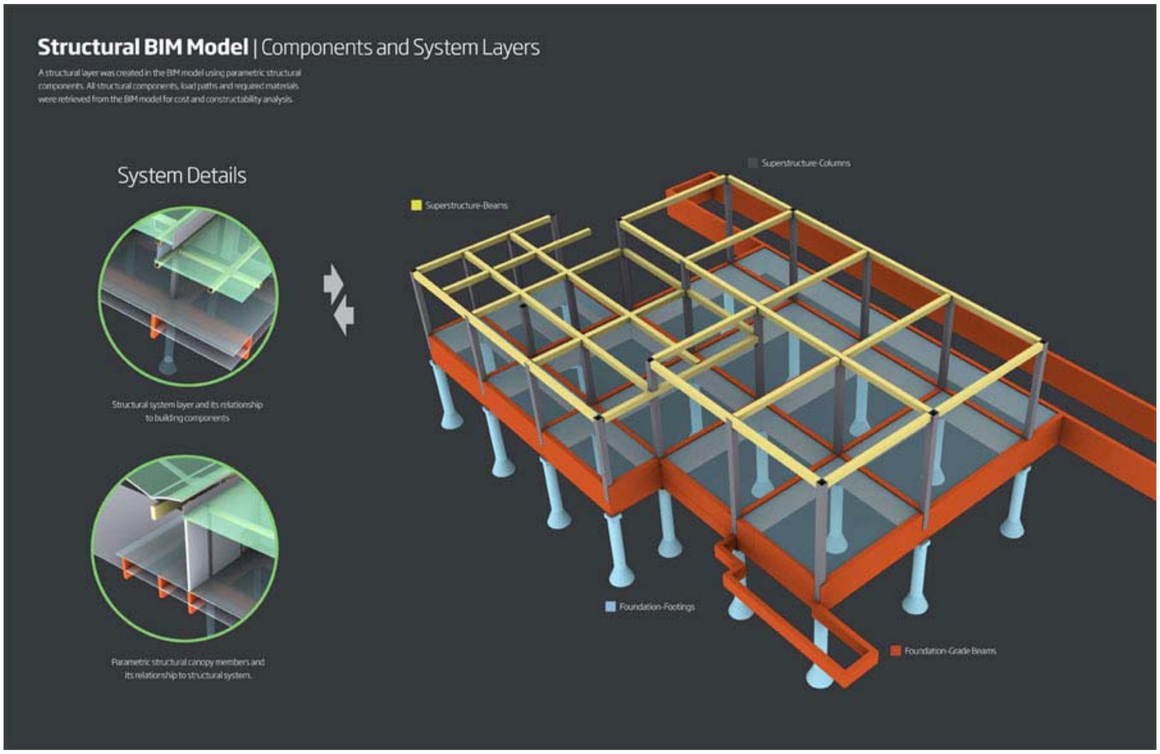


Figure 5.40: Structural BIM model of a final design alternative

5.2.11 Final Projects and Content

Final projects included wide-range information about the building form and performance. Presentations were comprised of both analog and digital material for comprehensive evaluation. Case studies returned a huge collection of process information and performance data for assessment.

Results of the case studies support both theoretical and practical conclusions and invite further exploration of integrated studios. Case studies demonstrated the potentials of performance-based and integrated design processes for educational purposes as documented in the practice world. For effective learning in the integrated studio, deprogramming of students knowledge was necessary. Instruction in design methods helps overcome a natural tendency to cling to old patterns of behavior. With new knowledge of BIM and IPD, students were able to design and evaluate building alternatives considerably faster than with conventional studios. In contrast to the conventional studio process that would require weeks for developing a scheme, by using the proposed integrated studio model a design alternative can be conceived, documented, and analyzed in four to six hours. Table 5.5 illustrates the number of alternatives, domain models and elapsed time for assessment procedures.

Table 5.5: Accomplished tasks and time table for the case study projects

Case Study 1

iteration	architectural	structural	cost/schedule	energy	daylighting
Base Case	2-3 Hours	1 Hour	1 Hour	0.5 hour	3 Hours
Week 1	5 Hours	1-2 Hours	1-2 Hours	2 Hours	4 Hours
Week 2	7 Hours	1-2 Hours	1-2 Hours	3 Hours	4 Hours
Week 3	8 hours	2-3 Hours	1-2 Hours	2 hours	4-5 Hours
Week 4	4 hours	2-3 Hours	3 Hours	2 hours	4-5 Hours
Accomplishments	**9 alternative BIM models**	**2 structural models** **w/foundation** **w/superstructure**	**8 cost breakdowns** **7 4D model/animation** **detailed schedules**	**22 Runs with domain models w/design & material alternatives**	**6 Simulations**

Case Study 2

iteration	architectural	structural	cost/schedule	energy	daylighting
Base Case	2-3 Hours	1 Hour	1 Hour	0.5 hour	3 Hours
Week 1	7 Hours	1-2 Hours	1-2 Hours	1 Hour	3 Hours
Week 2	7 Hours	1-2 Hours	1-2 Hours	3 Hours	3 Hours
Week 3	6 hours	2-3 Hours	1-2 Hours	2 hours	4-5 Hours
Week 4	4 hours	2-3 Hours	3 Hours	2 hours	4-5 Hours
Week 5	4 hours	2-3 Hours	3 Hours	2 hours	4-5 Hours
Accomplishments	**7 alternative BIM models**	**5 structural models** **w/foundation** **w/superstructure**	**13 cost breakdowns** **6 4D model/animation** **detailed schedules**	**16 Runs with domain models w/design & material alternatives**	**6 Simulations**

Case Study 3

iteration	architectural	structural	cost/schedule	energy	daylighting
Base Case	2-3 Hours	1 Hour	1 Hour	0.5 hour	0.5 hour
Week 1	5 Hours	1-2 Hours	1-2 Hours	1 Hour	1 Hour
Week 2	5 Hours	1-2 Hours	1-2 Hours	2 Hours	3 Hours
Week 3	7 hours	2 Hours	1-2 Hours	2 hours	2 hours
Week 4	6 hours	2 Hours	2 Hours	1 Hour	2 hours
Week 5	5 hours	2 Hours	1 Hour	1 Hour	2 hours
Accomplishments	**10 alternative BIM models**	**3 structural models** **w/superstructure**	**10 cost breakdowns**	**22 Runs with domain models w/design & material alternatives**	**22 Computations from GBS**

During the design sessions and discussions, students were challenged to use a broad range of knowledge from their previous classes such as systems, structures and previous design studios, thus achieving an integrative function in the overall curriculum. Students' responses and observations suggest that evaluations were richer than in conventional studios, by including cost, construction schedule, energy consumption, daylighting performance, structural analysis, and LEED certification, as well as spatial and visual sufficiency. Parametric modeling was a critical and powerful augmentation of BIM that permitted rapid development of design alternatives and the assessment of their performance. The media used for design had a positive impact on the facilitation of the integrated design process.

Issues and challenges encountered during the study involved the establishment of interoperability framework, students' knowledge level in downstream aspects of design, skills for parametric modeling, and advanced operations for the creation of domain models.

Observations show that formation of BIM equipped integrated teams relied heavily on extensive social communication. The effectiveness of the collaborative effort significantly increased when students were socially engaged during the course timeline. Students not only shared their ideas about the design problem, but also their viewpoints about design, process and other aspects of the profession in small gatherings, dinners, and coffee breaks between design sessions. Many major problems about the project or use of BIM tools were solved in these breaks and gatherings. Breaking the habits of the students was the toughest part of the case studies and it was accomplished through lectures, pizza, and persistence.

5.3 Post-study Survey

The post-study survey documented the changes in attitudes, experiences, learned concepts, and the student viewpoints after the case study experiment. Students gave in-depth feedback, made comparisons between the case study and conventional studio, evaluated the process, as well as provided suggestions and future directions. Results of the post study surveys suggest significant similarities in fundamental aspects of the integrated design process and the use of BIM, as well as minor differences due to case study settings, setups and experiences.

Students were asked to write down the concepts they have learned and elaborate on their experience. Responses demonstrate substantial level of understanding and receptiveness about IPD and BIM. Students emphasized the comprehensive nature of integrated studio and corresponding skill level of the architect. Unlike the pre-study survey, students' approach to BIM changed to a process for leveraging information for performance based design. Students also provided sound arguments about BIM tools as a collection of interoperable software. The following statements are taken from student responses:

I learned a method for producing energy efficient, cost effective, constructible buildings by using a team of consultants who are actively engaged in the design process. It requires a different way of thinking about the design process. If presented with a work situation such as integrated practice, I will be able to adapt the mode of working based on this experience.

Study Participant, M.Arch. 2nd year

Inter-connectivity of design. The design that we create as architects intersect with many other disciplines making it a very interactive process. And learning about the process is very difficult if one does not have a good experience. This project made a situation similar to the real world making it more like a trailer to a good movie.

Study Participant, M.Arch. 2nd year

Collaboration, Interoperability and different aspects of good architecture. We can work as individuals and create a design that looks good, but by following this process we can work in a group to create good architecture which envelops all the various aspects of architecture like - design, structure, HVAC, sustainability and above all practicality etc. The single central BIM model allows all parties to have real time information that allow for a greater depth of information to be applied to the design.

Study Participant, M.Arch. 2nd year

> *Sharing knowledge with professionals teaches us a lot of new concepts and how a basic design can be converted in to architecture. It is essential for architects to understand the various limitations of all the elements that they use in their design, this platform as a successful way to enhance the student and professional module of peer learning.*
>
> ***Study Participant, Ph.D. Student in Architecture***

5.3.1 Effectiveness of the Study

The second part of the survey was intended to measure the effectiveness of the study from students' point of view as given in the figure 5.43. Students in all three case studies reported that the study was effective for learning the fundamental concepts of BIM and integrated practice. The average rating values confirm the effectiveness of the pursued strategy for intensive instruction for BIM and IPD prior to design process.

As shown in the Figure 5.41, interoperability emerged as the concerned topic in terms of learning. Challenges for finding the appropriate data standards and establishment of the interoperability framework during the case studies had an impact on students' ability to grasp the interoperability concept. Nevertheless values and responses in open ended questions confirm the awareness of interoperability for IPD and BIM.

Due to the emphasis on energy use and environmental aspects, students reported that the study was highly effective for learning energy simulations using BIM and incorporating them to design decisions.

Rating averages across the case studies display differences in factors like coordination, information exchange and constructability analyses. Variations of case study settings, number of participants and the students' skill set may have affected the rating coordination and collaboration. Students also stressed the problems in constructability analyses since they had very limited experience on building cost and scheduling from their previous studio courses.

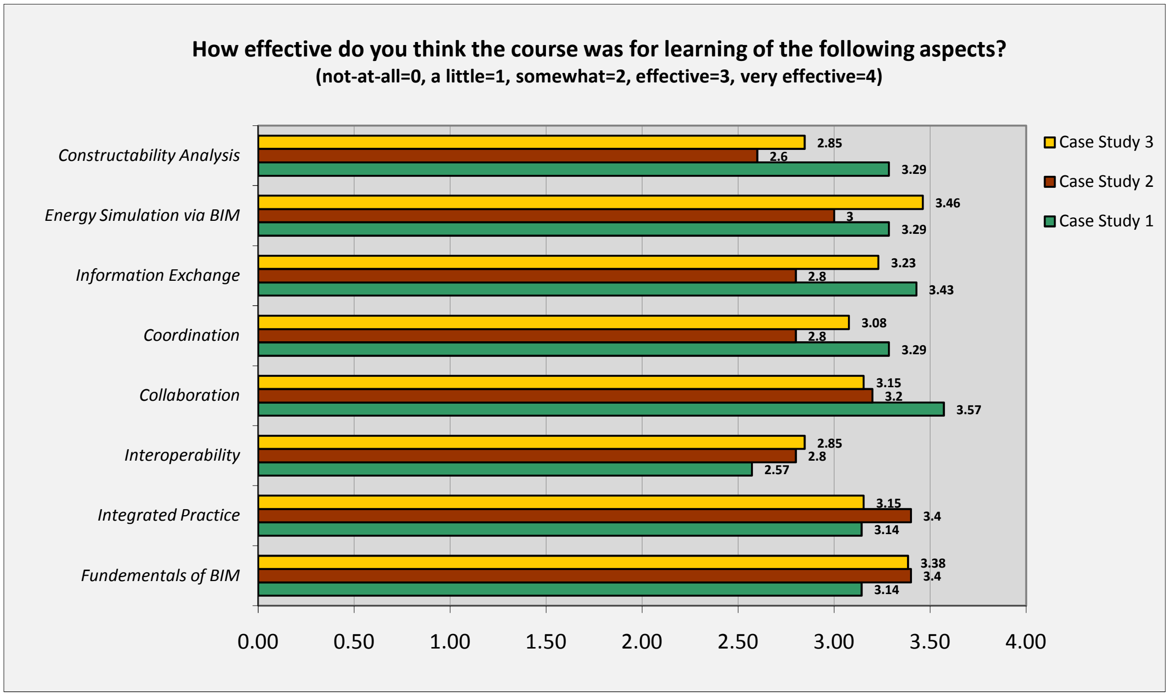


Figure 5.41: Rating averages for the effectiveness of the study

Responses to open-ended questions corroborated the findings for the effectiveness of the educational approach. Students were asked to be more specific on the effect of BIM in the following aspects:

Interdisciplinary Collaboration: Students emphasized collaboration as the most essential aspect for learning of IPD using BIM. Students grasped the importance of interdisciplinary collaboration in order to achieve high performance designs, as well as the core of integrated practice. However, students confirmed the difficulties during the early stages of the case study. According to students, BIM was the vehicle for collaboration. Students stressed the consistency in design and performance goals, and hierarchy of the integrated team formation, and roles as fostering the efficiency of collaborative process. Challenges included the software interoperability, and leadership and scope of the design task. The following statements are extracted from the students' responses:

> *Essential! It's a part of the integrated design, and the only way towards sustainable buildings design. Consistence with the principles and design goals, the schedule, the budget, etc., cannot be done without intense collaboration. After learning using the BIM tool for information exchange, it was more important for me to create the most appropriate data set for my consultants*
> ***Study Participant, M.Arch. 2nd year***

> *The BIM-enabled process works effective within a set hierarchy, especially if the decisions are made with mutual respect. All the disciplines need to collaborate to create the product, but it is also important to keep some challenges so as to create the need for progress. For me, form vs. technical performance could be addressed more. The balance between technical expertise and formal expression can be resolved with the collaboration using consistent data from the BIM models and simulations.*
>
> ***Study Participant, M.Arch. 2nd year***

> *It was somewhat hard for me to change my designing habits and get used to work with consultants for my design project, I sometimes felt that the amount of input was bit overwhelming, especially in the beginning.*
>
> ***Study Participant, M.Arch. 2nd year***

> *BIM became the vehicle for the collaboration. It allowed all of the involved parties work from the same, up-to-date file.*
>
> ***Study Participant, M.Arch. 1st year***

Design Learning: Students' responses showed that the case study drove them to learn and pursue a new way of design where they had to create and use consistent information about the design. According to some students this new paradigm can be seen as process based, pragmatic and goal oriented. Another major challenge reported by the students was the balance between expression of form and performance measures. This confirmed the early process observations of the students' tendency to make use of the conventional methods and to emphasize form. Reponses showed that BIM helped them to rapidly test a form alternative for performance and execute design cycles until both form and performance criteria were fulfilled. As intended in the case study framework, students reported that BIM reduced the intensive work for documentation and visual communication and gave students extended flexibility for design alterations.

> *The process could be an excellent way to learn a certain type of design method, but perhaps it can be labeled as pragmatic design. During the case study, I had to consider things beyond form that are more neglected in typical studios like impacts of my decisions on building cost and energy use.*
>
> ***Study Participant, M.Arch. 2nd year***

> *I have had similar opportunities without the "state of the art" tools like BIM and the software's implemented. After implementation of these tools, I'm 100% positive about the benefits not only in the final result, but in the efficiency and effectiveness of the whole design and analysis process.*
>
> ***Study Participant, MSCM. 1st year***

> *BIM use allows the instructor and student to use more time on the design and less the craft of communication.*
>
> ***Study Participant, M.Arch. 2nd year***

> *BIM allowed for a large amount of analysis to be done easily and regularly. This helps in making informed decisions the building performance.*
>
> ***Study Participant, M.Arch. 2nd year***

> *It all adds up to high quality design presentations happening in a few days with only a couple of people, instead of weeks.*
>
> ***Study Participant, M.Arch. 1st year***

Communication /Information Exchange/Documentation: Students repeatedly stressed the importance of a working, intuitive, and simple interoperability framework. Responses show that interoperability and effective communication came out as major issues since students had very limited experience in these subjects. Combined with the challenge for learning the new design process, establishment of effective communication channels required some effort. The following statements indicate that the BIM consultant helped them to ease the communication and data exchange.

> *The communication could be better between design teams and consultants, but it was OK. Information exchange was OK. The interoperability issue demanded some time and effort (export/import/correct models previous simulation).*
>
> ***Study Participant, MSCM. 1st year***

> *BIM use increased my understanding of what is being communicated and thus how to communicate BIM use broadened my understanding of what kind and how information is exchange*
>
> ***Study Participant, M.Arch. 2nd year***

Decision Making and Assessment: According to students, BIM use drastically reduced the time for making design decisions. Students stressed the importance of making design decisions and prioritizing the performance variables and construction data. Students confirmed that BIM facilitated the collaborative assessment of the design alternatives and enhanced the confidence level for collaborative decision making with consultants, as described in the following quotes:

> *BIM use surely helped in design assessment. It not only gave workability to the design. But also helped to strike a balance between the designers' sensibilities, the project requirements and the consultants' practicability."*
>
> ***Study Participant, M.Arch. 2nd year***

> *There were several instances where input and evidence from lighting, energy, structural, and construction consultants made decisions much easier. And, because the turnaround time on the analysis was so short, it definitely reduced decision making time."*
>
> ***Study Participant, Ph.D. Student in Architecture***

> *Decisions are taken more rapidly, as most of the information is available from the day one. There is less need of redesigning and addendum on a later stage of the design process.*
>
> ***Study Participant, M.Arch. 2nd year***

Project Scope: Responses illustrated that the used tool set had impact on the scope of the design project as intended in the proposed pedagogical framework. Accessibility of the performance information and the incorporation of parametric modeling extended the scope of the studio project. Students indicated that information from BIM tools provided them better understanding of the scope of the given design task with simultaneous connection between upstream and downstream aspects of design.

> *BIM use allowed me to get a better grasp of a projects scope because understanding project scope has a direct link to understanding the tools used to produce and convey the information.*
>
> ***Study Participant, M.Arch. 1st year***

5.3.2 Process Experience

Students described their experiences during the case study process from early phase to final presentation. Confidence levels and priority of design aspects suggest that the case study caused sharp changes in students' views compared to pre-study survey responses. Following figures illustrate the priority levels of given design aspects during the case studies. Students confirmed the holistic design approach of the case studies. Priority levels indicate that students approached the process using information for both upstream and downstream aspects of architectural design. Result also point out the differences of emphases in case studies. For instance, students preferences in the first case study was to achieve a high performance building with conventional forms yet the second case study intended to achieve expressive forms by using parametric capabilities of BIM software.

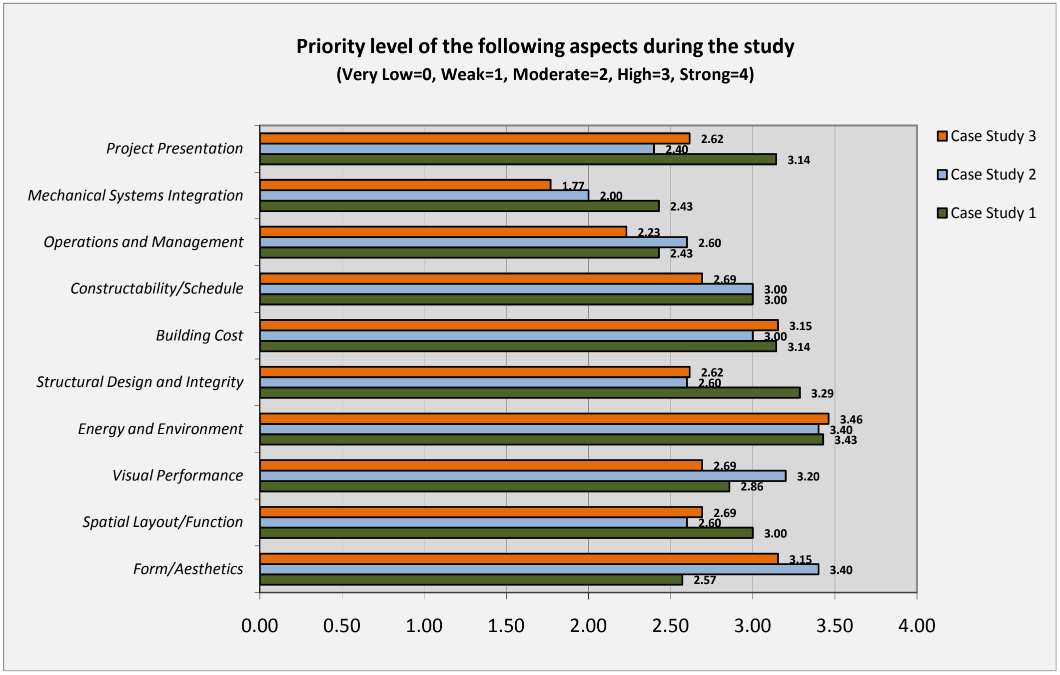


Figure 5.42: Priority levels of the design aspects during the case studies

Students also reported that the use of base case helped them to grasp the interconnectivity of design decisions. They used the base case as a prototypical reference for determining the possible impact of design decisions on various design aspects.

> *Pre-design remained similar to the traditional method of collecting information regarding the project and determining necessities, adjacencies, and space requirements. While some conceptualization was attempted first, the process was pushed to use a "base case" scenario and adapt that based on a concept after a detailed analysis could be performed. Because a rough representation of the pre-design information can be made, we could quickly see how our design decisions affect various elements.*
>
> ***Study Participant, M.Arch. 2nd year***

Confidence level of students during the decision-making process had variations due to different emphases on several design aspects. In-depth interpretation of the rating averages suggests that the interconnected nature of design aspects created a chain effect on the confidence levels. In the first case study, the emphasis on energy use, structural integrity, and other downstream issues increased the confidence levels but the complexity had a slightly negative impact on formal expression. On the other hand, the emphasis on parametric forms in the second and third case studies returned acceptable yet lower confidence levels for the structural integrity (Figure 5.43).

Compared to pre-study survey, students declared significantly increased level of confidence in energy and environmental issues, constructability, building cost and operations and maintenance. Mechanical systems integration arose as an issue in all case studies. Students declared that mechanical systems integration stays in the limits of component selection and implementation in a lower detail level.

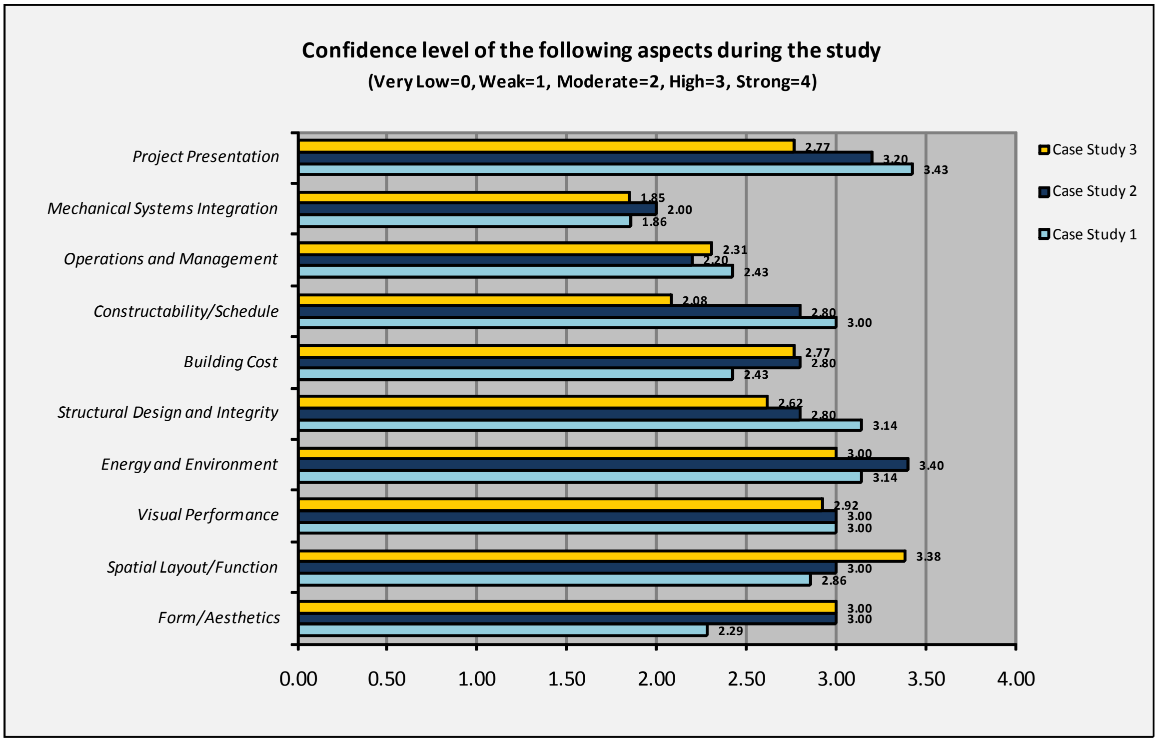


Figure 5.43: Students' confidence levels of the design aspects during the case studies

5.3.3 Self-Evaluation of the Case Study Projects

Students were asked to evaluate the outcomes of the case study regarding to the devised quality criteria. Responses suggest that students found the studio results strong and sufficient in terms of the major downstream aspects. Values for the first three quality criteria vary across the case studies since the approach and study settings were slightly modified to pursue different objectives for the final design. The only problematic topic was the mechanical systems integration, which was reported by students as a complex and time consuming task for the time limits of the case study process. Students demonstrated a consensus that the process returned adequate amount of visual material for the communication of different systems and formal content of the buildings (Figure 5.44).

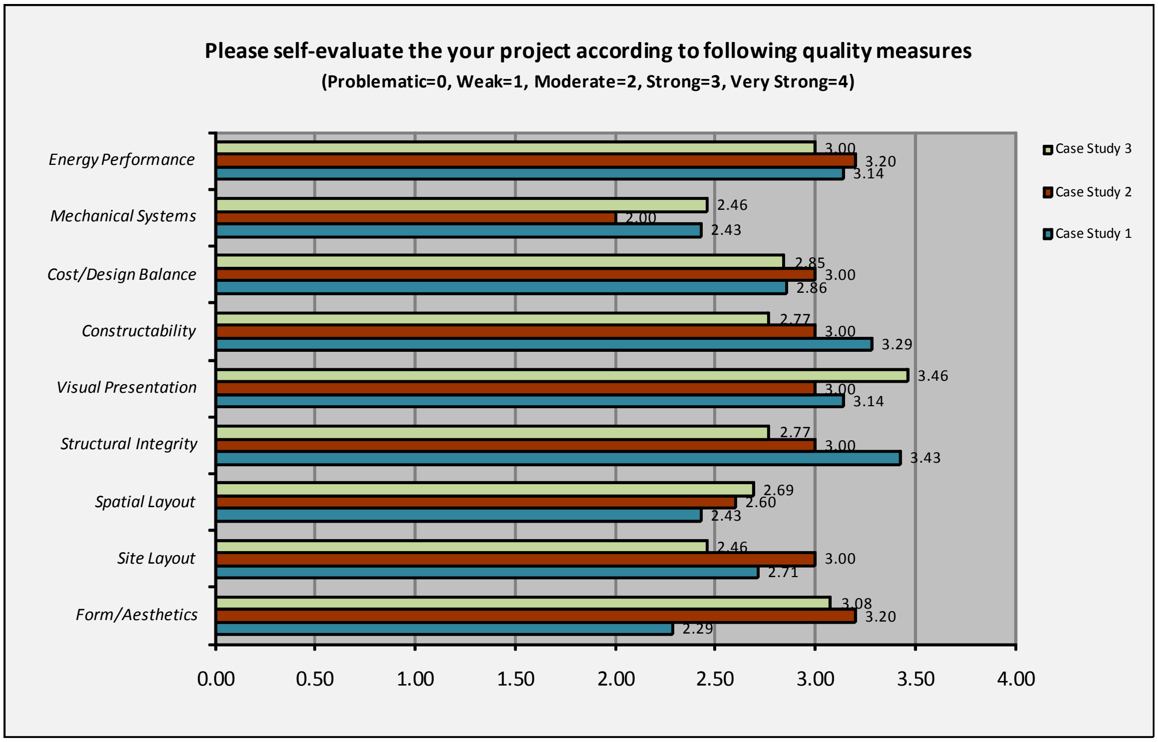


Figure 5.44: Self-evaluation of the case study projects

5.3.4 Comparisons to Typical Studio Experience

This part of the survey was intended to gain first hand comparisons of the proposed pedagogical approach to the typical studio paradigms. Responses to questions show that students felt that the impact of BIM use and integrated approach on form, spatial layout and site planning stayed within the limits of a conventional studio or was slightly better due to the use of 3D parametric components. Students favored the results of the study over typical studio regarding the downstream aspects and performance measures in all three case studies. Observations in all case studies were confirmed by the students who stated that the final results were richer in content by providing wide-range data about the building performance. Although mechanical systems integration was reported as a complex task with low confidence levels, students still felt that the results from the simulations and discussions on mechanical systems helped them understand more about this aspect, as compared to a typical design studio (Figure 5.45).

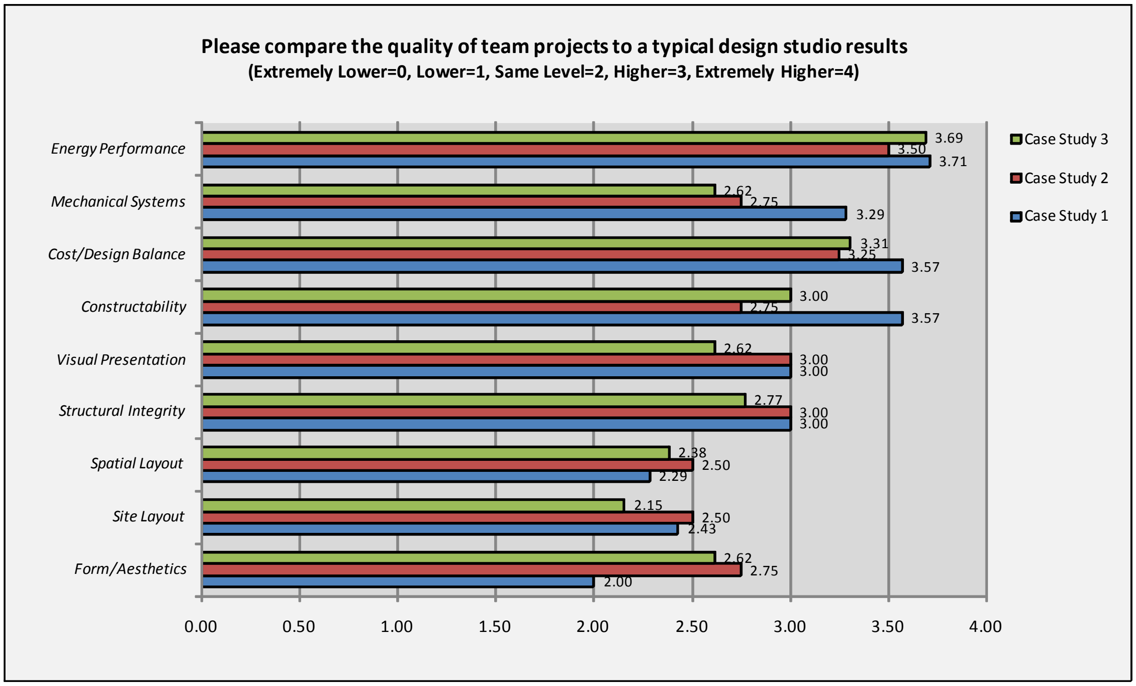


Figure 5.45: Comparison of projects to typical studio results

I learned the whole process of collaboration based on BIM. Actually, because current design studio just focuses on the design phase, it is hard to consider to other phases such as construction management, structure analysis and energy analysis. However, through this project, I can learn how I can consider the whole parts.

Study Participant, M.Arch. 2nd year

> *This is indeed the new way of architecture practice. It is a valued design process and it becomes difficult to learn these practical things in the regular studio. One can even take out of department courses to learn these things, but it becomes a challenge to integrate the various disciplines together.*
>
> ***Study Participant, M.Arch. 2nd year***

> *This model provides and opportunities for students to really get into a project, to pass the schematic level achieved by the majority of studios and really get into figuring out what it means to do architecture.*
>
> ***Study Participant, M.Arch. 2nd year***

> *It is much more complete a process than the typical studio process. I suggest that a course of this level become a full fledged studio option. However the design problems with larger scopes may result more problems in information exchange, creation of performance data and interpretation of the result with consultants. In my opinion, conventional studios can be transformed into an integrated studio but logistics issues, required expertise as I have seen in this study and the convenience of pursuing traditional methods may be the factors…*
>
> ***Study Participant, M.Arch. 1st year***

Students also reported various challenges and issues which they encountered during the case studies. Although the case study process provided creative interpretation of design objectives, one future concern was potential pragmatization of studio projects with BIM and IPD as opposed to a decent level of creative freedom existing in the conventional design studios. Another challenge was the expert level skill requirement of BIM software for the incorporation of complex forms using parametric design templates.

> *I found this experiment to be extremely interesting and beneficial. However, I feel this should be an offered course perhaps closely tied to the "Professional Practice and Ethics" course, or a choice of studios. There are design responses that need to push the envelope of current ideologies, methodologies, and technologies. At the moment, IPD can still achieve these goals, but BIM software has issues to accommodate the complex designs in a more flexible and intuitive workflow. In principle, the software could be very beneficial to large scale CAD/CAM operations that could make possible some of the crazier stuff.*
> ***Study Participant, M.Arch. 2nd year***

> *My observation is IPD presents a very effective method for performance based architecture. However It is equally important that the architect does not get carried away by the constraints of the IPD process and loses his creativity and design freedoms to comply with only pragmatic objectives. Using the experience from this study it is possible to be proactive on this issue for future design studios.*
> ***Study Participant, M.Arch. 2nd year***

5.3.5 Suggestions from the Students

Suggestions from the students highlight the content of the case studies and offer solutions for future experiments. The most common suggestion was to implement the case study in a larger studio context with expanded project scopes. Such implementation may increase the level of collaboration and quality of the process. A better interoperability framework and reinforced link between BIM tools and capable surface modelers may increase the understanding of parametric modeling. Such use of kit of parts framework prior to design may yield complex forms and constructible buildings with benchmarked performance.

> *Maybe if this project is spread over a longer period it would make the solution satisfying in all aspects personally think giving more time to everything will optimize the design and will eliminate the local prejudice about design sacrifice in integrated practices*
>
> ***Study Participant, M.Arch. 2nd year***

> *Most suggestions will require that this experiment be repeated several times. First, adjust the scale and budget of the projects from large low budget, to large projects with large budgets, and the same for small projects. Attempt to use designs that are based on geometry exported from other 3D modeling programs. Then see if it is possible to generate a kit of parts as specifications using BIM data. In other words, focus more on the parametric and specifications output.*

> *There is loads of room for integrated practice here, which would benefit greatly from cross collaboration with mechanical engineers, chemical engineers, civil engineers, and robotics engineers. It may be difficult, but find a real project and run the process as a studio. Get real world data results that do or do not support the hypothesis of this process.*
>
> ***Study Participant, Ph.D. Student in Architecture***

Post-study survey results indicated that implementation of proposed pedagogical approach was well received by the students. Responses show a high level of comprehension of the concepts regarding IPD and BIM. When compared to the pre-study survey results, it is evident that students' knowledge level about integrated design, interoperability, parametric modeling, and performance simulation has increased. Responses confirmed that the scope of the design process was extended; frontloading of the process was received by students; and levels of confidence for both upstream and downstream of design were improved.

5.4 Design Review, Focus Group Discussion and the Evaluation Survey

Case study projects were evaluated by a large group which consisted of studio instructors and Ph.D. students. A total of eight jurors participated in the focus group discussion and the evaluation survey. Similar to other research stages, focus group discussion and surveys were employed. Case study results, prototype pedagogical framework, and the process of the study were thoroughly assessed during the focus group discussion. The proceeding survey included the evaluation of the study process, comparisons and further suggestions.

Results of the case study led to the discussions on design curriculum, changes in the design practice, existing studio practices, and various dimensions of architectural production processes. Findings of the research effort prior to the evaluation stage were triangulated and articulated with the results from the evaluation survey and the focus group discussion.

Participants commented on the proposed model and its components like technology, human resources and the scope expansion as opposed to the typical studio content and roles. Participants reached a consensus supporting the involvement of experts and consultants. However they also noted this as a possible challenge for pursuing the process of the proposed model. Some participants pointed out the inapplicability of the proposed model under the condition of one studio master and low level use of BIM technology and methods. Comments underlined the advantages of the whole setup of the studio, such as frontloading of the studio with the explicit performance criteria, introduction of theoretical and practical knowledge for BIM and IPD as well as the emphasis on performance based design.

> *Although we have a large number of research students for the consultant roles, this model requires meticulous planning and human resources. As a policy you*

want to make sure that you institutionalize some form of remuneration for somebody. I mean you can not make a policy rely on someone's goodwill to do something free. So to really do it, it seems you have to have a team of people…may be not fulltime in the studio but experts that people go to…

Graduate Level Studio Instructor, Practitioner

I can see this working very well if I had a team of two MS students and I had another person who is a friend of mine in construction and estimating. They will come in there day one and it will work fine or work just like you guys did it…but with just one instructor it could never work and that's the whole problem…and so you have students that essentially use BIM for that very low order like another way of modeling something…Unfortunately that's problem is that the way our studios are setup as you know… but I think the integrated studio our seven section at once, we have to look at as a department for how we can leverage this model…

Graduate Level Studio Instructor, Practitioner

Looking at this study and the comments have been made here, I have been thinking about a model is to have a some kind of a central hub with experts and consultants in it…that may be staffed by MS and PhD students with access to the hotline out. So students who kind of have these problems nowhere else to go get the answer will go back and keep working…So kind of a resource hub… that's

> *probably be the missing ingredient we would want to go with the integrated studio for example in our fourth year. Well, we have six or seven section of that…*
>
> ***Graduate-Undergraduate Level Studio Instructor, Practitioner***

> *This is the only way I can conceive us delivering a project like the Galapagos Research Station… is with a team of undergraduate studio students but in conjunction with more expert MS and PhD students that could follow a project for more than more one studio even…and each studio involvement you need to have that vertical connection to pursue that process.*
>
> ***Graduate-Undergraduate Level Studio Instructor, Practitioner***

> *There is an example how this would have helped on the Costa Rica Center. The teams came up with the design of Costa Rica Center broke the budget by the factor of three or four…so just retaining any though of the original concept was a big challenge while staying in the budget. So this would be very useful to project like that…I mean projects which have a real world component…well the advantage of frontloading…Getting the input in the conceptual level would have been fantastic rather than the project architect stage.*
>
> ***Undergraduate Level Studio Instructor, Local Firm Owner***

The participants highlighted the value of the model and the BIM technology as the catalysts for integrated education. Participants underlined the shortcomings of the conventional studio model in order to implement information-driven and performance-based design processes. Discussions and opinions were significantly aligned with the findings from the literature survey and focus groups. Changing dynamics of the society, increasing responsibilities of the architects, and the impact of IT on project delivery methods were all stressed as the drivers for change in education. Students also emphasized the importance of relationships between the proposed studio model and the novel project delivery methods as opposed to the common goals and objectives of the traditional design studio. Participants also stressed the added value of the model for its references to the major courses in the curriculum. The students found the content of the given design problem to be compact and reasonable for the objectives of the exercise but noted that it can represents a future concern for more complex building programs.

> *In a typical studio you don't have any ability to credibly engage any of that whole first series of things you are talking about…any of those parameters like cost, energy, daylighting, sustainability… except with a conceptual view with no data. You just have almost of an intuitive level…because there is no data, no analysis to back up decisions…well may be you can do it without using the software which are tedious and lengthy…*
>
> ***Graduate Level Studio Instructor, Practitioner***

I would just call this building intelligence into your design; you can design all kinds of stuff as you know it does not mean anything unless you have a reality factor.

Graduate Level Studio Instructor, Practitioner

So, I think the inherent educational value from purely design point of view is that this enables students to spend more time on design innovation. I mean architectural design improvement. Because you are dealing with a comprehensive processes and you cope with all that technical stuff using software and add all of those on to our core objectives in the design studio.

Studio Instructor, Academic Administrator

It's closer to the real life model of project delivery than the studio was traditionally which had to just focus on things like aesthetics, proportion, scale, texture… now you can add all this all to it… and obviously the fact you can go iterations so quickly enables you to refine things. If you can do things in 4 hours rather than 4 weeks then you can do lot more refinements…

Graduate Level Studio Instructor, Practitioner

If you add a little bit architectural history here and you got the whole curriculum in one semester.

Undergraduate Level Studio Instructor, Local Firm Owner

> *But at the same time you deliberately chose a very simple, almost a simplistic program. If you were to engage more difficult complex program like a school or hospital then you would not be able to cycle through that so quickly…because engaging of the program and understanding it functionally would a be process…*
>
> ***Graduate-Undergraduate Level Studio Instructor, Practitioner***

Although the case studies encompassed a broad range of design aspects for professional level studios, focus group participants also commented on the modularization possibilities of the proposed model for early stages of design education. Opinions led to the reductionist strategies that may focus on particular capabilities of BIM - like modeling or energy simulation- and various processes of integrated project delivery which may be incorporated to the undergraduate levels. The accuracy and the reliability of the information from the simulations were discussed but the idea of relativistic improvements through the design iterations such as energy use and daylighting had common support from the participants. Concerns for information overload were also noted which may obstruct design thinking:

> *The quality of the information might not be up to credible to real life standards but that's ok because you're going through the process…so the types of things that you have to look at to really do a project, they will already accept that it is not going to be a hyper-detailed cost estimate or a completely reliable energy model. So creation of information even in this level is important to show them*

> *how to design with various types of input. But it is also possible that you can get caught up in the weeds like only information creation and not get out of the weeds actually have design excellence which stands up as design itself…*
>
> ***Graduate Level Studio Instructor, Practitioner***

Software training and software learning curve versus design studio process was reported as a concern for the proposed model. One major suggestion was to discard any form of software training during the studio as opposed to incorporation of software learning combined with the actual design process.

> *The problem I have with my studio students is that they are coming from very different places with no experience on BIM…and they design projects with whichever tools they feel comfortable with…so there is a danger that studio may probably turn into a mere BIM software training*
>
> ***Graduate Level Studio Instructor***

> *Most of the undergraduate student in these days regardless of where they are coming they are getting the expose to these new technologies. The dynamics of the studio population is changing radically…*
>
> ***Undergraduate Level Studio Instructor, Local Firm Owner***

Survey results demonstrated significant similarities between the student post study survey results in terms of quality of the case study products and comparisons to the typical studio. Values for the quality variables showed that the evaluators found the process in adequate quality level for the typical quality measures. Upstream variables were close to the strong levels. Evaluators commented on the strict time limitations of the case study coupled with the learning curve for the new performance-based process as the possible issues for more flexible form exercises. Aligned with the focus group comments and opinions, variables like energy efficiency, cost, structural integrity and constructability were rated with significantly high values for successful incorporation into the designs. Although simulations involved preliminary preferences for HVAC system alternatives, mechanical systems integration was noted as an emerging issue because of its complexity. It is suggested that mechanical systems could be addressed in more depth by using pre-defined system components and templates. As a very obvious outcome, the quality and the rich content of the visual outputs of the design process were confirmed by the evaluators (Figure 5.46).

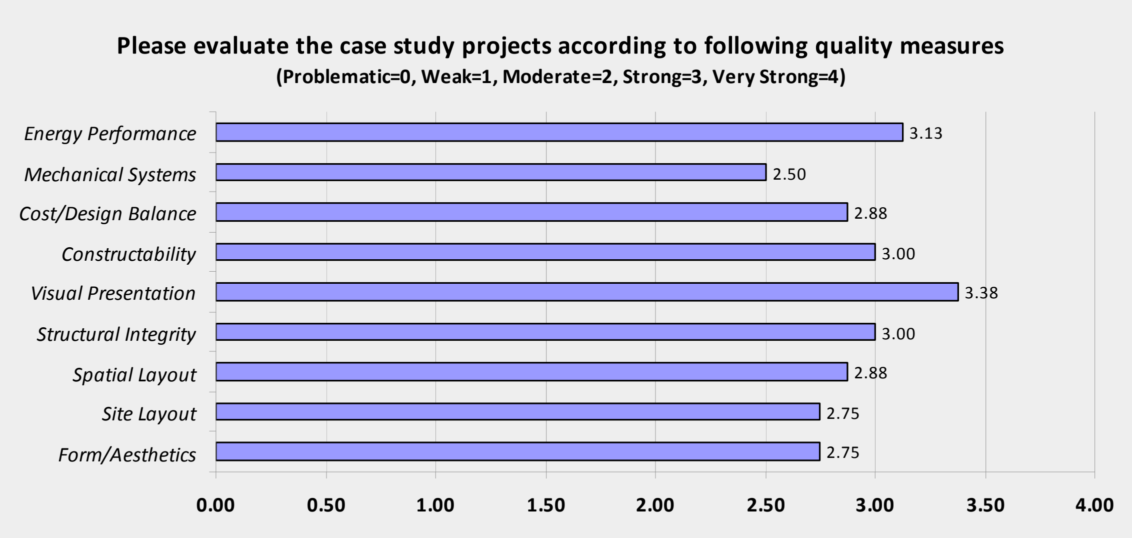


Figure 5.46: Expert evaluation of the case study projects

As shown in Figure 5.47, the focus group participants favored the process of the proposed framework or its distinct advantages for the teaching of emerging issues of architectural design. Participants also confirmed that the results demonstrated a substantial level of design maturity in terms of form aesthetics, materiality, site layout, and spatial configuration; however, they were not distinctive in comparison with the typical studio outputs. Other than these variables, evaluators were clearly in favor of the case study process and results as compared to the typical studio. Downstream issues like energy performance, constructability and cost, and design balance were rated significantly high, which confirmed the effectiveness of the model and pedagogical intent of the study.

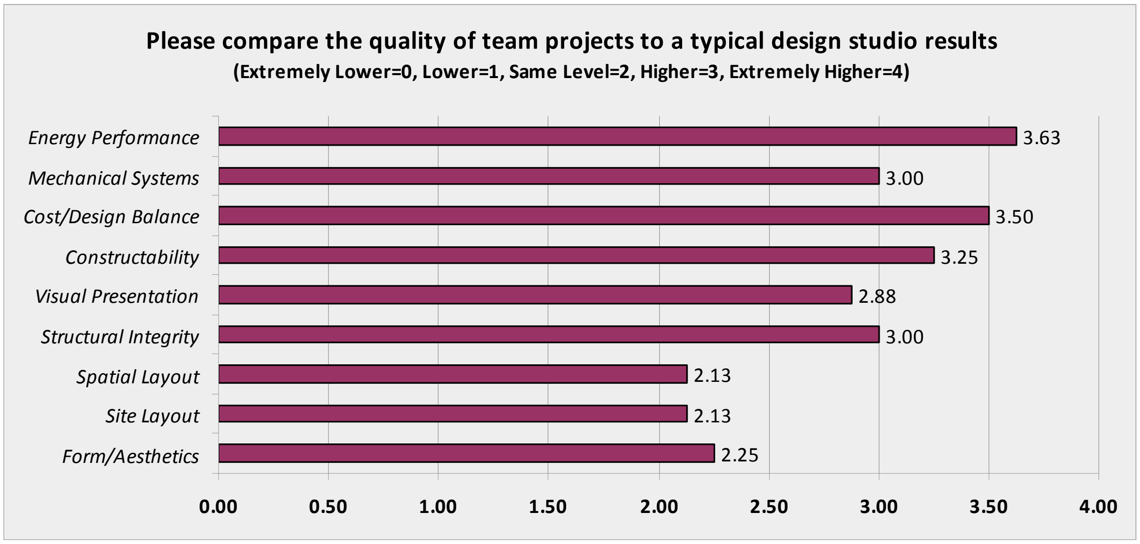


Figure 5.47: Comparison of the case study projects to the typical studio

Open-ended questions in the survey included insights and comments about the proposed model, BIM use, and suggestions for further improvements. Participants compared and contrasted the potential benefits of the study and challenges for implementation in graduate and undergraduate level studios. In terms of the comprehensive approach to the performance based design, BIM use and informed decision making were given as major benefits of the study. Resources, required expertise, and current educational practices were listed as potential challenges.

> *I saw this exercise as a very useful class in integrated design techniques, as they are taking place in industry. As other colleagues mentioned, this is an important set of tools that are required to attain design excellence. The additional ingredient is what I would define as architectural thinking in a larger context*

and a flexible timeframe. It is important to recognize that the profession of architecture has an educational component - university - and a training component - internship. Though the boundaries between the two are somewhat blurred, we in the university, as you recognize, can feel comfortable dealing with the realm of theory as we educate architects.

Anonymous survey response

The study demonstrates an evidence-based and objective process as opposed to a highly inductive and intuitive process. The study process is faster and incorporates cycles of generate and test, as suggested by Herbert Simon, as opposed to a single design that is refined.

Anonymous survey response

Benefits appear to be more consistently comprehensive design products, as well as explicit training in process and design methods theory. Challenges are largely the personnel demands. Few faculty are not trained in the method and there is not a structure to provide for the expert consultants on a regular basis or spread across multiple studio.

Anonymous survey response

The benefits include real-time or early design stage feedback about performance, and multi-disciplinary approach in the studio. The challenges are how to enable

> *the organization of such studios from the course registration point of view, and how to enable students learn from each other of different disciplines.*
>
> ***Anonymous survey response***

> *I think the proposed model is fine and applicable. The question is how to implement it, given the resources available. You did great design studio with two or three experts from industry and two MS candidates focusing on a couple of student projects. But this is fives times the teaching resources currently available to our students. I'd like to see us try this approach for our 2010 4th year ARCH406 Integrated Design Studio.*
>
> ***Anonymous survey response***

5.5 Summary

The data from the BIM-B level case studies returned evidence about the implementation of the prototype pedagogical framework. Pre-study and Post-study surveys documented the attitude changes and provided in-depth information about the students' process experience. Observations returned a broad range of data about the design process in accordance with performance criteria, as well as the role of BIM use in every stage of the case studies. Evaluation surveys and the focus groups provided expert opinions about the pedagogical approach and scope of the proposed design studio model for further development and implementation.

According to the triangulated evidence, BIM and simulation tools facilitated the integrated and collaborative process and helped students to understand performance dimensions in connection to formal, spatial and visual aspects of design. However challenges emerged in terms of team formations, deprogramming of conventional design knowledge, interoperability, establishment of team decision making, and implementation within a curriculum given conventional instructor assignments and credit allocation.

Collected data and evidence from the focus groups, the pilot study, and the case studies established a strong basis for theoretical model development for integrated studio using BIM methods.

CHAPTER VI

SYNTHESIS OF THE FINDINGS

This chapter outlines the findings from the research study. Evidence from all research efforts is summarized to establish the theoretical and empirical foundations of the study. Synthesis of the findings is given using the following two theoretical models:

> 1) *Studio21* provides a comprehensive pedagogical model for the 21st century studio education as it is related to performance based design. The model comprises the ideologies, social, economic and professional constructs, and the drivers for the paradigm shift from traditional models to integrated education. The model describes the functions and the components of the integrated studio and approaches the integration issue by leveraging advanced technology for the innovation of architectural curriculum.
>
> 2) *CircleX* model emerges from the empirical findings of the study. It explains the mechanisms of integration between designers and consultants through BIM in the early phases of design.

Findings of the research study are discussed in the final section along with theoretical premises and precedents.

6.1 Studio 21: A Studio Model for the 21st Century

As a synthesis of the prototype pedagogical framework and the findings from the research study, Studio 21 model is proposed to address the need for transformation in the professional level studios. According to the findings from the literature survey and focus groups, perceived need for change in the profession suggests dissatisfaction with the status quo. Researchers and practitioners assert that the design paradigms are being transformed under the influence of social, economic, environmental and technological changes (Barrow 2004; Kieran and Timberlake 2004). Education of future professionals emerges as a major issue for transforming the profession (Smith and Tardif 2009). Current educational paradigms, pedagogical strategies, and curriculum can be claimed as outmoded for preparing future architects for an integrated, information-centric, performance based practice. Studio approaches based on Beaux Arts model need substantial revisions. Interdisciplinary and collaborative studio models are more likely to replace the old models (Freidman 2007).

Evidence form the study revealed that there are various approaches to the adoption of BIM in connection to the levels of interdisciplinary integration. BIM-A, BIM-B and BIM-I level adoptions imply different design and production processes resulting in different value returns. As a justification for the developed performance model, pilot study results suggest that introduction of BIM in the conventional studio will increase several quality measures, yet stay in the BIM-A level. Within this view, implementation of BIM in design education is more than a technology use issue. Leveraging BIM for design education implies an integrated studio with a BIM-B approach with substantial revisions to the existing studio paradigms. Changes in the studio include design approaches, participation of interdisciplinary consultants, representation-communication styles, instruction strategies, introduction of sustainability, constructability, parametric modeling, interoperability and performance simulation, and others.

Based on these findings, the proposed model is devised around the integration of disciplines and the state-of-the art BIM methods and technologies. Studio 21 model offers an inclusive framework by balancing upstream and downstream aspects of architectural design. The objective of the proposed studio model is to teach students the essentials of performance-based design through information exchange and intense collaboration. The underlying idea of the model is to extend the common understanding of *creativity* by incorporating the novel methods in design, construction, fabrication and advanced information technologies. In brief, Studio 21 is a prescriptive model that creates a social situation for integrated design, BIM, and high performance architecture. The model conceives BIM and interdisciplinary collaboration as the main catalysts for the cognitive processes in the design studio.

The components of the Studio 21 model are derived from the following prototype pedagogical framework and case study observations:

Instructors: The case study processes confirmed the need for extensive theoretical instruction on design aspects, integrated project processes, BIM tools, and technology. Instructor's role in the Studio21 model is to provide the required knowledge, deliver constructive criticism for the full spectrum of design aspects, and facilitate the integrated processes in a proactive fashion.

Consultants: Participation of consultants in the design studio may represent the most important distinction between Studio 21 and conventional studio. Interpretation of performance-based information, assessment of design alternatives, and creation of macro and micro design solutions can be listed as the roles of consultants in the Studio 21 model.

BIM Assistant: Pilot study and case studies show the need for just-in-time support for minimizing the problems of complex parametric modeling procedures, software interoperability, and information exchange between employed tool set. BIM assistant reduces the unwanted time commitments for software training for complex operations.

Tools and Facilities: As described in the case study chapter (Chapter V), integrated studio is based on a large set of BIM and related software tools such as off-the-shelf BIM software, 4D modeling/integration tool, surface modelers, rendering engines, and spreadsheets and databases. Case studies also involve the intense use of active plasma screens. The screens allow projecting BIM models on a large active screen where students and consultants have conversations on multiple levels of the design alternative.

Workspace: Unlike the typical individual settings in conventional studios, “club” type workspaces are suggested. The collective nature of the workspace is a catalyst for increased social communications and teamwork among studio participants, which leads to better integration and information exchange. Case studies show the amplifying effect of collective workspace and intense social interaction on collaborative design and production processes.

Implementation framework of the Studio 21 model has several aspects. Case study results demonstrate the need for deprogramming of students from conventional studio practices to the proposed studio framework. Significant amount of time was dedicated to provide both theoretical and practical knowledge about integrated design process with BIM. Instruction during the case studies involved three main domains: BIM technology, parametric modeling, and interoperable information exchange; integrated and collaborative design processes; and theoretical foundations for form, computational aesthetics, sustainability, constructability, and building systems. Derived from these findings, the interconnected domains of the Studio21 model are: *technology, process, and theory*. These domains are referencing each other and address the targeted pedagogical objectives for the integrated education. Details of the model are explained as the following:

Technology Domain: Studio 21 model is based on the use of state-of-the art BIM methods and technologies along with capable modelers and simulation tools. This layer involves the modeling of design alternatives; parameterization of design criteria; creation of domain models like energy, sunlight, daylight, and 4D; as well as derivation of information from the models. The technology core is the facilitator of collaborative design and assessment activities in the studio. The pedagogical goal in this layer is to teach students the essential concepts of BIM, software interoperability, and formulation of consistent information exchange procedures.

Process Domain: Design activities in the Studio 21 model involve rapid, iterative, and comprehensive cycles through the technology core as BIM. The multi-channeled communication between design students and the consultants is the key for design and assessment procedures. Providing a foundation for this process flow, emerged design flow in the case studies heavily relied on the design-simulation-assessment cycles between designers and consultants. These cycles produced substantial information and immediate feedback for development and improvement of the alternative. Shared BIM models facilitated this information-rich process with domain models and interoperable file formats. Duration of the cycles varied between two and six hours. Wide-range of performance specific information was articulated with design decisions as explained in the previous chapter.

Process domain is tightly connected to the technology and the theory domain. As observed during the case studies, students execute of the synthesized knowledge regarding integrated design methods by frontloading the process with explicit interdisciplinary knowledge of topics such as aesthetics, constructability, sustainability, structural integrity, building systems integration, lighting, etc. The process domain requires students to make both macro and micro level design decisions simultaneously.

Theory Domain: As explained in literature review section and the prototype pedagogical framework, the theoretical intent of the integrated studio is to provide students with an understanding of performance-based design and high-performance buildings. This can be achieved by the introduction of a broad range of theoretical concepts and motivation of students to synthesize the knowledge around a comprehensive design problem. Referring to the curriculum Studio 21 model drives students to use prior knowledge and skills from other courses.

Figure 6.1 illustrates the interconnected domains of the Studio21 model and components of the pedagogical approach.

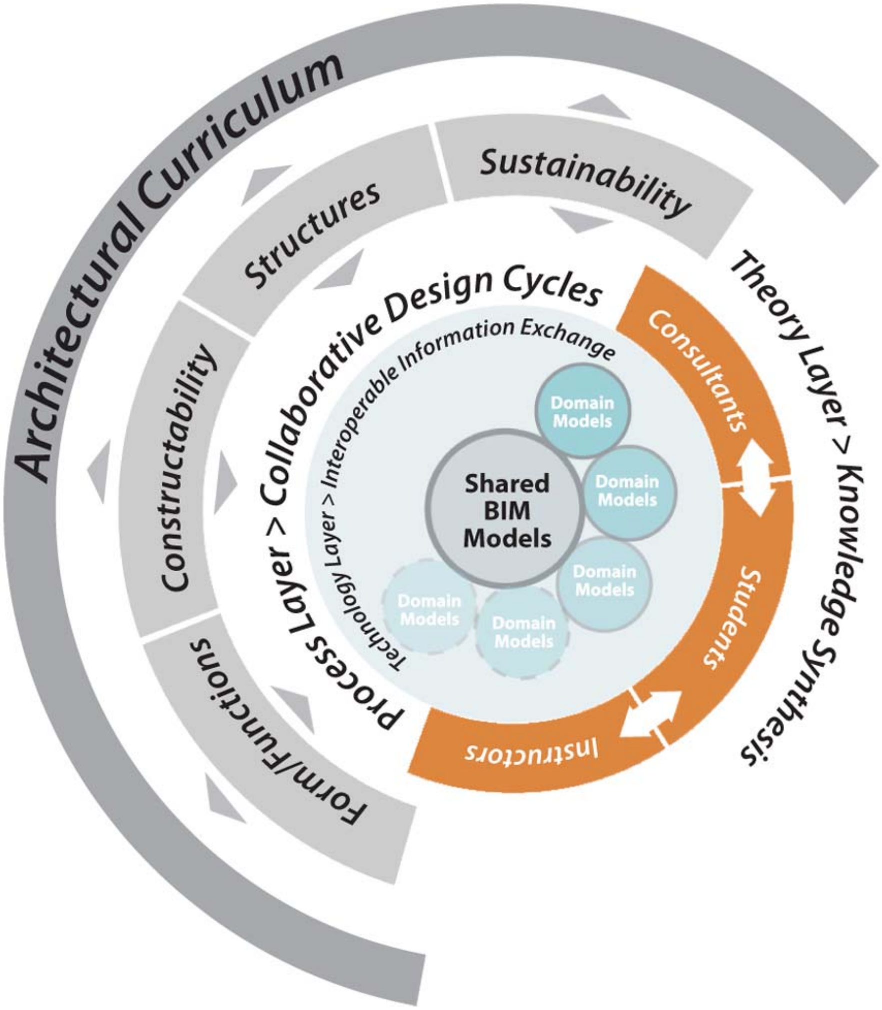


Figure 6.1: Studio21 Model

Steps in the Studio 21 Method: From a tactical standpoint, the setup and procedural steps of the Studio 21 model are explained as follows:

Prerequisite of Moderate Level Skills in BIM technology: The technological layer and information exchange tasks require moderate skill levels in BIM. Understanding of parametric modeling procedures and gaining basic knowledge for deriving 3D, 2D, and text information from the models are the prerequisites for the Studio 21.

Lecture to Make Explicit the Assumptions of Conventional Studio Education and Contrast the Studio 21 Method: The findings of the research study suggest that prior attitudes and preferences of conventional processes may prevent students from forming the notion of integrated design. Careful instruction will address this issue with detailed process information, goals, and objectives of the studio. Discussions on conventional and integrated approaches may provide comprehensive theoretical understanding of Studio 21 method.

Instruction in Parametric Modeling: Parametric modeling significantly differs from typical CSG and surface modeling approaches. Process reports and observations from the case studies suggest that introduction of parametric modeling methods requires extra attention and expert support for the creation of building envelopes and components. Specific examples show that students took the advantage of parametric building components for making macro and micro level design decisions. Exploration of parametric adaptability of the solutions was made through design iterations and propagation of new components. This step also refers to the discussion of computational aesthetics and novel approaches in contemporary form making.

Instruction in Interoperable Design Analysis Tools: In addition to BIM tools, students should be instructed about the use of simulation methods and available tools for performance analysis. This step should include different capabilities of the tools in accordance with design tasks, decision levels, and studio objectives.

Design Problem Challenge: Design problems in Studio 21 encompass a broad range of criteria regarding qualitative and quantitative performance measures. A detailed set of criteria and a building program should be provided for preliminary discussions between students and consultants in the frontloading stage. Qualitative requirements like form expression, architectural discourse, contextual relevance, and social performance can be defined as a flexible framework for designer’s interpretation. Quantitative objectives like energy use, daylighting intensities, structural integrity, cost, and schedule are incorporated into the building program. Existing building certifications like LEED can be used as a template for performance assessment.

Formation of Teams: Collaborative and integrated teams need to be formed to include explicit roles of designer and consultants. Decision priorities and team hierarchies are embedded in the team definitions.

Establishment of Interoperability Framework: This step includes determination of file formats and data standards that will be utilized through the studio process. Capabilities of the employed software and common file formats should be provided. According to research findings from the case studies, moderate problems due to building form and model consistency are unavoidable. Just-in-time solutions and expertise may be required to facilitate the information stream.

Frontload of Design with Information: The processes in the case studies were frontloaded with performance requirements and design objectives. The initial cycle was carried out with an initial prototype design –base case- for benchmarking the performance metrics and better identification of the design problem. Performance comparisons referred to the base case for every design alternative. In order to address performance-based problems, the base case step is expected to assist students to identify the design problem, performance dimensions, and system requirements by pushing the design intent and design objectives to a preliminary alternative.

Cycles of Design and Analysis: Design tasks include the creation of alternatives, modeling of form, and building components. Design teams are free to make creative decisions in order to meet any aesthetic notion in conformance with the performance criteria. Design teams broadcast the alternative models for simulation and analysis. The major point is to explore the search space by creating and analyzing a wide range of macro and micro solutions for achieving a sound design alternative. Assessment and analysis cycles are structured to demonstrate to students the interconnected effect of design decisions from preliminary levels to whole building lifecycle, even including the supply chain. Developed alternatives are further refined through the same cycle by micro level solutions, building materials and alternative systems components. Performance trajectories are analyzed and optimized for final solutions. Referring to the research results for downstream design aspects, energy use, daylighting, and building cost data suggests that students may or may not meet the exact requirements but design decisions were made with justifications based on explicit information. Process data demonstrated minor variations and final results were stayed in an acceptable level for the required performance criteria.

Documentation of Design: Unlike typical studio, documentation of design in the Studio 21 model is heavily based on wide range information in 4D, 3D, 2D, numeric and qualitative information. Student work in the case studies shows that BIM models are capable of providing detailed 3D visuals and real time visualizations along with simulation results. Studio results can be articulated with explicit information from the process. Building form, systems, components, and their performance influence can be illustrated in a connective fashion.

Post-mortem Discussions: Discussions after the studio process are the integral part of the integrated process to evaluate performance achievements of the produces design artifacts from designers' and consultants' perspective. Case study observations suggest that post-mortem discussions allow students to verbally and visually externalize their design intents in accordance with multiple performance variables. Discussions were supported with comprehensive visual information like 4D, 3D and 2D and extensive numeric data regarding energy use, CO_2 emissions, renewable potentials, water balance, cost, and scheduling.

Survey results show that employed pedagogical framework and case studies can make significant changes in students' approach to design problems, attitudes and perceptions when it comes to balancing the upstream and downstream aspects of design. Interconnectivity and chain effect of decision-making in the building lifecycle were perceived effectively by the case study participants. The findings and evidence suggest that the model is both effective and replicable. The model involves theoretical foundations, pedagogical objectives and strategies, as well as technological infrastructure and implementation steps. The model is flexible and capable of incorporating any performance aspect, utilizing different sets of integrated software, or pursuing reengineered design and assessment cycles. Overall, Studio 21 model offers a particular framework for performance-based studio that enables students to create more alternatives, assess performance with consultants, and use BIM for decision support.

6.2 CircleX Model: Circle Integration Extended

The integration schemes that emerged during the case studies provide qualitative evidence for comparing and contrasting the theoretical premises of circle integration. The study findings suggested an empirical and descriptive integration model for the early design phases. The model involves the interactions between designers and consultants via shared BIM models. The CircleX integration model is based on the idea of circle integration but it is an extended and revised version due to the nature of the early design phases. In these early stages extensive effort is applied to form and spatial and visual aspects of the design, and it can be posited as a blurred process where designers give iterative decisions about different layers of the design. Using a semi-central BIM model, designers are able to show extended initiative while enabling a comprehensive feedback cycle and maintaining the integrity and effectiveness of the integrated loop from the conceptual design standpoint. This model also allows consultant teams to work on more sophisticated design alternatives. Figure 6.2 illustrates the flow of CircleX model process.

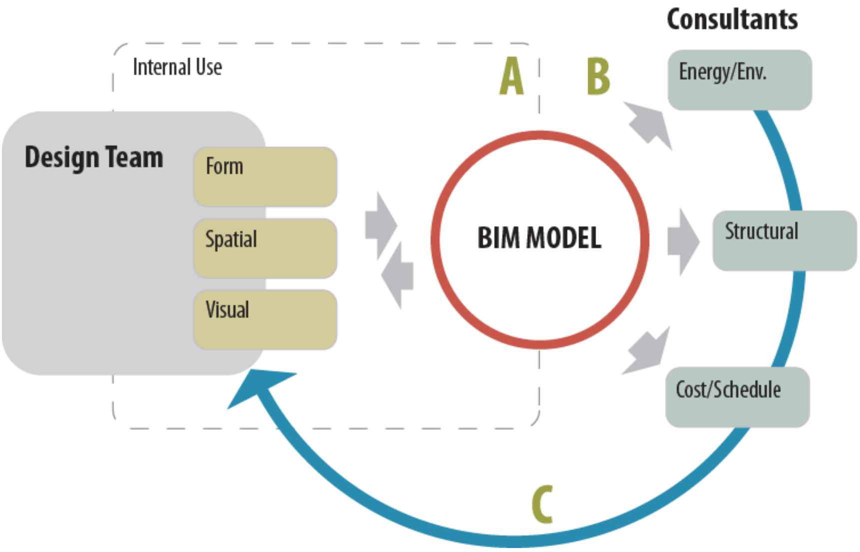


Figure 6.2: CircleX-Developed integration model from the findings of the study

The model has three major process phases illustrating the integrated design flow that emerged during the study, which are the following:

Internal Use: In this phase shared BIM models are set for communication and collaboration of the design team members. In the initial stages, design teams mainly focused on the form, spatial layout, and visual performance under the impact of energy use, daylighting, structural integrity, and cost information.

Model Broadcasting: Design team can initiate a feedback loop by broadcasting the design model to consultant teams.

Feedback Loop: Consultant teams create domain models, interpret the design model and given data, and create discipline specific information. This information is either pushed into the model or given as compatible text/visual information.

The model is flexible in terms of accommodating additional consultant nodes and multiple design teams in the early design phases. However, the CircleX model is based on the assumption that both designers and consultants have certain expectations and mutual understanding of the type and content of information they will provide while collaborating on an interoperable BIM model.

6.3 Discussion of the Findings

Findings from the research study and proposed theoretical models offer strong assertions for further discussion.

Studio 21 model contrasts with the Beaux-Arts competitive studio model and envisions a collaborative design and learning process with integrated approaches. As explained in the Studio 21 model design objectives, setups, participants, tools, and design domains differ significantly compared to the contemporary design studio as observed and described by Schön (1985). One example that illustrates this particularly well is how descriptive and normative design domains in Schön’s model are heavily extended by new and essential performance variables proposed by Studio 21 model. Significant changes in communication style, media, and instruments are direct results of this scope extension and the new opportunities due to advanced IT methods. Here it can be claimed that the Socratic dialog predominantly concerning aesthetics and design artistry will not satisfy the pedagogical needs for performance based design. Learning mechanisms based on mimicking, observation, and execution carry tacit forms of knowledge but may not satisfy the need for interpretation of explicit performance information. Using the research findings as the evidence, the balance between creativity and performance during learning can be achieved through multi-channeled collaboration and integrated design methods such as IPD and BIM.

The research findings returned no evidence for identification of the occurred integrated processes either with problem-solving or reflection-in-action paradigms. Observations suggest that design teams used explicit knowledge with intense interpretation. Solutions were considerably different in terms of form, building envelope, and space configuration. Here, it can be claimed that the use of tacit knowledge is valid as a part of the integrated design process. Experience can be transferred through the process as suggested by Schön. However, process and the sequence of the case studies were significantly different than Schön's observations from the conventional studio processes.

The adoption performance model with BIM-A, BIM-B-BIM-I levels indicates various levels of understanding and perception about BIM. Comparisons between pilot case and case studies leveraging BIM are possible with integrated processes as predicted by the theory. Results from the case studies and findings suggest that the introduction of BIM in an integrated studio setting is effective as claimed by Freidman (2007), Clayton (2006) and Ambrose (2007). Confirming Cheng's (2006) statements for a hypothetical model integrated studio, the study demonstrates the incorporation of new pedagogical opportunities raised by new forms of design practice and BIM. The threefold domain structure of the Studio 21 model intends to provide students the underlying logic of integrated processes and technology. Case study findings also align with the propositions of Krygiel and Nies (2008) as they show the BIM's functionality for sustainable design processes. As an educational and empirical implementation of their assertions, the study explores the integration capacity of BIM methods and technology related to the early stages of sustainable design process.

The research study attempts to address the problems, suggestions and assertions with a comprehensive research design and provides solution proposals through models for further implementation. As it is expected in any type of research, the study reveals new problems and challenges based on findings and evidence. This Popperian mechanism of the employed research framework offers strong research paths for future studies. More specifically, the explored pedagogical framework suggests that the formation of an integrated team in the studio requires extensive deprogramming of students previous knowledge on conventional design process. Overcoming the pedagogical issues of integration is extremely challenging, particularly from a theoretical standpoint. Introduction of integrated methods in early stages of architectural education emerges as a discussion topic among academic initiatives. Scope of architectural education can be questioned as the theoretical knowledge of architectural design is acquired through a large number of courses in the curriculum. As discussed in various chapters of this study, social, economic, and environmental challenges are severe and can dramatically change the trajectories of the profession. Advances in information technologies, building systems and construction paradigms also imply significant revisions in the graduate and the undergraduate education. Therefore, the restructuring of the design studio is also bound to wider changes in the whole curriculum. Future research studies and discussions in the appropriate venues should address this important issue.

Other problems can be listed from tactical points regarding BIM tools, technology literacy, and the requirement of interdisciplinary expertise. The case study results suggest that integrated studio processes involve participation of interdisciplinary consultants in order to avoid superficial assessment of the performance criteria. Interpretation of performance information, creation of domain models, and simulation processes are considerably complex tasks. Consultants' role and expertise level have direct effects on the process. Problems that occurred during the case studies included finding skilled consultants, defining their roles in the process, and establishing the hierarchical decision-making structure. Constant need of a broad range of expert skills on simulation, cost estimation, 4D modeling, and scheduling emerged as a challenge. Connected to this issue, students' knowledge level on these aspects caused inconsistencies during information exchange and assessment tasks.

Interoperability framework of the case studies included a large set of BIM tools, surface modelers, rendering programs, and spreadsheets. Some tools like simulation and 4D modeling demand expert level operations. Streamline of the information requires intensive support from skilled consultants and the BIM assistant. Although the major obstructions were avoided, incompatibilities of the particular software tools and learning curve of the students affected the speed and efficacy of the design-simulation-assessment cycles. Students pointed out the encountered difficulties in the surveys and progress reports but also confirmed the effectiveness of the pursued just-in-time instruction methodology for software related issues.

Based on the evidence, it can be claimed that concerns of instructors about negative effects of BIM on design process reported by Khemlani (2006) did not occur in any of the research steps. Observations suggest that BIM use requires intensive effort to create parametric building models. Such difficulties and problems occurred during information exchange but none of the case studies were dominated by extensive modeling tasks. With careful instruction, just-in-time support, and theoretical knowledge, students were able to achieve desired design objectives. BIM does not appear to have reduced the quality of soft aspects of design and aesthetics.

It is very arguable that approaching the issue from the comparison of CAD versus BIM tools would produce valid points for further discussions. Diffusion of CAD in the profession and education happened due to drivers very different from BIM. The underlying idea of 2D CAD was to digitize the typical overlay drafting and automate the representation process. 3D CAD extrapolated the 2D to the third dimension and provided distinct advantages for digital form making and visualization (Clayton 2005). As opposed to conventional CAD, BIM derived from a database approach where building information can be graphic, or non-graphic, as well as both qualitative and quantitative. The intent of BIM is to support decision-making in integrated design workflows (Jernigan 2007; Eastman 2008). As a matter of fact, assumptions that BIM will have the same diffusion steps and implications as did CAD may downgrade the distinct values of BIM in architectural education.

From this perspective, the results of the research study and the theory of BIM imply more than a technology implementation problem. Referring to Cheng's arguments, determination of the appropriate place for BIM in the curriculum emerges as an issue. As a quick response, it is perfectly possible to integrate BIM into the conventional curriculum with carefully designed technology courses; however, integration of disciplines and new models of practice implies other significant revisions which are related, yet greater than the BIM technology itself. Therefore the question can be formulated in the following way: How can we leverage BIM and peripheral technologies to facilitate the integration of the architectural curriculum?

Current status of the BIM technology, interoperability standards, complex or counter-intuitive interfaces, industry-driven characteristics, and software capabilities may be perceived as major concerns for supporting educational activities and creative design processes. Based on the study findings and observations, it can be claimed that BIM still needs improvements for better studio integration. Such challenges and missing features include direct and interactive energy simulation, human behavior simulation, direct testing of constructability, simultaneous cost analysis, more intuitive interfaces for parametric component design and better connection between solid-surface modelers and BIM tools. Nevertheless, the case studies substantiate the assertion that the current limitations of the technology are not debilitating.

The growing interest in integrated project delivery methods, changing models of practice, and rapidly increasing level of BIM technology are more likely to remain in the agenda of academic initiatives. Future research on this issue should address these questions as well as provide well-reasoned arguments for devising novel methods, strategies, and approaches for the BIM-enabled integrated education.

CHAPTER VII

CONCLUSIONS

The data describes several aspects of design methods and design education and led to the development of theoretical models that are the conclusions of the research. As stated previously, the main research objective was to provide a comprehensive understanding of the potentials of BIM methods and technology in the context of integrated architectural education. Research questions involved the following:

1. What are the theoretical propositions of BIM for integrated and performance based design?

2. How does BIM influence the AEC industry and the practice of architecture?

3. Does BIM catalyze performance based design learning in an integrated studio environment?

Being formative and exploratory, the study employed a broad range of qualitative methods and techniques in order to provide answers to the research questions and achieve the research objectives. Results of the study addressed the research questions using evidence from literature survey, focus groups, instrumental case studies, surveys, reports and studio results.

7.1 Significance of the Research

Findings from the focus groups and literature review provided strong evidence about the emerging challenges of the 21st century design practice and education. The continued viability of the conventional studio is arguable as it prepares students for highly hierarchical and authoritarian organizational forms of practice (Anthony 1991; Fisher 2004; Hamilton and Watkins 2009). Emerging professional context includes technological innovation, acute environmental issues, imperatives for sustainability, socio-economic changes, and globalization. New mandates of this era are drastically changing the project scopes, aesthetic perceptions and quality expectations as opposed to financial resources and time limits for design and construction. Hi-tech and lean manufacturing methods in aerospace and automotive industries are diffusing into the AEC industry (Kieran and Timberlake 2004). Design processes, construction techniques, methods, and influence of advanced IT require new educational practices and studio approaches to mold accomplished architects who possess a wide range of skills and are capable of comprehensive decision-making. Suggestions and well reasoned arguments based on empirical studies are necessary for restructuring the design studios and architectural education. This research has produced conclusions that provide educators with concrete patterns for conducting studios that address the issues described above.

7.2 Contributions

The research study consisted of several research components which led to multiple contributions for BIM adoption, integrated studio approaches, and pedagogical strategies. The focus was on architectural conceptual design synthesis, which is valued as a core skill for an architect.

The first contribution of the study is the BIM Adoption-Performance model which analytically explains the potential value gains in accordance with the integration level of BIM in the production processes. BIM-A, BIM-B, and BIM-I levels provide an understanding of BIM deployment ranges, performance thresholds and BIM's intrinsic conceptions as *tools, technology, and process*. The model can be applied in practice and education when creating effective strategies for BIM adoption. Content analysis of the focus groups and participant responses confirmed the rapid transformations in the AEC industry and the architectural design practice. Benefits and challenges of BIM and IPD were thoroughly investigated. Viewpoints and thoughts on practice and architectural education lead to the discussion of necessary revisions in the studio approaches and curriculum.

The second contribution of the research is the Studio 21 model for the integrated studio through BIM. Referring to the criticisms of the conventional studio approaches, the Studio 21 model addresses the questions raised by the rapid changes in the practice environment, and proposes a comprehensive pedagogical framework. The model includes strategies, tools, roles, studio settings, and setups for further studio studies. In brief, Studio21 model shifts the pedagogical goals from form making to a more wide range set of objectives with both upstream and downstream aspects of architectural design.

The model was developed from the investigation of the preliminary pedagogical framework though a set of instrumental case studies. Findings from the case studies illustrate both effectiveness and challenges of the proposed studio model. Results showed the capabilities of BIM for the facilitation of a performance based design process. Comparisons from pre-study and post-study surveys indicate significant changes in attitudes and perceptions for design process and its content. Proposed studio model significantly balanced the upstream and downstream aspects of design. Student responses were mainly positive about the collaborative nature of the experiments. According to case study results, BIM use in an integrated studio setting results in an increased number of alternatives, more depth about performance and sustainability and rapid assessment of the design alternatives. Refinement of designs and changes in performance are illustrated with qualitative and quantitative data. Use of parametric modeling motivated students to think about the relationship between computational aesthetics, form, and space.

However, process observations and student responses suggest significant challenges to be addressed in future studio studies. Formation of a consistent and collaborative studio setup requires effort to overcome the issues of consultant roles, hierarchical decision structure, computer data interoperability, and technology-related problems. Design assessment and inconsistencies between design and analysis stages demand expertise and rapid responses. Lack of knowledge on downstream aspects of design is more likely to occur in any studio setting and will demand sufficient instruction. Parametric modeling seems to represent a complex task for most students. For that reason, shifting from solid-modeling to parametric thinking requires expert support and just-in-time solutions.

As a third contribution, the CircleX model describes the collaboration and integration mechanisms that are observed in the integrated studio. The model provides a process flowchart and integration scheme for the early phases of a collaborative design process. CircleX model posits that design teams can initiate rapid assessment cycles by sharing the BIM model. Consultants can create quick domain models and run simulations for feedback. These iterative cycles may lead to sound design alternatives with high performance returns.

7.3 Originality of the Research

According to the literature search, there exist a large number of studies on CAD education and digital design studios. However, research and development efforts for BIM-enabled integrated education are relatively new and draw significant attention from the academics, studio instructors and educational initiatives. Previous research studies either approached the problem from a largely theoretical perspective or focused on very specific, technical tasks for the implementation of BIM methods.

For example, Eastman (2008) provides theoretically-driven viewpoints for the future of education under the influence of BIM and related technologies, while Clayton (2006), Freidman (2007), Cheng (2006) and Ambrose (2007) discuss different dimensions of existing educational practices, potentials of BIM, and implications of integrated practice on studio pedagogies, also from a theoretical standpoint. Experimental works have provided evidence and insights about BIM implementation to design studio or BIM use for specific tasks in the classroom, but largely from a technology adoption and operational perspective. Previous studio experiments were either based on conventional studio settings and processes or focused on the technological aspects of BIM (Guidera 2006, Plume and Mitchell 2007).

This research unites strong theoretical models (the BIM value model and CircleX) with a clear prescription for organizing and conducting a design studio (Studio 21). The combination of theory and practice substantiates the claim for originality of the research.

7.4 Reliability of the Research

The present study employs a large and diverse set of research steps with a unique methodological framework for the particular research domain. Unlike specific case studies on typical studio settings, this study was based on an empirical research design and encompassed a large spectrum of design processes with various upstream and downstream tasks that have not been investigated in much depth before. The collected data and findings cover a wide range of information and are reliable, as demonstrated by data consistency over the multiple participants and multiple studio trials. The BIM adoption model is supported by multiple focus groups, theoretical arguments, and observations from practice. The proposed pedagogical framework was investigated with three instrumental case studies in two M.Arch programs. The theoretical models of Studio 21, and CircleX are detailed, evidence based, and replicable.

The strength of the evidence provided here is exceptional as it contains the following triangulated findings from the study:

1. Suggestions, viewpoints and experiences of experts, practitioners and faculty;
2. Pre and post-study attitudes and preferences of the case study participants;
3. Process reports from all stages of the instrumental case studies;
4. In-depth observations of the integrated design process; and
5. Design artifacts, simulation outputs, visuals, and numeric data from the design process.

7.5 Limitations and the Validity of the Research

The research study has several limitations due to methodological considerations, participant samples, educational approach, and tool sets employed in the trials. Findings of the study may raise validity questions from a purely methodological viewpoint, as discussed below.

Focus group participants were selected largely from professionals in the state of Texas, as well as faculty and students in Texas. Although the participants have presence both nationally and globally, the gathered data and analysis may have limited generalizability beyond the firms and schools represented in the focus groups.

Instrumental case study approach in certain studio environments may decrease external validity of the data. However, previous works suggest that studio studies are largely based on carefully structured case studies using similar research methods. The present research study provides detailed information, findings, and evidence for replication and further development of the Studio 21 and arguably exceeds the norm for studio instrumental case study research. The model was implemented in two NAAB accredited M.Arch programs. Further exploration of the model with different design problems and larger project scopes could provide arguments for greater generality and validity.

From the pedagogical view, results of the study are specific to graduate-professional level studios. Studio 21 model is based on preexisting skills and knowledge regarding design processes and BIM. Therefore, results may not be generalizable to undergraduate level studios, especially in the early stages of design education, where students lack as thorough knowledge of design process, construction, building performance, or computational methods.

Due to time limitations and logistics, case studies were mainly concentrated on the early and mid phases of design. The design problem of the case studies was compact and specific and the design process models may not generalize well to different design problems. The focus was on the integrated processes, so a pragmatic approach was employed regarding BIM tools and technology. Full scale uses of interoperable data standards were not investigated. Use of IFC's, utilization of cost estimation tools, or accurate analysis with high-end energy modeling software may be integrated into the research frameworks for further research. Investigations on large-scale projects with precise cost estimations, structural simulations, supply chain optimization, and detailed construction planning may add more depth to future studies. The Studio 21 method requires a variety of expertise that is typically found only in a variety of instructors, and may thus be excessively demanding with respect to course staffing.

7.6 Implications of the Research

This research study has implications on various levels. In particular, the relationship between BIM and sustainable and high performance architecture which is depicted in this study represents new thoughts about organizing practice and novel pedagogical approaches for the design studios.

The research suggests a progression of strategies and context for success of strategies with respect to BIM. It also reveals the relationship between BIM and IPD. As such, the research can contribute to the development of strategic positioning, operations procedures, and middle-range planning for architecture firms, construction companies and other participants in the construction industry.

The scope of the research study involved well reasoned arguments for contrasting conventional pedagogical approaches versus the imperatives of the socio-economic environment and the resulting need for reformations in architectural education. The practical implications include further development of integrated studios for performance-based design using BIM by designing integrated process modules for design studios. The Studio 21 model provides a detailed framework with performance aspects of architectural design, integrated delivery processes, and interdisciplinary collaboration. Employed tools, learning objectives, facilities, and social context of an integrated studio are explained in detail for tailoring new case studies for different design problems and student groups on graduate and undergraduate level.

Proposed educational approaches in this research study may also address the continuing education issues in the design practice. Focus groups and literature search suggested the human resource is a big obstacle for reengineering the business models for IPD and the deployment of BIM. Both Studio 21 and CircleX models can be used for outlining compact education programs for IPD and BIM. Unlike widely used software training sessions with small pre-defined exercises and procedures, the project-based approach used in this study may provide in depth understanding for educators and professionals about the potentials of BIM and IPD in architectural production.

7.7 Future Research

The findings of this research led to propositions that could direct future research. Further study of practical adoption of BIM and IPD in the industry could verify or rebut the arguments for BIM-A, BIM-B, and BIM-I developed by this research.

From a theoretical point of view, the research has established empirically that an altered framework for design studio education can exploit both advanced computer technology and advanced models of integrated practice. However, the research does not establish that the framework developed in the research is unique or even ideal. Further research may develop additional models for studio education.

One obvious potential continuation of this research is replication of the study in various M.Arch programs with different students groups, modified settings, and new tools. New experimental studies can serve as case studies for continuing research toward the creation of sound pedagogical strategies for BIM and IPD. The content of the research will be further developed with larger design scopes in full-scale studio classes. Future integrated studios may be based on alternative course setups focusing on preset building components and the incorporation of parametric modeling in connection to rapid prototyping and small-scale fabrications.

As highlighted in previous sections, this research study focused on graduate level studios and pedagogical objectives. Applicability of the research to undergraduate level education should be addressed in future research studies. Teaching entry-level studios, systems, and technology courses with BIM and integrative approaches in the architectural curriculum represents both an advantage and a significant challenge for further investigation.

The case study frameworks may be modified to test the integration of multiple courses within the curriculum. The design studio may be integrated with related courses to contribute to the studio activities. In-class courses may become the satellite domains of the integrated studio where students will further develop, assess, and evaluate their studio projects regarding particular course content.

As explained in implications of the study, continuing education represents a major challenge, which is why evidence from the professional domain may be useful. Experienced professionals are more likely to have different attitudes and preferences in design process. Data and empirical evidence from carefully designed case studies may reveal the challenges and problems for continuing education for BIM and IPD.

Another potential study may push the envelope of this study to a virtual design studio context with state-of-the-art Internet technologies. Potential experiments may involve integrated design processes with distributed architectural design and consultant teams in various schools or professional consultants. BIM models, domain models, performance data, and information spreadsheets can be shared in carefully structured network spaces.

Synchronous and asynchronous integration mechanisms can be further studied. Utilization of BIM in a virtual and integrated design studio may return applicable findings for increased collaboration beyond the physical learning space.

7.8 Final Words

The research has developed theoretical models for understanding the opportunities and impediments to BIM adoption in the industry. The model of BIM-A, BIM-B, and BIM-I has extensive explanatory value and is also easy to comprehend. The CircleX model of the behavior of collaborators in the early stages of design provides a strong framework by which individuals adopting the various roles may contribute to the process. The Studio 21 model of design studio education is responsive to demands of the 21st century for faster design that produces buildings with higher performance. These three contributions can enable improvements to the practice of architecture and more broadly the betterment of the environment.

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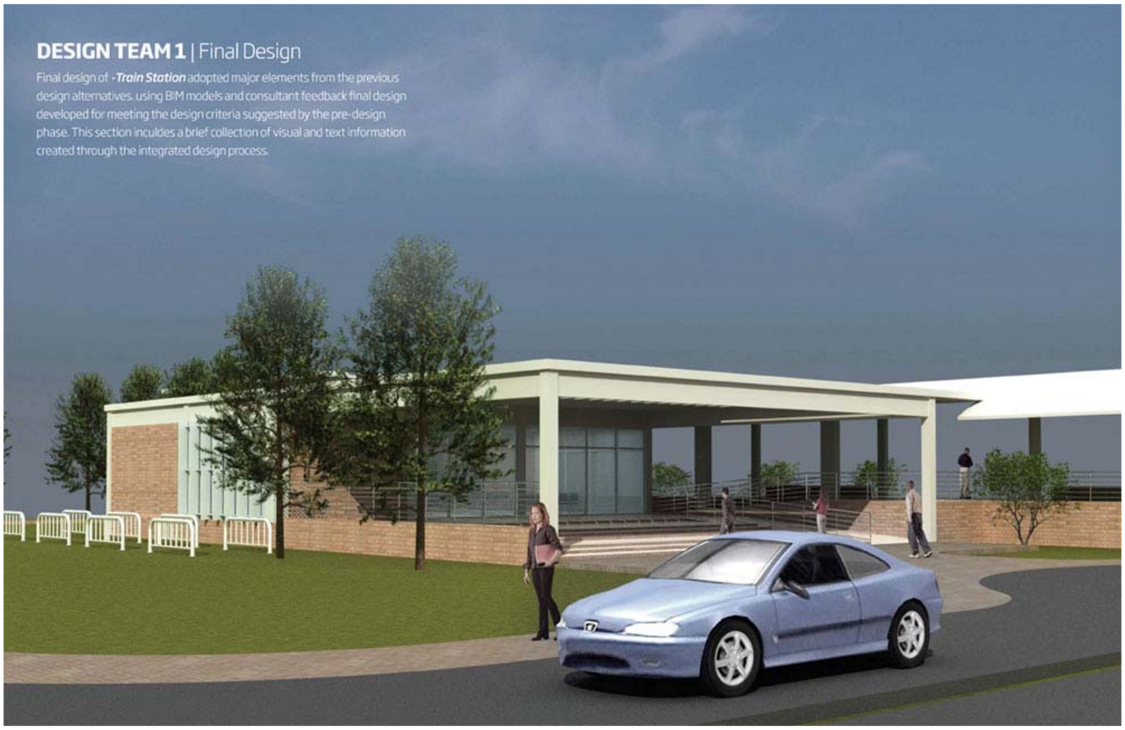
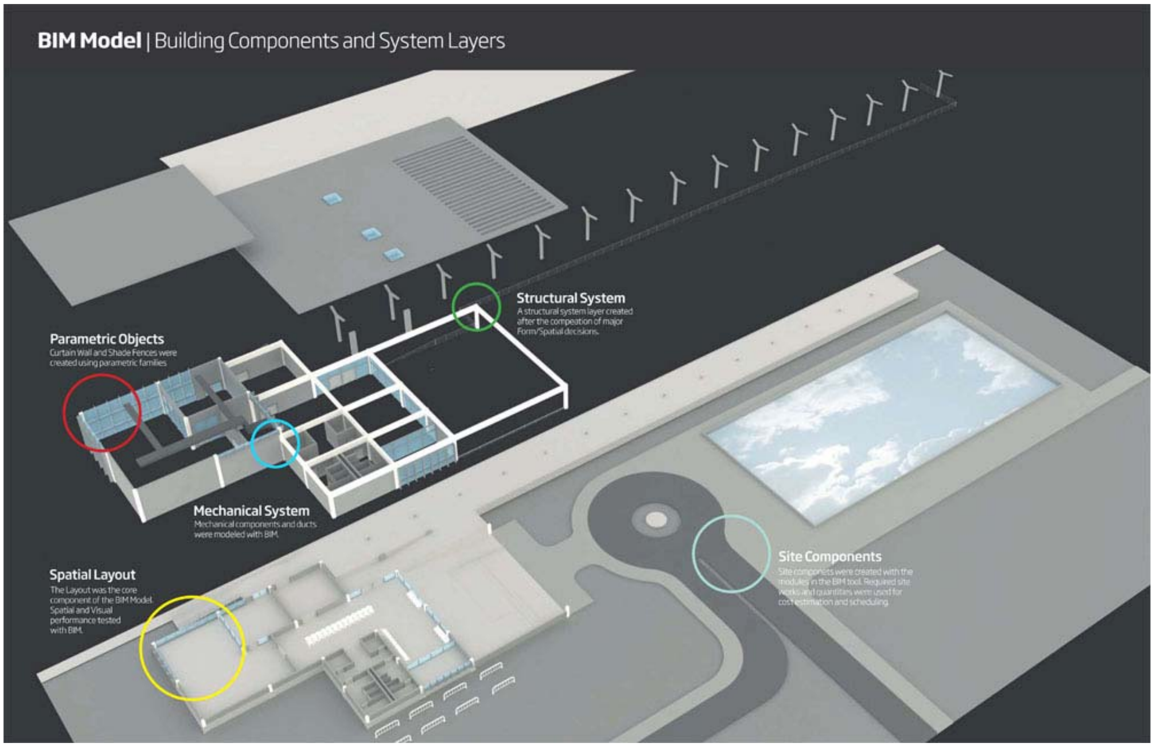
APPENDIX



DESIGN TEAM 1 | Final Design

Final design of *-**Train Station*** adopted major elements from the previous design alternatives. using BIM models and consultant feedback final design developed for meeting the design criteria suggested by the pre-design phase. This section inculdes a brief collection of visual and text information created through the integrated design process.

DESIGN TEAM 1 | Plan View



BIM Model | Building Components and System Layers

Structural System
A structural system layer created after the compeation of major Form/Spatial decisions.

Parametric Objects
Curtain Wall and Shade Fences were created using parametric families

Mechanical System
Mechanical components and ducts were modeled with BIM.

Spatial Layout
The Layout was the core component of the BIM Model. Spatial and Visual performance tested with BIM.

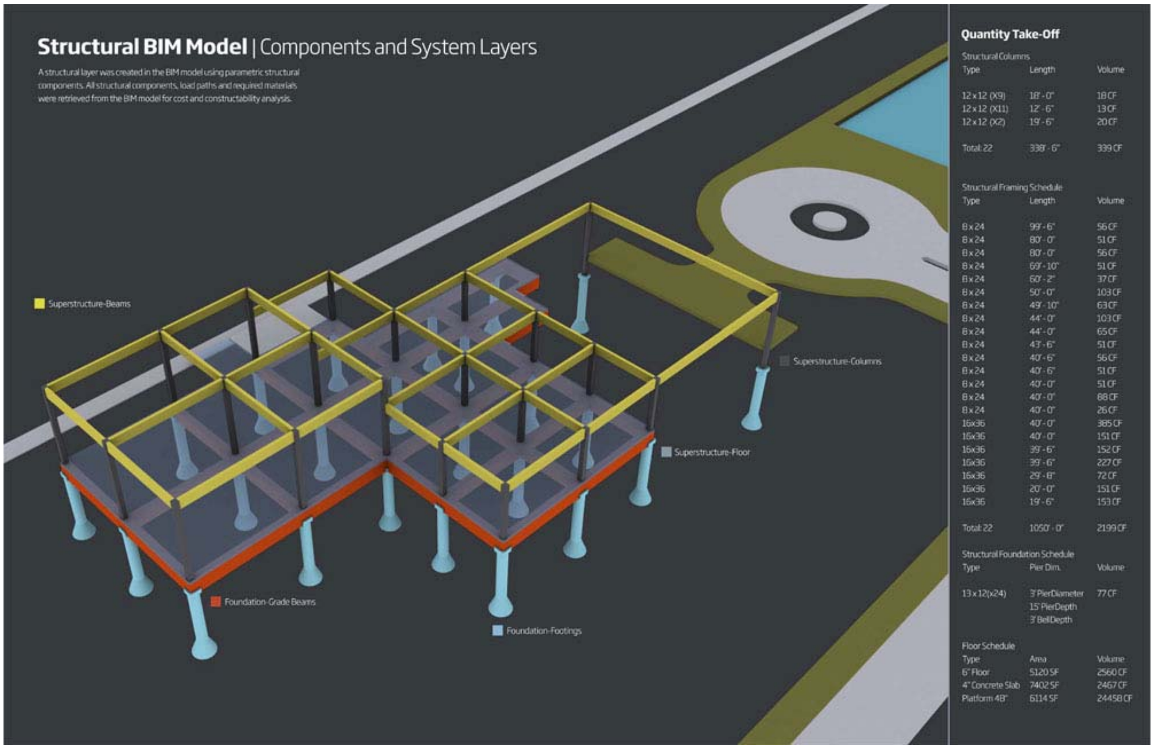
Site Components
Site componets were created with the modules in the BIM tool. Required site works and quantities were used for cost estimation and scheduling.

Visuals | Photorealistic Elevations

BIM Model was linked to a hi-end surface modeler tool (3D Studio MAX Design 2009) for GI based renders. Quick material assigments made by modification of Revit material definitions.

Elevation 1

Elevation 2



Structural BIM Model | Components and System Layers

A structural layer was created in the BIM model using parametric structural components. All structural components, load paths and required materials were retrieved from the BIM model for cost and constructability analysis.

Quantity Take-Off

Structural Columns

Type	Length	Volume
12 x 12 (X9)	18' - 0"	18 CF
12 x 12 (X11)	12' - 6"	13 CF
12 x 12 (X2)	19' - 6"	20 CF
Total: 22	338' - 6"	339 CF

Structural Framing Schedule

Type	Length	Volume
8 x 24	99' - 6"	56 CF
8 x 24	80' - 0"	51 CF
8 x 24	80' - 0"	56 CF
8 x 24	69' - 10"	51 CF
8 x 24	60' - 2"	37 CF
8 x 24	50' - 0"	103 CF
8 x 24	49' - 10"	63 CF
8 x 24	44' - 0"	103 CF
8 x 24	44' - 0"	65 CF
8 x 24	43' - 6"	51 CF
8 x 24	40' - 6"	56 CF
8 x 24	40' - 6"	51 CF
8 x 24	40' - 0"	51 CF
8 x 24	40' - 0"	88 CF
8 x 24	40' - 0"	26 CF
16x36	40' - 0"	385 CF
16x36	40' - 0"	151 CF
16x36	39' - 6"	152 CF
16x36	39' - 6"	227 CF
16x36	29' - 8"	72 CF
16x36	20' - 0"	151 CF
16x36	19' - 6"	153 CF
Total: 22	1050' - 0"	2199 CF

Structural Foundation Schedule

Type	Pier Dim.	Volume
13 x 12(x24)	3' Pier Diameter 15' Pier Depth 3' Bell Depth	77 CF

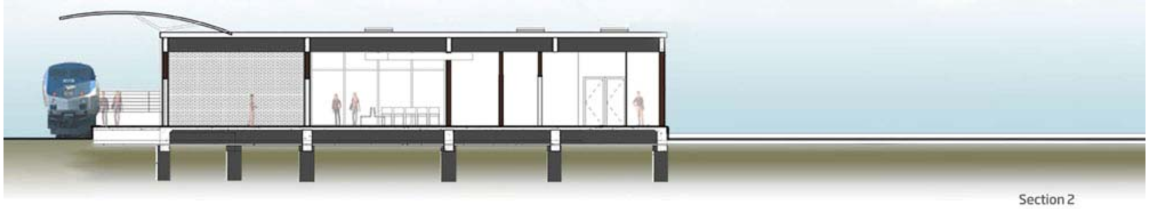
Floor Schedule

Type	Area	Volume
6" Floor	5120 SF	2560 CF
4" Concrete Slab	7402 SF	2467 CF
Platform 48"	6114 SF	24458 CF

Visuals | Automatic Sections

Required 2D visuals were derived from the BIM Model and further processed with raster-vector image editing tools. All 2D and 3D visuals are internally coordinated.

Section 1



Section 2

Daylighting | BIM Connection

BIM Models were used to create 3D Models for the daylighting analysis of the buildings. Autodesk Ecotect and DaySim were the tools for the simulations.

Daylight Factor (DF) Analysis: 69% of all illuminance sensors have a daylight factor of 2% or higher. If the sensors are evenly distributed across 'all spaces occupied for critical visual tasks', the investigated lighting zone would not qualify for the LEED-NC 2.1 daylighting credit 8.1 as the area ratio of sensors with a daylight factor over 2% would need to be 75% or higher (see www.usgbc.org/LEED/).

Daylight Autonomy (DA) Analysis: The daylight autonomies for all core workplane sensors lie between 0% and 95% .

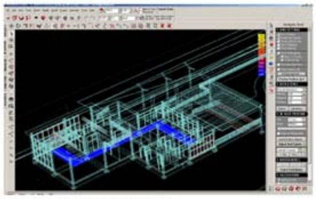
Useful Daylight Index (UDI) Analysis: The Useful Daylight Indices for the Lighting Zone are $UDI_{<100}$=24%, $UDI_{100-2000}$=3%, $UDI_{>2000}$=73% .

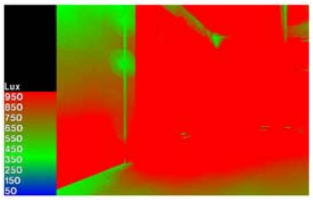
Continuous Daylight Autonomy (DA_{con})and DA_{max} Analysis: 83% of all illuminance sensors have a DAcon above 80% . 11% of all illuminance sensors have a DAmax above 5% .

Electric Lighting Use: The predicted annual electric lighting energy use in the investigated lighting zone is: 2.4 kWh/unit area.

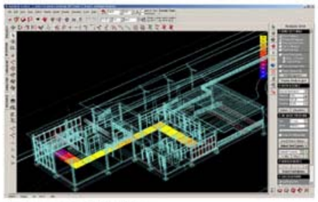

March 21st 16:00hrs / cafe-museum space

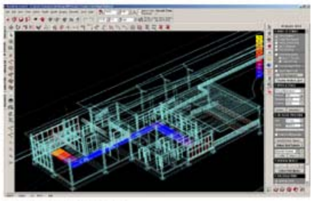

March 21st 16:00hrs (Human Sensitivity) cafe-museum


Screenshot from Daylight Factor Analysis (DF)



March 21st 16:00hrs / False Color


Screenshot from the UDI 100-2000 lux


Screenshot from UDI >2000 lux

Energy & Environment | BIM Connection

BIM Models were used to create gbXML files for the analysis of the buildings. Autodesk Green Building Studio and Autodesk Ecotect were the tools for Energy and Environment simulations.

Project Title: Train Station
Run Title: Team1_Final_Analysis
Building Type: Transportation
Floor Area: 3995 SF (Indoor) - 4375 SF Gross

Location Information

Building: Train Station
Electric Cost: $0.105/kWh
Fuel Cost: $1.140/Therm
Weather: GBS_04R20_159061

Estimated Energy & Cost Summary

Number of People	191 people
Average Lighting Power Density	0.60 W/ft²
Average Equipment Power Density	1.03 W/ft²
Specific Fan Flow	0.9 cfm/ft²
Specific Fan Power	0.651 W/cfm
Specific Cooling	303 ft²/ton
Specific Heating	9 ft²/kBtu
Total Fan Flow	3,482 cfm
Total Cooling Capacity	13 tons
Total Heating Capacity	451 kBtuh

Estimated Energy & Cost Summary

Annual Energy Cost	$9,293
Lifecycle Cost	$135,633
Annual Energy	
Electric	75309 kWh
Fuel	2134 Therms
Annual Peak Electric Demand	30.4 kW
Lifecycle Energy	
Electric	1,928,040 kWh
Fuel	84,479 Therms

Annual CO^2 Emissions

Electric	42.5 tons
Onsite Fuel	16.3 tons
Large SUV Equivalent	5.3 Large SUV's

Carbon Neutral Potential1 (CO^2 Emissions)

Base Case:	87.6 tons
This Run:	58.8 tons
Onsite Renewable Potential:	-45.1 tons
Natural Ventilation Potential:	-2.0 tons
Onsite Fuel Offset/Biofuel Use:	-16.3 tons
Net CO2 Emissions:	-4.6 tons
Large SUV Equivalent:	-0.4 Large SUV's

Water Usage and Costs

Total:	762,516 Gal/yr	$3,578/yr
Indoor:	458,356 Gal/yr	$2,787/yr
Outdoor:	304,159 Gal/yr	$791/yr

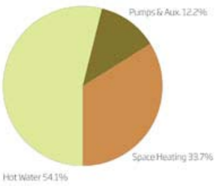
Water Efficiency Potential

Rainwater Harvesting:	82,155 Gal/yr	$214
Greywater Reclamation:	76,040 Gal/yr	$462
Site Potable Water Sources:	18,250 Gal/yr	$47
Total Net-Zero Savings:	176,445 Gal/yr	$723

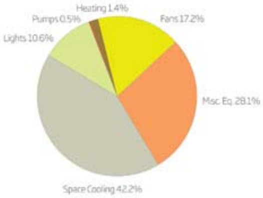
Photovoltaic Potential

Annual Energy Savings:	52,384 kWh
Total Installed Panel Cost:	$434,149
Nominal Rated Power:	54 kW
Total Panel Area:	4221 SF
Maximum Payback Period:	49 yrs @ $0.10 / kWh

Annual Electric End Use



Annual Fuel End Use

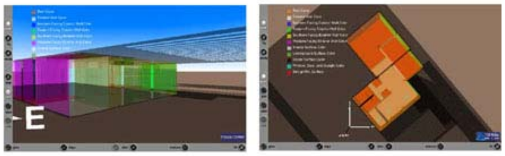


Wind Energy Potential

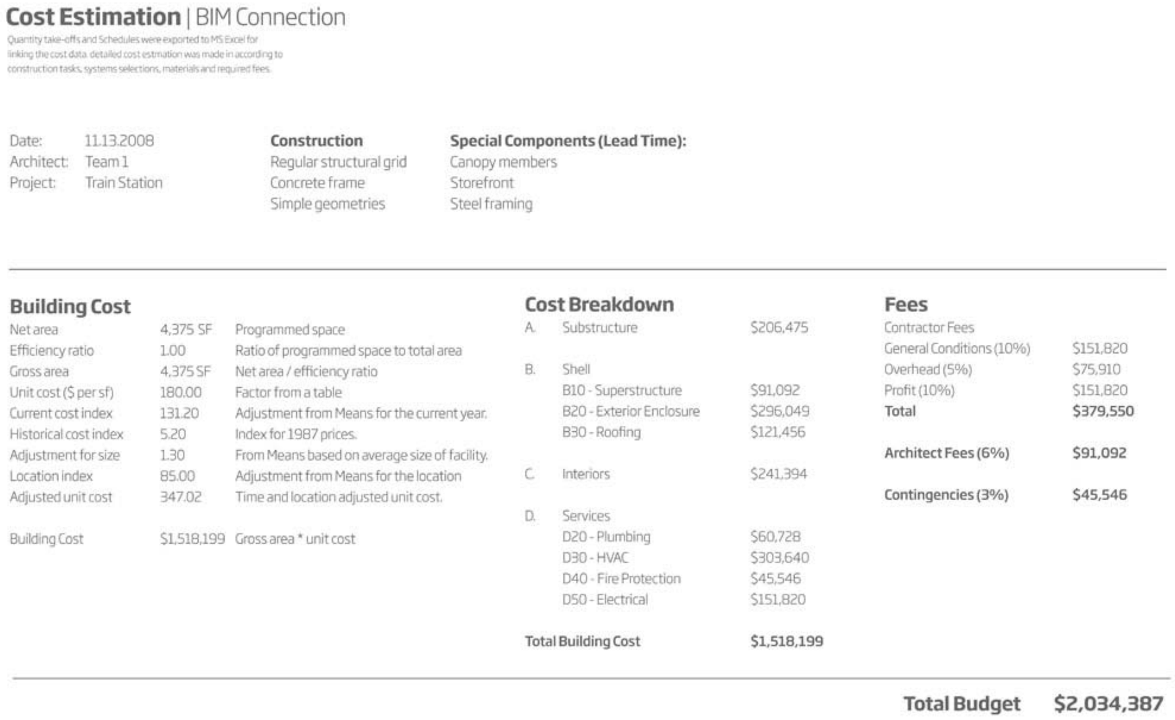
Annual Electric Generation:	1,307 kWh

Natural Ventilation Potential

Total Hours Mech. Cooling Required:	3,371 Hours
Possible Natural Ventilation Hours:	526 Hours
Possible Annual Electric Energy Savings:	2,391 kWh
Possible Annual Electric Cost Savings:	$251
Net Hours Mech. Cooling Required:	2,845 Hours



Thermal Surfaces, gbXML/VRML View



Cost Estimation | BIM Connection

Quantity take-offs and Schedules were exported to MS Excel for linking the cost data. detailed cost estimation was made in according to construction tasks, systems selections, materials and required fees.

Date: 11.13.2008
Architect: Team 1
Project: Train Station

Construction
- Regular structural grid
- Concrete frame
- Simple geometries

Special Components (Lead Time):
- Canopy members
- Storefront
- Steel framing

Building Cost

Net area	4,375 SF	Programmed space
Efficiency ratio	1.00	Ratio of programmed space to total area
Gross area	4,375 SF	Net area / efficiency ratio
Unit cost ($ per sf)	180.00	Factor from a table
Current cost index	131.20	Adjustment from Means for the current year.
Historical cost index	5.20	Index for 1987 prices.
Adjustment for size	1.30	From Means based on average size of facility.
Location index	85.00	Adjustment from Means for the location
Adjusted unit cost	347.02	Time and location adjusted unit cost.
Building Cost	$1,518,199	Gross area * unit cost

Cost Breakdown

A.	Substructure	$206,475
B.	Shell	
	B10 - Superstructure	$91,092
	B20 - Exterior Enclosure	$296,049
	B30 - Roofing	$121,456
C.	Interiors	$241,394
D.	Services	
	D20 - Plumbing	$60,728
	D30 - HVAC	$303,640
	D40 - Fire Protection	$45,546
	D50 - Electrical	$151,820
Total Building Cost		**$1,518,199**

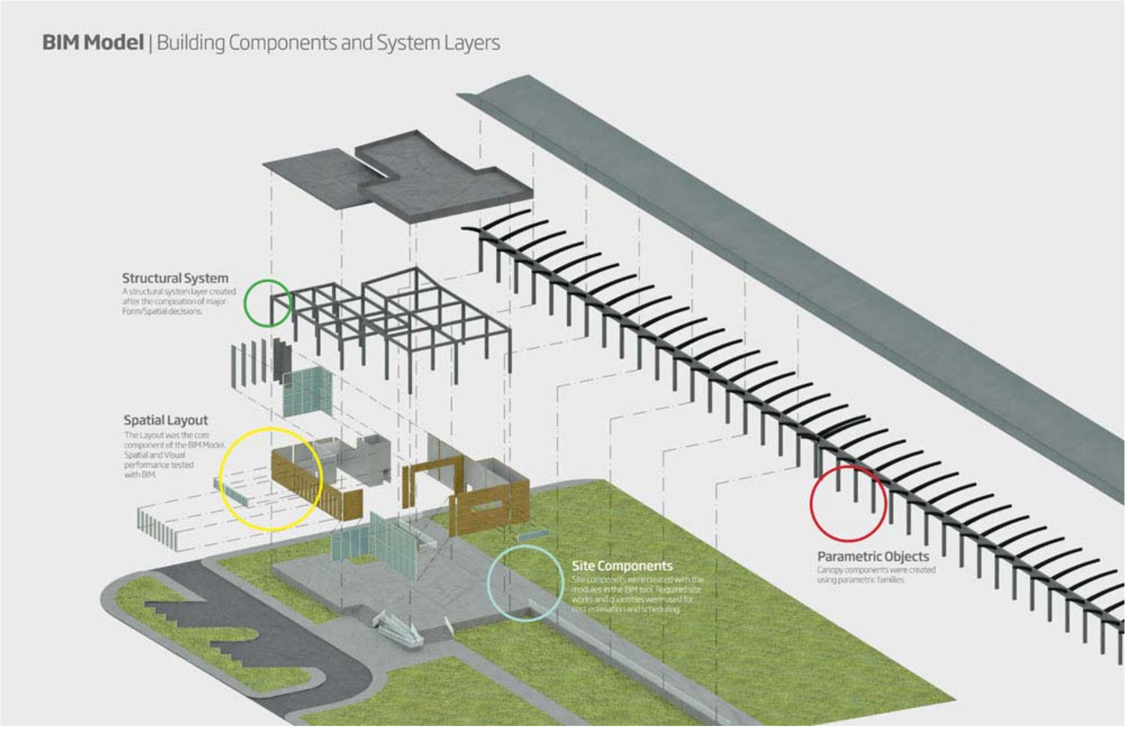
Fees

Contractor Fees	
General Conditions (10%)	$151,820
Overhead (5%)	$75,910
Profit (10%)	$151,820
Total	**$379,550**
Architect Fees (6%)	**$91,092**
Contingencies (3%)	**$45,546**

Total Budget **$2,034,387**

DESIGN TEAM 2 | Final Design

DESIGN TEAM 2 | Plan View



Visuals | Photorealistic Elevations

BIM Model was linked to a hi-end surface modeler tool (3D Studio MAX Design 2009) for GI based renders. Quick material assigments made by modification of Revit material definitions.

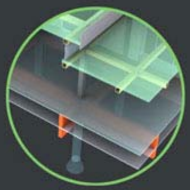
Elevation 1

Elevation 2

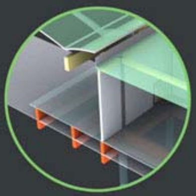
Structural BIM Model | Components and System Layers

A structural layer was created in the BIM model using parametric structural components. All structural components, load paths and required materials were retrieved from the BIM model for cost and constructability analysis.

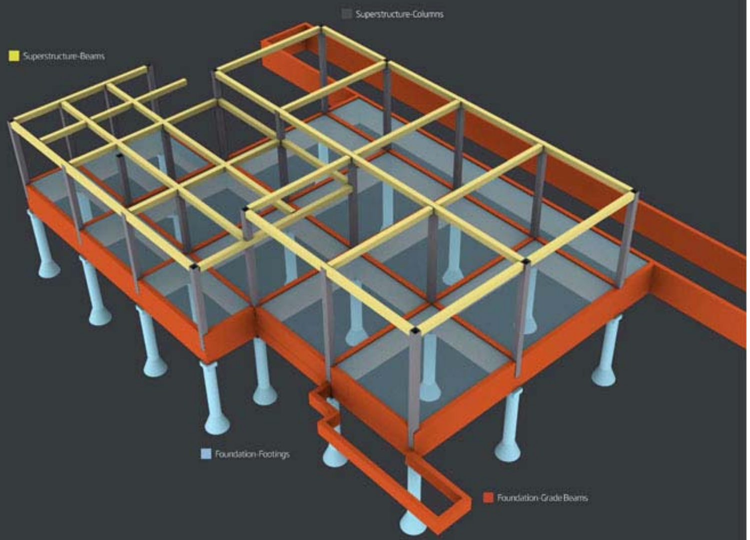
System Details



Structural system layer and its relationship to building components.

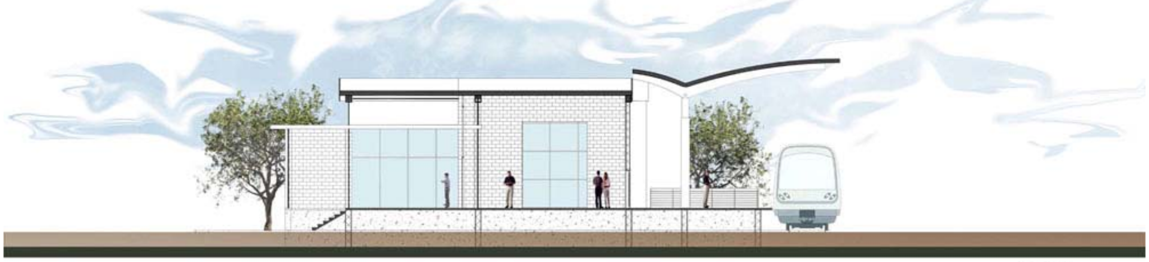


Parametric structural canopy members and its relationship to structural system.

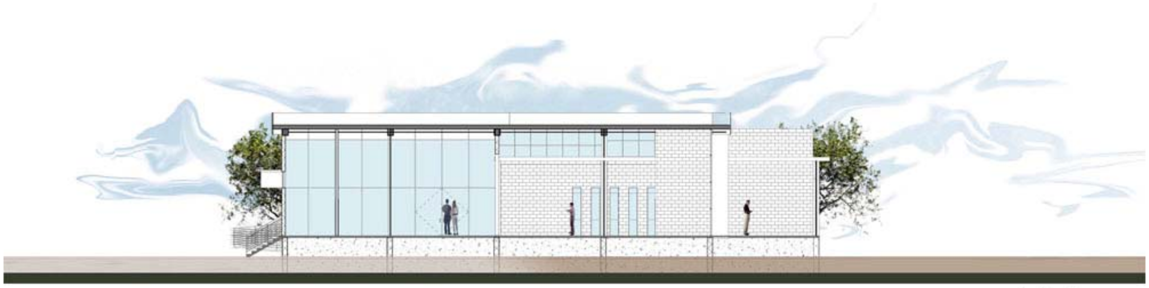


Visuals | Automatic Sections

Required 2D visuals were derived from the BIM Model and further processed with raster-vector image editing tools. All 2D and 3D visuals are internally coordinated.



Section 1



Section 2

Daylighting | BIM Connection

BIM Models were used to create 3D Models for the daylighting analysis of the buildings. Autodesk Ecotect and DaySim were the tools for the simulations.

Daylight Factor (DF) Analysis: 93% of all illuminance sensors have a daylight factor of 2% or higher. If the sensors are evenly distributed across 'all spaces occupied for critical visual tasks', the investigated lighting zone should qualify for the LEED-NC 2.1 daylighting credit 8.1 (see www.usgbc.org/LEED/).

Daylight Autonomy (DA) Analysis: The daylight autonomies for all core workplane sensors lie between 69% and 94%.

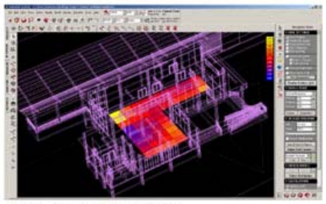
Useful Daylight Index (UDI) Analysis: The Useful Daylight Indices for the Lighting Zone are $UDI_{<100}$=6%, $UDI_{100\text{-}2000}$=13%, $UDI_{>2000}$=80%.

Continuous Daylight Autonomy (DA_{con})and DA_{max} Analysis: 83% of all illuminance sensors have a DAcon above 80%. 31% of all illuminance sensors have a DAmax above 5%.

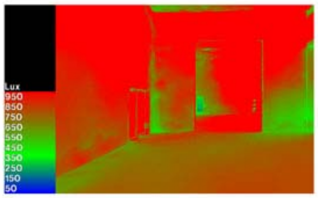
Electric Lighting Use: The predicted annual electric lighting energy use in the investigated lighting zone is: 2.1 kWh/unit area.

March 21st 16:00hrs / cafe-museum space

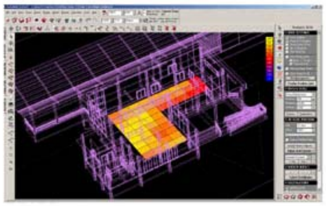
March 21st 16:00hrs (Human Sensitivity) cafe-museum



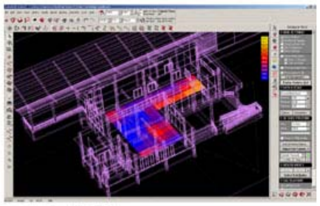
Screenshot from Daylight Factor Analysis (DF)



March 21st 16:00hrs / False Color



Screenshot from the UDI 100-2000 lux



Screenshot from UDI >2000 lux

Energy & Environment | BIM Connection

BIM Models were used to create gbXML files for the analysis of the buildings. Autodesk Green Building Studio and Autodesk Ecotect were the tools for Energy and Environment simulations.

Project Title: Train Station
Run Title: Team2_Final_Analysis
Building Type: Transportation
Floor Area: 4011SF (Indoor) - 4315 SF Gross

Location Information

Building: Train Station
Electric Cost: $0.105/kWh
Fuel Cost: $1.140/Therm
Weather: GBS_04R20_159061

Building Summary

Number of People	198 people
Average Lighting Power Density	0.62 W/ft²
Average Equipment Power Density	1.03 W/ft²
Specific Fan Flow	1.1 cfm/ft²
Specific Fan Power	0.651 W/cfm
Specific Cooling	189 ft²/ton
Specific Heating	9 ft²/kBtu
Total Fan Flow	4,508 cfm
Total Cooling Capacity	22 tons
Total Heating Capacity	465 kBtuh

Estimated Energy & Cost Summary

Annual Energy Cost	$9,250	
Lifecycle Cost	$132,193	
Annual Energy		
	Electric	70227 kWh
	Fuel	2301 Therms
	Annual Peak Electric Demand	27.8 kW
Lifecycle Energy		
	Electric	2,269,769 kWh
	Fuel	74,241 Therms

Annual CO^2 Emissions

Electric	53.3 tons
Onsite Fuel	14.4 tons
Large SUV Equivalent	6.1 Large SUV's

Carbon Neutral Potential (CO^2 Emissions)

Base Case:	87.6 tons
Base Run:	77.5 tons
This Run:	67.6 tons
Onsite Renewable Potential:	-43.2 tons
Natural Ventilation Potential:	-2.1 tons
Onsite Fuel Offset/Biofuel Use:	-14.4 tons
Net CO^2 Emissions:	8.0 tons
Large SUV Equivalent:	0.7 Large SUV's

Water Usage and Costs

Total:	609,458 Gal/yr	$2,916/yr
Indoor:	505,058 Gal/yr	$2,712/yr
Outdoor:	104,400 Gal/yr	$204/yr

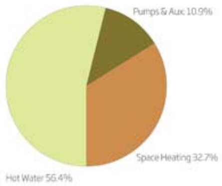
Water Efficiency Potential

Rainwater Harvesting:	84,667 Gal/yr	$220
Greywater Reclamation:	26,100 Gal/yr	$59
Site Potable Water Sources:	18,250 Gal/yr	$47
Total Net-Zero Savings:	129,017 Gal/yr	$426

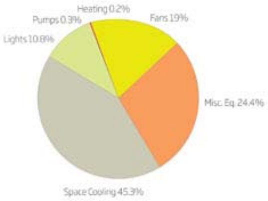
Photovoltaic Potential

Annual Energy Savings:	50,135 kWh
Total Installed Panel Cost:	$377,845
Nominal Rated Power:	47 kW
Total Panel Area:	3673 SF
Maximum Payback Period:	47 yrs @ $0.10 / kWh

Annual Electric End Use



Annual Fuel End Use



Wind Energy Potential

Annual Electric Generation:	1,307 kWh

Natural Ventilation Potential

Total Hours Mech. Cooling Required:	3,350 Hours
Possible Natural Ventilation Hours:	528 Hours
Possible Annual Electric Energy Savings:	2,453 kWh
Possible Annual Electric Cost Savings:	$235
Net Hours Mech. Cooling Required:	2,822 Hours

Cost Estimation | BIM Connection

Quantity take-offs and Schedules were exported to MS Excel for linking the cost data. detailed cost estmation was made in according to construction tasks, systems selections, materials and required fees.

Date: 11.13.2008
Architect: Team 2
Project: CS Train Station

Construction

Regular structural grid
Load bearing masonry
Simple geometries

Special Components (Lead Time):

Complex canopy framing
Storefront

Building Cost

Net area	4,700	Programmed space
Efficiency ratio	1.00	Ratio of programmed space to building area
Gross area	4,700	Net area / efficiency ratio
Unit cost ($ per sf)	190.00	Factor from a table
Current cost index	131.20	Adjustment from Means for the current year.
Historical cost index	75.20	Index for 1987 prices.
Adjustment for size	1.30	From Means based on average size of facility.
Location index	85.00	Adjustment from Means for the location
Adjusted unit cost	366.30	Time and location adjusted unit cost.
Building Cost	$1,684,960	

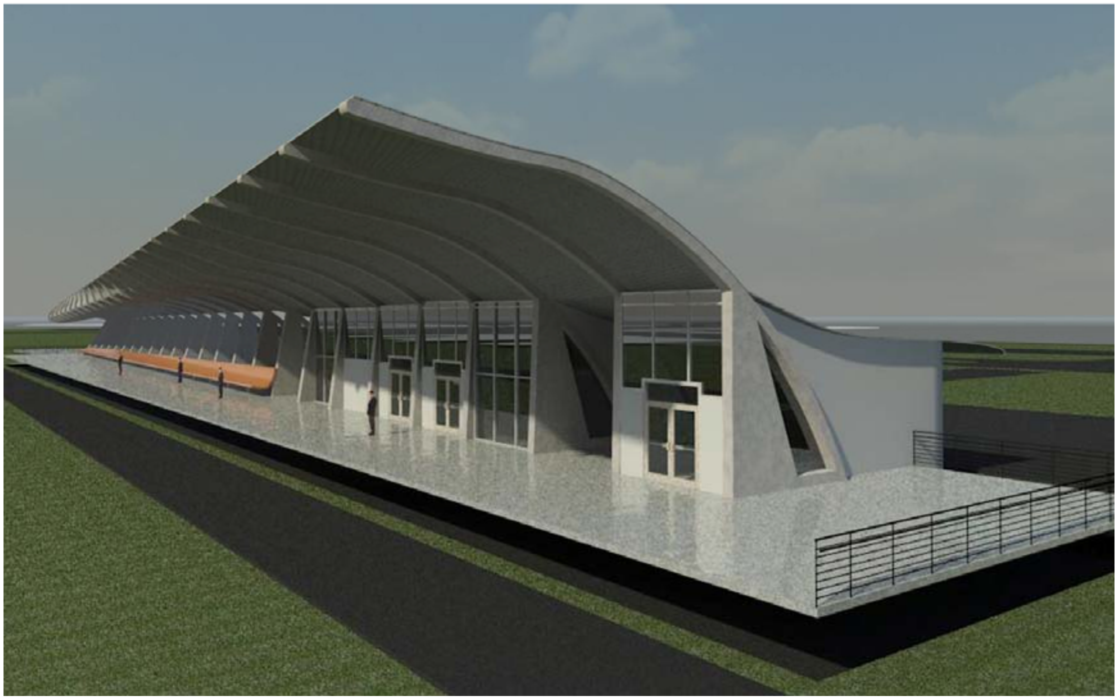
Cost Breakdown

A.	Substructure	$229,155
B.	Shell	
	B10 - Superstructure	$101,098
	B20 - Exterior Enclosure	$336,992
	B30 - Roofing	$134,797
C.	Interiors	$259,484
D.	Services	
	D20 - Plumbing	$67,398
	D30 - HVAC	$336,992
	D40 - Fire Protection	$50,549
	D50 - Electrical	$168,496

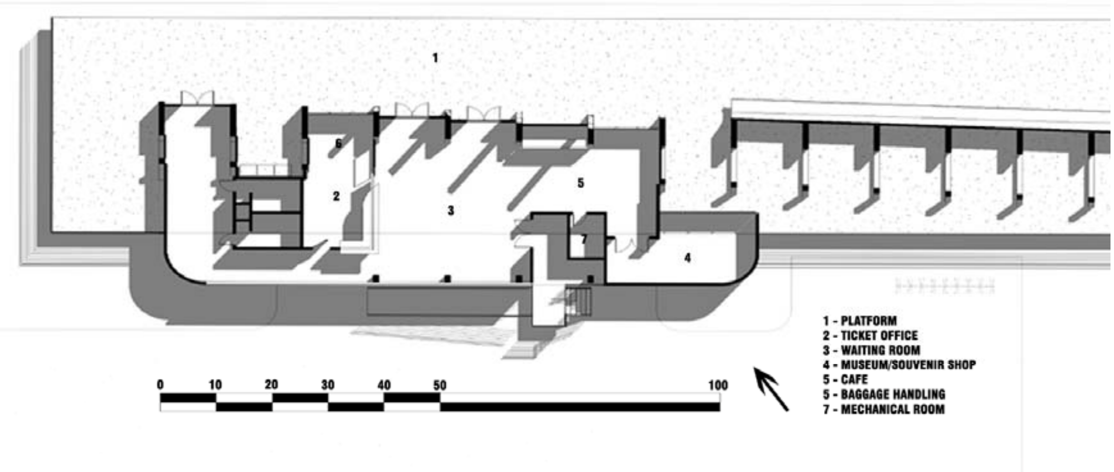
Fees

Contractor Fees	
General Conditions (10%)	$168,496
Overhead (5%)	$84,248
Profit (10%)	$168,496
Total	**$421,240**
Architect Fees (6%)	**$101,098**
Contingencies (3%)	**$50,549**

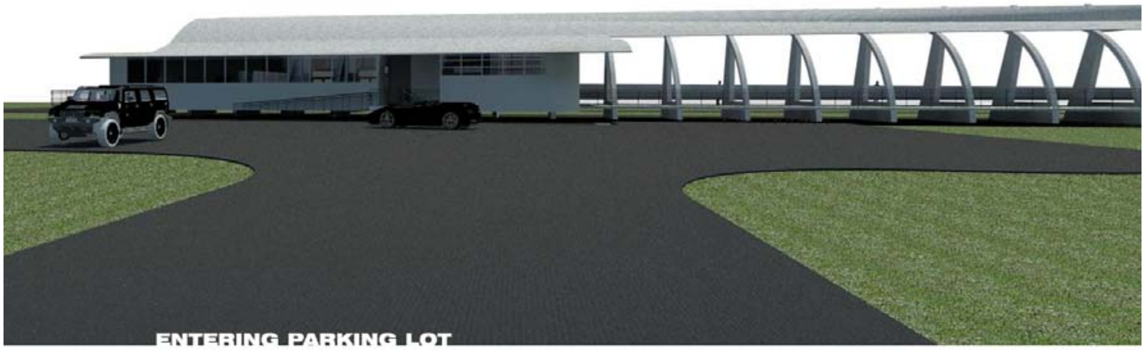
Total Budget **$2,257,847**



GROUND FLOOR PLAN

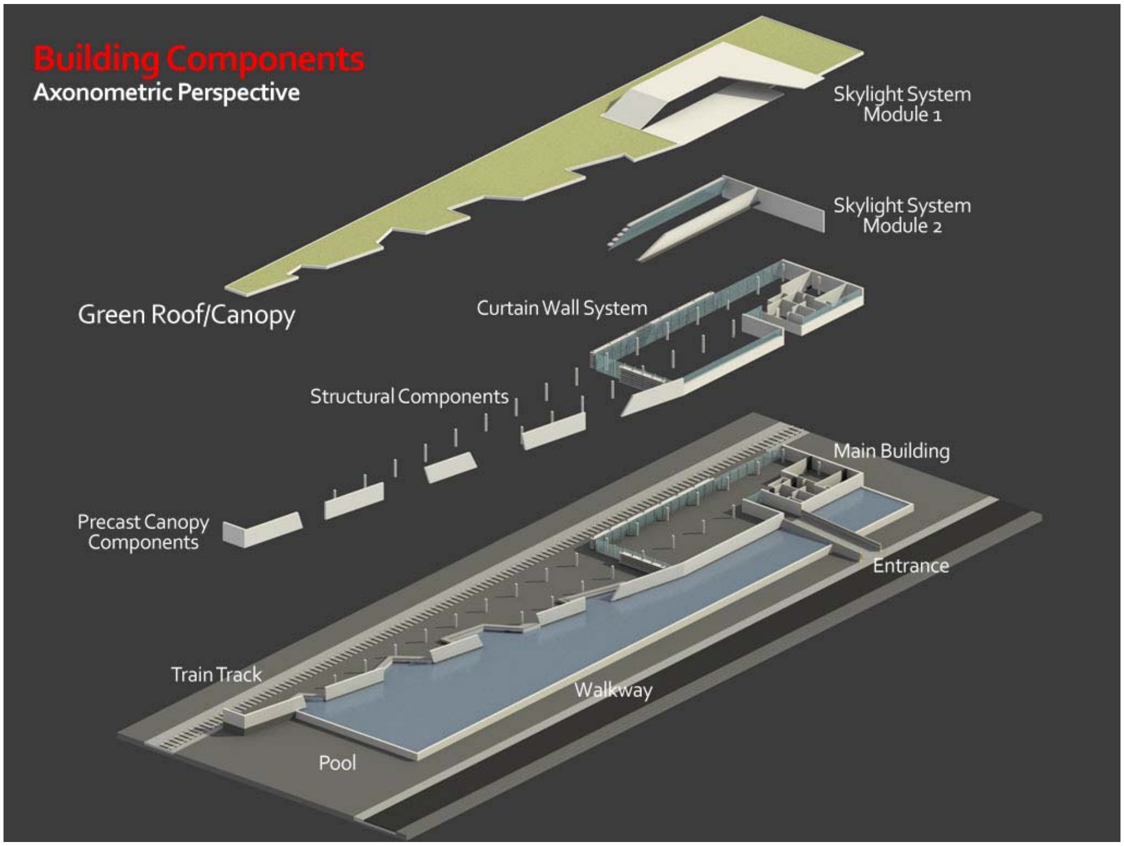


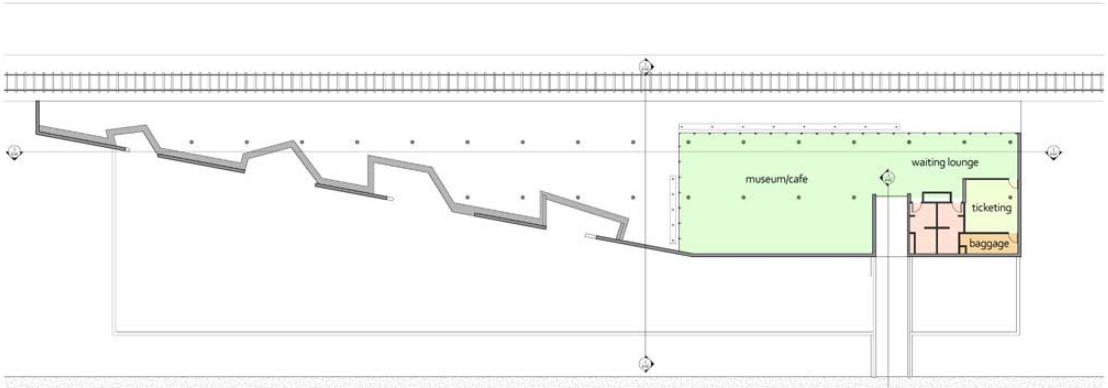
BIRD'S EYE VIEW FROM ACROSS THE TRACKS


ENTERING PARKING LOT

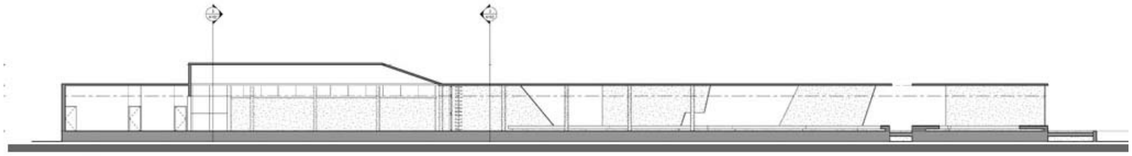

VIEW FROM ACROSS TRACKS


PERSPECTIVE: LOOKING AT BAR


Building Components
Axonometric Perspective
Skylight System Module 1
Skylight System Module 2
Green Roof/Canopy
Curtain Wall System
Structural Components
Main Building
Precast Canopy Components
Entrance
Train Track
Walkway
Pool

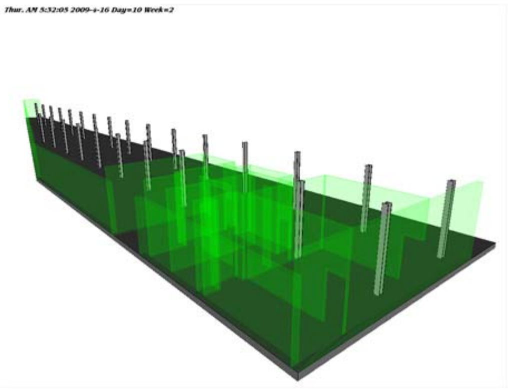


Plan View



Section

Project 2
Exterior Perspectives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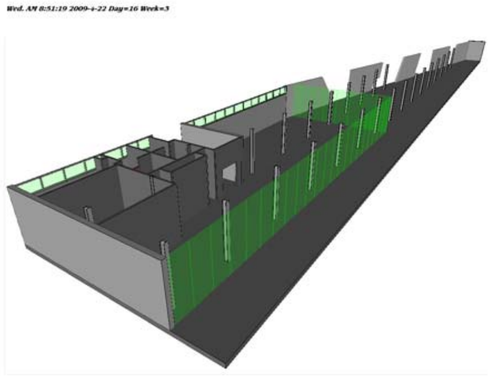
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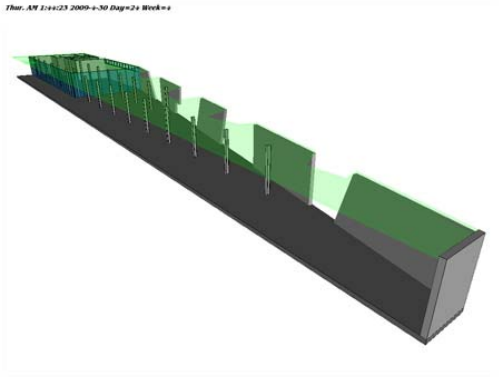
Fri. PM 12:48:36 2009-4-24 Day=19 Week=3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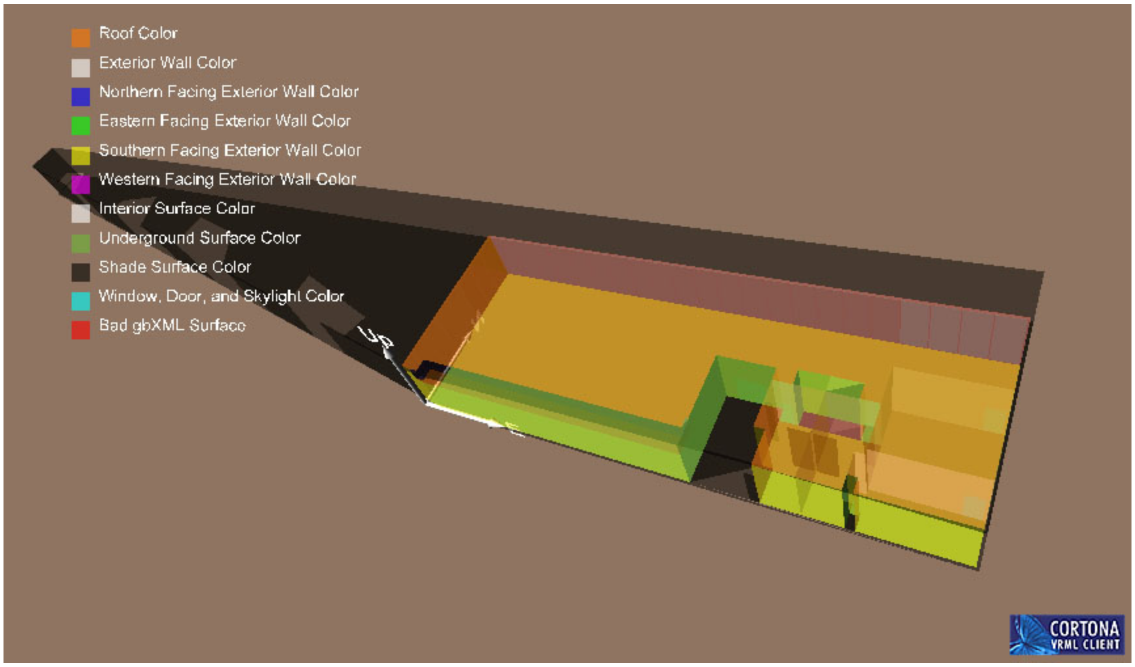
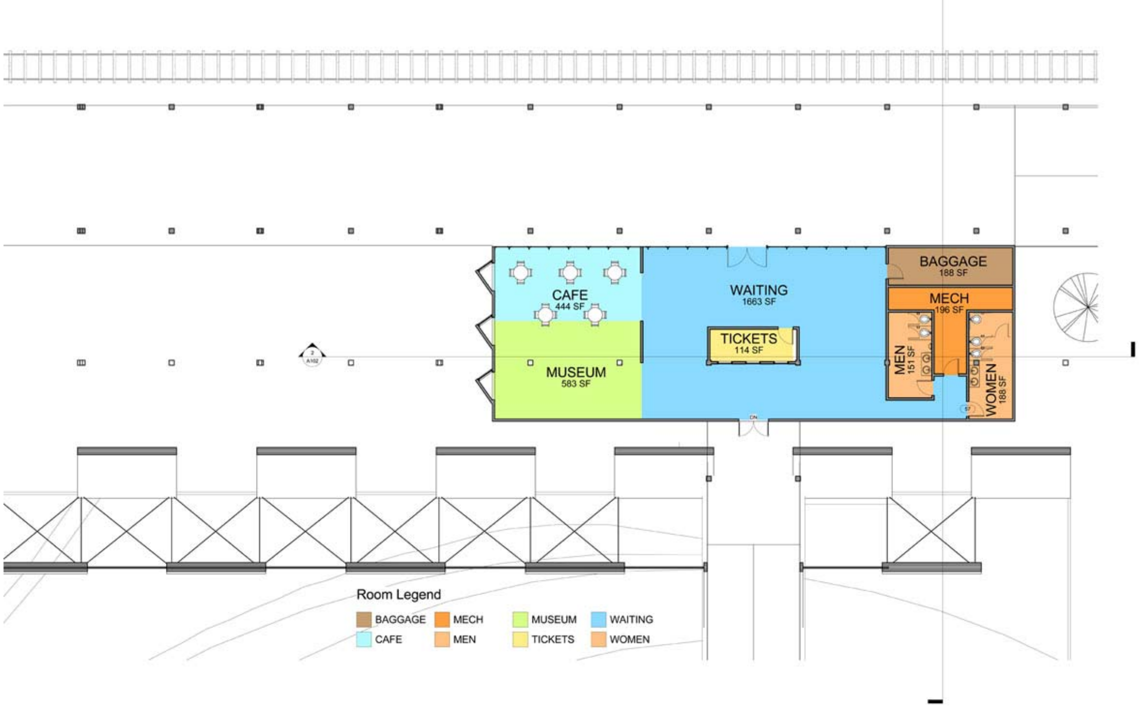

Roof Color
Exterior Wall Color
Northern Facing Exterior Wall Color
Eastern Facing Exterior Wall Color
Southern Facing Exterior Wall Color
Western Facing Exterior Wall Color
Interior Surface Color
Underground Surface Color
Shade Surface Color
Window, Door, and Skylight Color
Bad gbXML Surface
CORTONA VRML CLIENT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CAFE
444 SF
WAITING
1663 SF
MECH
196 SF
TICKETS
114 SF
MEN
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MUSEUM
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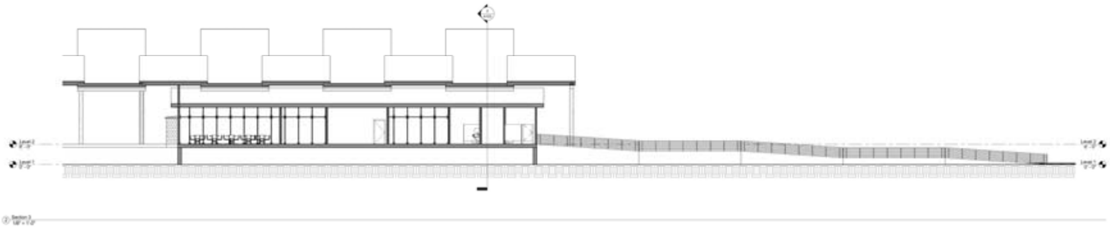
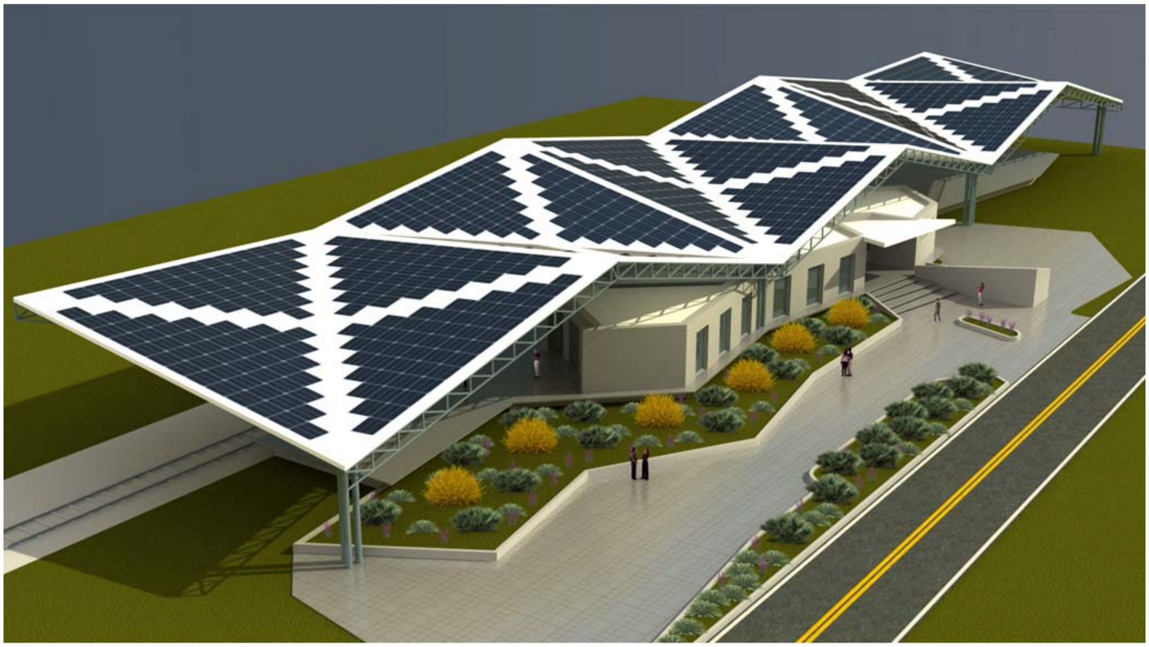
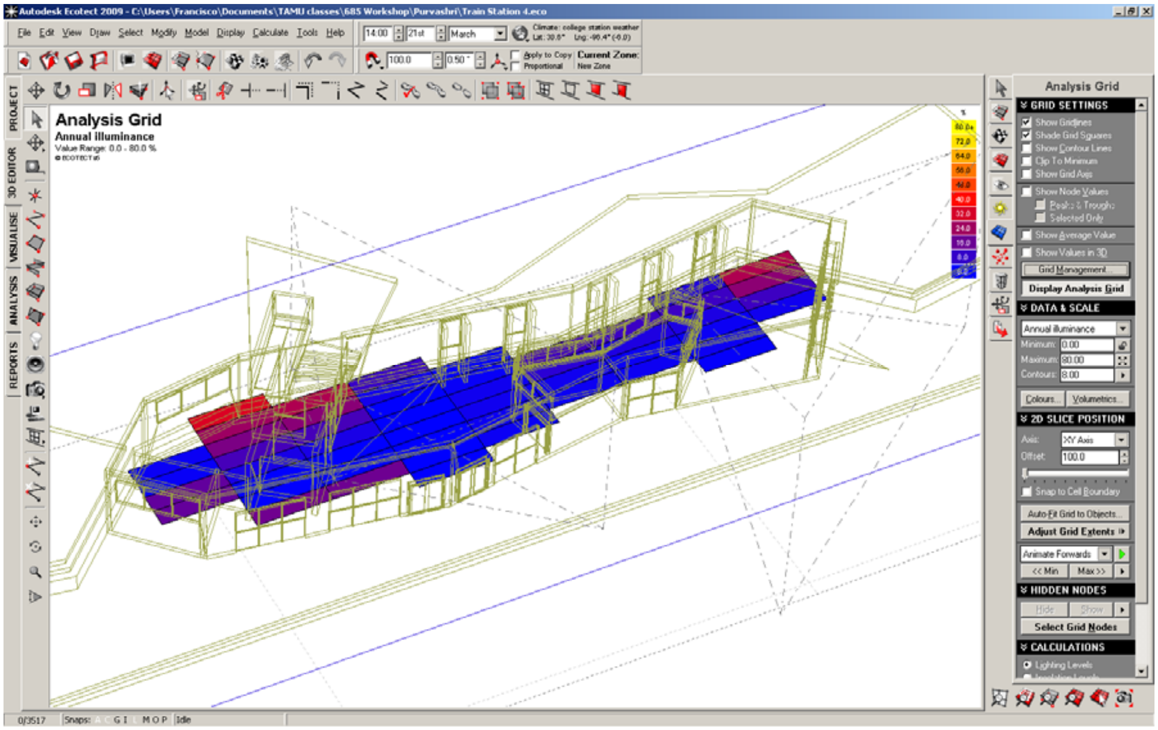
WOMEN
188 SF
Room Legend
BAGGAGE
MECH
MUSEUM
WAITING
CAFE
MEN
TICKETS
WOMEN


Level 2
Level 1
Section 2





Autodesk Ecotect 2009 - C:\Users\Francisco\Documents\TAMU classes\685 Workshop\Purvashri\Train Station 4.eco

Climate: college station weather Lat: 30.6° Lng: -96.4° (-6.0)

14:00 21st March

Current Zone: New Zone

Analysis Grid

Annual illuminance

Value Range: 0.0 - 80.0 %

GRID SETTINGS

☑ Show Gridlines
☑ Shade Grid Squares
☐ Show Contour Lines
☐ Clip To Minimum
☐ Show Grid Axis
☐ Show Node Values
☐ Peaks & Troughs
☐ Selected Only
☐ Show Average Value
☐ Show Values in 3D

DATA & SCALE

Annual illuminance

Minimum: 0.00

Maximum: 80.00

Contours: 8.00

2D SLICE POSITION

Axis: XY Axis

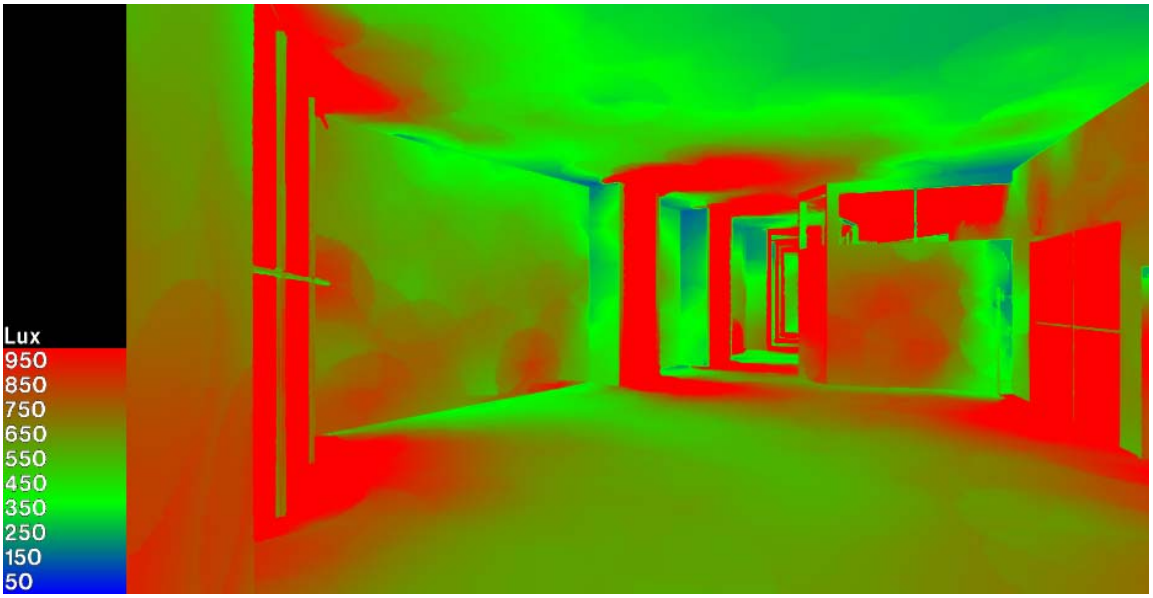
Offset: 100.0

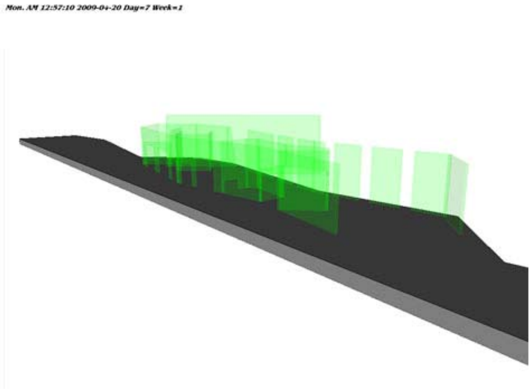
☐ Snap to Cell Boundary

Animate Forwards

CALCULATIONS

● Lighting Levels


Lux
950
850
750
650
550
450
350
250
150
50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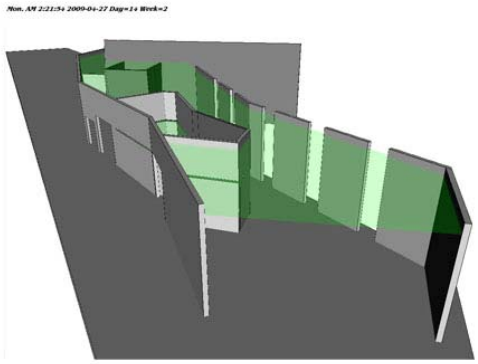
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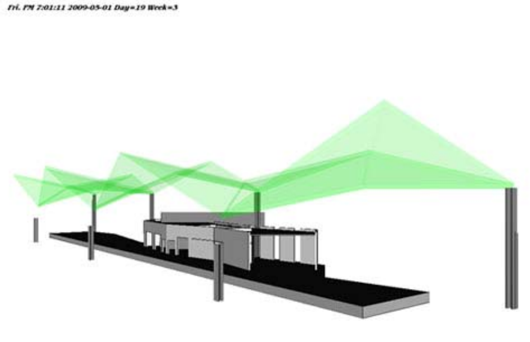
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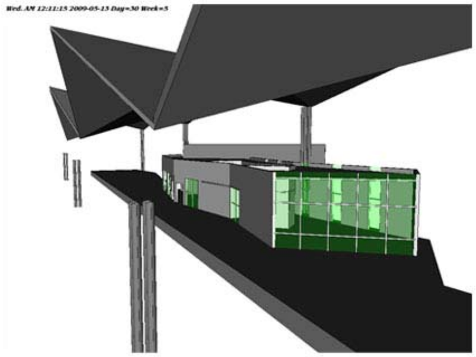
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VITA

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B.Arch., Istanbul Technical University, Turkey, 2000
M.Arch. Design Computing, Istanbul Technical University, Turkey, 2003
Ph.D. Architecture, Texas A&M University, 2009

Selected Publications:
Clayton M.J., O. Özener, C. Nome. 2009. BIM to CAFM: An Investigation of Adapting a Building Information Model to a Legacy Computer Aided Facility Management System In *Proceedings of CIB W78 26th International Conference on Managing IT in Construction* Istanbul, Turkey 1-3 October, 2009. pp. 34-39.

Clayton, M.J., R.E. Johnson, J.A. Vanegas, O. Özener, C.A. Nome, and C.E. Culp 2009. Downstream of design: Lifespan costs and benefits of building information modeling. Technical Report. College Station, TX: CRS Center for Leadership and Management in the Design and Construction Industry.

Evrenosoglu, C.Y., A. Abur, E. Akleman, O. Özener. 2009. Bewley diagrams revisited *IEEE Transactions on Power Systems* 24 (3):1401-1407

Landrenau, E., O. Özener,, B. Pak, E. Akleman, and J. Keyser. 2006. Interactive rule-based design: An experimental interface for conceptual design, In *Innovations in Design & Decision Support Systems in Architecture and Urban Planning*, ed. Van Leeuwen, J.P. and H.J.P. Timmermans, 433-446. Dordrecht, Netherlands: Springer.

Özener, O., E. Akleman, V. Srinivasan. 2005. Interactive rind modeling for architectural design, *International Journal of Architectural Computing* 3 (1):93-106

Memberships:
FIATECH, ACADIA, eCAADe, IFMA TAMU Chapter