AC 2011-2401: USING PERFORMANCE MODELING AS A VEHICLE FOR RE-INTEGRATION

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Using Building Performance Modeling as a Vehicle for Re-Integration

Section 1 Introduction

Section 1.1 The Challenge

One of the biggest challenges in today’s building design industry revolves around the management of an integrated design team. This issue is particularly painted by the need for deep energy savings in buildings. An integrated team should be equipped with the tools and knowledge to work between professional areas of focus. Design decision making will always be rife with competing interests between the professions; however an improvement in the process of design can provide designers with the evidence needed to make empowered decisions about energy use in buildings. The origin of this improvement lies within academia, whose structure must address the collaborative problems inherent within the professional practices of the building industry. This paper proposes a new, combined architecture and engineering course that addresses the education and implementation of integrated design through the use of building performance simulation as a vehicle for reintegration.

Section 1.2 The Problem

Throughout the latter half of the 20th century standard practice workflow between the design professions involved giving engineering consultants rigidly defined problems and variables around which to design systems, but the growing need to achieve deeper energy savings has proven this process ineffective. This concept is not new, however there are challenges that persist in academia that have slowed its implementation and this paper addresses several of those roadblocks. The impediments began mostly during the mid-century when architects began to sub-contract the design of the comfort systems to specially trained consultants or engineers in mechanical systems. This transition between the skills of designing the “architecture” of the building and to deliver human comfort, reflected a further schism between the professions and reached an apex in the years after World War II. According to Dr. Joseph Lstiburek, “During the post-war building boom, the emphasis on educating architects shifted to aesthetics and design theory relating to aesthetics and away from the fundamental aspects of construction and understanding of materials, assemblies, building systems, and subsystems2.”

The division of labor is a logical outgrowth of the increased knowledge needed to master the expanding profession. For instance, it would be quite a challenge to learn all the new complex structural technologies and theories concurrently with a full architectural education. This could again be said of the further specialization that took place in the mid twentieth century with the outgrowth of Heating, Ventilation, and Air Conditioning (HVAC) engineering and electric lighting design.

This creates a dilemma for modern practice and education. On one hand, there is a growing need for increased specialization to tackle complex emerging technologies; on the other hand, there is an even greater need for these specialties to commune in the design process. It is
obvious that this division of knowledge is convenient for the academy and practice due to concerns of professional licensure and academic accreditation, but diminishes the potential for creating integrated designs.

Section 1.2 The Difficulty and Prospects of Integrated Design

The challenge of low energy buildings is primarily one of integrated design, which at its core is more about the fundamentals of leadership, team dynamics, and design process than it is about any technical skill or training. In the end, a well educated and knowledgeable integrated designer will fundamentally be a skilled team member able to communicate their expertise and opinion as well as be able to ascertain and synthesize the ideas of other team members from other professions. These skills are hard to learn in the field, therefore it is becoming increasingly important to incorporate the education of how to work together early in academic curriculums.

The goal of educating future designers then should become much more engaged between what are now silos of academic realms of theory and practice. Though this particular problem exists between many of the design and trade professions it is particularly poignant between architectural practice and building systems designers taking into account the priority that has been placed on drastically reducing energy use over the next few decades and looming discussions of carbon cap and trade.

After addressing the fundamental teaming aspect of integrated design, a more defined system must be taught as a framework for operating within and as a conceptual basis for design. While the course should function under a holistic design philosophy that addresses every aspect of sustainability, this proposed course will pay special attention to energy efficiency goals and human comfort objectives. This is because the energy reduction component in the sustainability nexus is often the hardest to achieve, takes the most collaboration, and has the potential to provide a tangible milieu upon which to revolve around. To focus the course towards the goals of energy reduction it will focus on Integrated Design as defined by Brown and Cole, 2006, “Integrated design synthesizes climate, use, loads, and systems resulting in a more comfortable and productive environment, and a building that is more energy-efficient than current practices”.

In the last decade, there has been a renewal of regional utility energy conservation programs aimed at improving awareness of the value of energy in our economy. These regional utility programs have funded a network of university-based energy efficiency research and outreach institutions that perform technical consulting on sustainable building projects. The primary goal of these entities is to affect market transformation and reduce energy use in buildings through direct involvement in design projects, the application of in-house research, and educating the professions. This process hinges around using the integrated design process outlined above and has gained much wider acceptance in the market as a result. The utility-funded technical assistance projects required the employment of student research assistants to implement iterative building performance simulation as a method of consulting. Given that these entities reside within the university colleges of architecture, most of the research assistants have been graduate students of architecture, and sometimes engineering. These students have the opportunity to learn about the process of using iterative performance modeling within a professionally integrated team setting. The educational model is designed so that the students then graduate and populate the profession as champions of the integrated design process, further effecting market transformation for energy efficiency. This paper was also created to document the educational model of the research assistants, and help define an educational curriculum that will lead to a career of successful integrated design by architectural, mechanical, and electrical engineers of the future.

The following seven constructs serve to provide a more thorough description of integrated design as practiced and promoted by the Pacific Northwest University Integrated
Design Lab Network. They are also useful as evaluation criteria for the design team and design process with regard to its level of design integration, listed below:

1. The design team established building performance goals in both energy and comfort (quantitative or qualitative) and compared the building’s performance (during design) to these goals.
2. The design team worked outside of normal disciplines to identify and exploit synergies between climate, use, building and site design, and system selection and design.
3. Energy efficiency related analyses were completed to inform design decisions.
4. The design team considered climate as a resource.
5. The design team considered whether occupancy schedules and comfort criteria were malleable.
6. The design team designed the building to create small loads.
7. The design team matched the system design to actual loads.

Section 1.3 Using Building Performance Simulation for Education and Praxis

Integrating building performance simulation into the design curriculum affects two crucial parameters. First, the use of building performance simulation provides a horizon upon which to ground the design of a building. Too often contemporary architecture students are taught to exercise unbridled formal ambitions that lack grounding in engineering, cost estimation, or constructability. While teaching design is a critical aspect of architectural education, it must be balanced with an approach that grounds architecture within its broader framework of collaboration. At the more advanced levels of engineering and architectural education, the curriculum should include the use of building simulation and the idea of energy and comfort performance as an important driver for the design process. This will support student design decisions based upon the affect on a building’s lighting, heating, cooling performance, and the comfort of future occupants. In this setting, for example, the glazing of a façade becomes less about referential stylistic applications and more about whether the window pattern provides the defined daylight illumination levels while avoiding thermal penalties. Aesthetics must play a central role in creating vitality between people and the built environment, but in the proposed curriculum it will be founded upon an ethic that design must also be grounded in physics and energy efficiency. The students will learn that it is the combination of aesthetics and performance that create sustainable buildings.

Building performance simulation not only has the potential to improve the process of design, but it can also improve the process of collaboration. The full integration of energy and daylight modeling early in the design process has the potential to redefine the working relationship for both academic and professional praxis. We propose that by using performance modeling as a vehicle, multi-disciplinary teams of university students will learn the process of integrated design and effective project delivery. Utilizing performance modeling throughout the
The design process requires involvement from multiple professions throughout the entire project’s progression. For example, as architects employ energy modeling early in the design process to analyze building orientation, form, and envelope in order to reduce primary building loads and promote comfort, input is needed from the engineers to optimize these designs, as well as on how to specify HVAC systems within the energy model. Everything from orientation, form and envelope design, to insulation content, coefficients of performance, and sizing specifications can be worked on concurrently by the two professions. Additionally, the energy and daylight modeling process can create large quantities of data that can only be understood through an integrated team approach. The resultant data from these outputs are interconnected and require collaborative thinking to understand their full impact on energy consumption.

Figure 2 – Diagram showing the energy modeling process in conjunction with architectural and engineering discipline involvement during design. The gray bars refer to the energy use on the left axis while the colored curves in the background represent the two different disciplines involvement throughout the different phases of design.

The course described in this paper is designed to cover two major challenges in building design education. First, the team process by which architects and engineers will face the challenge of synthesizing design throughout the disparate divisions of practice. Second, the curriculum will provide the students with a framework of process using building simulation that will guide their decision making through the final building design.

Section 1.4 Literature Review

The literature search for this paper explored past examples and pedagogical approaches to integrated building simulation within a design curriculum as well as established models in professional practice. The Society of Building Science Educators (SBSE) created a database of
studio projects that documents teaching methodologies that align with the Carbon Netural Design (CND) Project (http://www.architecture.uwaterloo.ca/faculty_projects/terri/carbon-aia/introduction.html). This CND project was created by the SBSE in response to the magnitude and urgency of the ecological challenges that face architectural educators and professionals. The project’s goal is to disseminate the resources and tools needed to integrate carbon neutral and zero-energy design into professional architecture programs and praxis. As a result, the SBSE Carbon Neutral Studio initiative was implemented in Fall 2007 to develop carbon-neutral teaching resources and tools and share these educational resources and studio outcomes. The studio initiative includes a network of 50 professors from around the world and about 30 carbon neutral studio projects. The web database displays a matrix that documents each professor’s studio project, course objectives, software approaches, resources, etc according to the different areas of focus throughout the design process. These areas of focus include frameworks and goals setting, site, envelope, passive strategies, and even energy simulation.

Upon researching several different projects within the matrix, multiple patterns started to emerge that illuminated different strategies used currently within academia regarding building performance simulation. First, most of the projects were seminars and not studios and the majority of courses did not use any type of simulation software to verify or explore different energy implications of design strategies. The projects that did utilize performance modeling approach typically focused only on a fragment of the building energy picture. Some approaches were interested in the analysis of early massing approaches, some were concerned with envelope, others with passive design measures, but it was very rare to see a continuous software approach across an entire design focused on whole building optimization. Additionally, none of these projects attempted to integrate an architecture studio and mechanical engineering project together which precluded the exploration of the effect of HVAC systems and their relationship to the rest of the building’s architecture. Also present was a disconnect between the software tools used in the studios and the industry tools used in professional practice which are geared toward providing documentation requirements needed by certification programs such as the Leadership in Energy and Environmental Design (LEED) standard. In some cases Ecotect was the only software utilized for both daylight and energy analysis, when much more accurate tools exist for these types of simulation.

One studio at the University of Texas directed by Professor Hazem Rashed-Ali utilized a similar approach to this paper’s proposed course in an undergraduate seminar called “Applications in Sustainable Design”. The seminar integrated eQUEST into the course to create annual energy use intensity (EUI) stats and disaggregated energy end use monthly consumption graphics. Additionally, an Ecotect and Radiance daylighting model was also required to integrate detailed daylight analysis within the course. Even though an iterative approach was not taken, the results from the model were compared against EnergyStar’s Target Finder benchmark buildings to identify potential design modifications and strategies. The instructor cautioned that although eQUEST is a graphic user interface, and specific schematic design wizard options made the program easier to use for beginners, taking advantage of all of its capabilities requires extensive energy modeling experience.

Another introductory graduate level course from the University of Minnesota served as a good example of integrating a rigorous building simulation approach throughout the entire design process. The course utilized Ecotect for thermal modeling and Radiance for daylight
analysis and renderings. The course was broken into six phases that focused on envelope study models, daylight analysis of a single room, iterative detailed load analysis, graphic models and architectural integration sections, and finally a written analysis documenting the entire process. The instructors noted that emphasis should be placed upon the integration of daylighting and thermal strategies early in the process, so that the two refrain from becoming disconnected and in conflict. While the course was extremely comprehensive, it did not emphasize mechanical systems integration or an upfront thorough research of energy goals and analysis techniques.

Our literature search also reviewed different professional approaches to integrated design and their varying emphasis on building simulation processes. The Whole System Integration Process (WSIP) concept, developed by the Institute for Market Transformation to Sustainability, discusses the importance of the integrative design process above and beyond the assembling of an integrated design team. The purpose of which is to effectively manage the optimization of complex systems while pursing sustainable practices in design and construction. Their research argues that to be able to achieve cost effective and sustainable performance, it is necessary to shift from a conventional linear design and delivery process to the practice of interrelated systems integration. This process solves problems iteratively and in such a way that allows feedback loops to affect decision making and influence earlier design decisions. The model spells out a series of interrelated charrette meetings dispersed throughout the entire design process where all disciplines of the project are involved in actively co-solving design problems. While the process is well defined in terms of project milestones, issues to consider, goals, etc throughout the design process, it lacks in content describing specifically how to work across the disciplines.

Another guideline-oriented document titled “Roadmap for the Integrated Design Process”, created by Busby Perkins+Will and Stantec Consulting, serves as a comprehensive professional guide to developing both an integrated team and process. The document provides a means to explore and implement sustainable design principles on a project while staying within budgetary and scheduling constraints. It follows the design through the entire project life, from pre-design through occupancy and into operation. This document, similarly to the WSIP concept, speaks about the importance of utilizing an iterative design process that allows for feedback loops and mechanisms to evaluate all design team decisions. While it briefly mentions energy modeling as one of these mechanisms to evaluate design decisions based upon energy consumption and life cycle costing analysis, it does not go into detail about the extent of how to incorporate modeling into this integrated process. The document does spell out the role of energy modeling in the different phases of the integrated design process, but it lacks the specifics on how the team can use simulation to help solve a variety of different design problems.

A literature source that does illuminate the specific role of simulation into the integrated design process comes from the Northwest Energy Efficiency Alliance. The recent document, “Integrating Energy Engineering & Performance Modeling into the Design Process”, is a guide that looks at how to incorporate building simulation throughout all phases of design. The document spells out the scope of building performance modeling, areas of focus, potential useful outputs, and how it can be specifically used for the integration of different building systems in each design phase. Each phase is broken down into a series of questions that building simulation can be used to analyze and solve amongst the different disciplines of the project. The document also presents this information in the light of an integrated design process that
incorporates rigorous energy engineering activities. These activities extend beyond modeling and include goal setting/benchmarking, measurement and verification, post occupancy analysis, and other energy related activities. While the engineering/modeling function is part of the project team, it is not necessarily part of the design team. It can be part of the mechanical engineer’s scope or may be performed independently. Regardless, the main job of the energy engineer is to continuously champion issues concerning energy performance and simulation of the building.

Section 2 The Proposed Course

Section 2.1 Concept and Structure

The following section elaborates upon the parameters of a proposed curriculum that could be used as a model for teaching the concept of building simulation-oriented integrated design. The curriculum is broken down into the three main project delivery phases of Pre-Design, Conceptual Design, and Schematic Design. Each phase is further broken into multiple sections of the integrated design process that describe their areas of focus, methods of teaching, and the possible deliverables of the curriculum. To illustrate some of the concepts and ideas discussed herein, the following course proposal includes graphics from an actual design project that was analyzed by University of Idaho students working with professionals through the Integrated Design Lab in Boise, Idaho. Although this paper uses a fairly straightforward office building program to demonstrate the ideas used in the course, it would be desirable to utilize a program that provides more variation of use types and occupancy patterns as a way to demonstrate the power that the building’s form, shape, and organization have on the ability to reduce loads. Additionally, having the students define and model two different programs within the same building, such as a manufacturing facility coupled with an office program, would help reinforce some of the simulation concepts woven throughout the curriculum.

Section 2.2 Course Information and Learning Objectives

The course is designed to cover a one semester class for both graduate mechanical/electrical engineering and architecture students. The students would work as integrated teams in a studio format throughout the entire semester. The learning objectives for the course are as follows:

- The students will learn about energy performance standards from the industry and how to achieve high performance buildings through the use of integrated performance modeling
- Both student groups will gain valuable insight into the integrated design process through the application of project-based education
- All students will gain a deep understanding of how all pre-design, conceptual design, and schematic design decisions affect quantifiable energy performance
- Engineering students will learn how to play a significant role in the design of buildings. Rather than reacting to forms and facades handed to them by architects, the students will take an active role in helping to shape the envelope and form of a building.
- Architecture students will learn more about building physics, HVAC systems approaches, and their potential integration into the architecture and passive design measures of the building.

- The students will also gain valuable knowledge from their interaction with the other student disciplines around the common goal of overall reduced energy demand. They will also gain experience on how to work in charrettes with a diverse range of players.

Throughout the entire course, the students will constantly document and record their integrated design process in the form of a final professional building simulation report. This reflects the need in practice to be able to provide deliverables throughout every phase of the project while also submitting a final report at the end of the project. This continuous documentation will challenge the organizational skills, group coordination strategies, and writing methods of the students as a preparation for professional project delivery. It will also serve as a constant reference between their initial research and strategic planning, and between their modeling strategy and design assumptions. The diagram below illustrates the structure of the 16 week course along with design phasing, major milestones, and workshops/charrettes integrated throughout the class.

Figure 3 – Diagram showing the timeline and major components of the proposed curriculum.

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Section 2.3 Software Proficiency and Prerequisites

The curriculum requires a proficient if not advanced knowledge of certain building simulation strategies to execute the analysis approaches central to the proposed course’s concepts. There are many software packages and pathways and each have certain strengths and
weaknesses when it comes to building performance modeling. This section focuses on the
criteria upon which to select the appropriate tools for the curriculum.

The students will need some previous knowledge of a few different performance
modeling software applications. Primarily, they will need proficiency with software(s) capable of
reliable yearly thermodynamic modeling for multiple zone buildings. It is critical that the
software be able to compute the load implications of passive systems as this will be a major
focus of load reductions and proper system sizing throughout the course. The engineering
students will also need to have some experience designing mechanical systems within a
simulation program. Lastly, some knowledge of daylight simulation software will also be
required and used as a starting point for the analysis and design of the building program. Energy
modeling software can calculate the daylight level in the space, but the calculations cover only
the impact of daylight on energy consumption. The energy simulation program will give no
indication of whether such a daylight level is realistic given a certain set of scenarios that is not
included in the energy model (e.g. the reflectance of the walls, the furniture types and
arrangements, the details of the shading devices, etc). As a result, students will need to address
criteria for illumination and luminance (glare potential) with software designed specifically for
daylighting analysis. Again, it cannot be stressed enough that successful energy reductions must
address fundamental issues of occupant comfort and productivity.

Such an intimate knowledge of building science and building simulation software creates
an interesting problem for the course’s proposed perquisites. Ideally, a building simulation-
oriented class for the architecture, and engineering students would be required before taking the
proposed integrated studio, so that the functional skills to implement the software programs are
already in place. This would allow the students to focus more on the application of this software
towards their studio problem. However, this is typically not available in most architecture and
engineering curriculums. A second option would be to include intensive 3-4 day workshops on
both energy and daylight modeling at the beginning of each major section of the curriculum.
Most four-year architecture programs contain an Environmental Control Systems (ECS) courses
that focuses (to a varying degree) on basic comfort and systems theory and building simulation
techniques. These courses are often available to engineering students as well. Many academic
programs also have elective classes that focus on other issues such as daylighting, while
providing either physical or digital modeling proficiency to students. This type of ECS course
and/or electives could expand and serve as adequate and useful prerequisite that could
complement and enhance any workshop conducted at the beginning of this course.

Section 2.4 Pre-design Phase

The Pre-design phase holds great importance in an integrated design studio with a focus
on energy modeling. Pre-design in this scenario goes beyond the typical precedent research and
site analysis first conducted in the academic architectural design setting. Instead, goal setting,
energy standards research, code understanding, rigorous climate/micro-climate analysis,
performance goals, and HVAC systems analyzed at this phase of the design will actively
influence all the proceeding phases of the design process. Each of these topics will be preceded
by exercises which emphasize the team or integrated nature of the studio. The introduction of a
full day energy-charrette will also be utilized at the end of this phase to kickoff the design of the
project.
Section 2.4.1 Integrated Design and Goal Setting

The course will begin by instructing students in the core principals of integrated design as it relates to how building’s consume energy and provide comfort for occupants. Consequently, both student disciplines will need to understand what a “good” energy use target entails for their project. This process involves the research of existing energy consumption data, industry standards, and energy codes. This section of the curriculum equips students with enough knowledge of current building energy use and benchmarking to be able to set rigorous energy goals for their projects based upon climate, location, and program. The students will learn how to navigate existing online databases such as the Commercial Building Energy Consumption Survey (CBECS) which can be used to understand typical energy use patterns for their project’s program, size, climate, and region. These types of data can even be used to analyze disaggregated end-use consumption to gain valuable insight on what type of energy end use is the most problematic and opportunistic for the students’ energy savings targets. Additionally, students will need to have some basic understanding of various industry standards while understanding the strengths and weaknesses of analysis-based on energy codes such as the latest International Energy Conservation Code (IECC) and ASHRAE’s spectrum of standards. In addition to energy efficiency goals, students will also learn the effects that these industry standards have in forming the criteria upon which comfort may be judged. Students will come to appreciate the effect that applying appropriate comfort criteria to spaces can have on energy use, such as marrying equipment sizing design days to program requirements. By the end of this section of the program, students will have identified multiple energy and comfort standards such as ASHRAE, LEED, Architecture 2030, the Living Building Challenge, etc. and will have selected a goal for their project.

Figure 4 – Data analysis conducted at the onset of a project with the goal to understand the energy consumption patterns of a typical office building in the Mountain West. The chart was created in excel from CBECs microdata and shows multiple office buildings disaggregated energy end uses.

Section 2.4.2 Climate Analysis
The next section of the Pre-Design Phase involves the rigorous climate data aggregation and analysis which will serve as the starting point for the design charrette later in the curriculum. It is imperative that the students gain a clear understanding of how to interpret climactic data charts, graphs, and tables into resources for the design of their building and systems. If the first step of the integrated design process involves utilizing the climate to reduce loads, certain types of information need to be considered using textbooks, online resources, or climate analysis software. As a starting point, basic temperature and humidity patterns, including heating and cooling degree day splits, should be aggregated to gain a basic understanding of the projects climate. Next, more specific climactic data that potentially directly influences passive design strategies should be considered. For instance, wind rose plots will be useful for natural ventilation analysis, while diurnal temperature and humidity patterns will be important for understanding the potential for night flush ventilation or evaporative cooling. Also, solar insolation patterns and shading angles will be needed for shading strategies and direct gain systems. Throughout this process, students will also gain an understanding of the structure and limitation between different weather file types such as typical meteorological data (TMY), Sampson wind data, and local weather station data.

Figure 5 – This climate data graphic is used to analyze the amount of time that the outdoor temperature is above the building’s balance point and below the upper comfort temperature, thus allowing the building to utilize free cooling from the environment.

Section 2.4.3 Energy Related Performance Goals and Design Criteria

In the goal setting portion of the curriculum, students will have already identified large-scale energy performance goals that deal with absolute annual energy consumption values. The next step is to create performance goals for the individual systems of the building design which will serve to reach the overall energy goal. These goals wouldn’t necessarily be energy-metric related, but would pertain to things such as infiltration rates, glazing ratios, etc. Regardless, defining performance criteria for something such as the ideal amount of daylight in a space will allow the students to efficiently design their energy and daylight modeling process to try and achieve occupant comfort appropriately. The creation of these performance criteria provides a direct mode of comparison between their simulation results and performance goals.
Additionally, this aspect of the curriculum closely relates to different aspects of the professional world of integrated design. For instance, the owner may or may not provide particular performance criteria when dealing with a high performance project in an integrated design setting and this may often be left to the discretion of the designer. This can create a scenario where the design team has a key role to play in helping shape those goals into something that will meet the desired overall energy aspirations.

This process would also inevitably produce an increased understanding of the different code and industry standard performance guidelines that would serve as a baseline for the students proposed goals. Different code and desired performance comparisons could relate to subject matter such as daylight illumination, lighting power densities, ventilation flow rates, glazing ratios, peak heating and cooling targets, indoor temperature ranges, etc. Sophisticated notions of alternative comfort criteria could even start to be considered, such as including predicted mean vote, operative temperature ranges, and indoor air speeds in the definition of performance criteria. Regardless of whether the analysis deals with code requirements, proposed performance goals, or other types of targets, having the students take an active role in defining these criteria will create a base knowledge of what performance levels are acceptable in a building and how they affect energy use.

Section 2.4.4 Systems Scheming

Though detailed design of systems will come at a later phase in the student projects, the engineering and architecture students must begin to think about the possible synergies created between the given climate, program, and mechanical systems to help inform how the initial shape and form of the building. This process has the potential to promote important dialogue between the engineering and architecture students as they both research the general advantages, disadvantages, and constraints of each system from an energy efficiency and comfort standpoint. One goal for this section of the course will be to challenge the engineering students to think schematically. This addresses the professional world’s tendency to avoid designing systems multiple times due to cost and project delivery schedules. Consequently, it becomes increasingly important for the students to learn how to consider multiple system alternatives through drawing schematically and supporting the architectural schematic design process.

Figure 6 – This quick environmental section analyzes how the buildings different active and passive systems strategies integrate with the architecture of the building.
In general, the students would focus on various options for heating, cooling, distribution, passive systems integration, and energy/heat recovery strategies for the building’s program. Analyzing the characteristics of these systems at the onset of design will also allow for more opportunity for integration with the building design during the charrette at the end of this phase of the course. For example, if the students were to design an HVAC system that uses thermally active surfaces as the distribution system for a heat pump, the architecture of the design would need to support this concept and vice versa. This also prevents the HVAC systems of the design from becoming an afterthought; rather the systems would shake their subservient role to the architecture and actively shape and form its design.

Written descriptions of the applicability of the systems to the project would be required in this section’s report along with schematic diagrams of how the systems function. The engineers will most likely be spearheading the research while the architects could focus on turning the information into informative schematic systems diagrams and sections. These diagrams would require both an integrated project team approach to the assignment as well as peer to peer teaching and learning.

This section of the curriculum is also the appropriate time to bring in local professionals to discuss the strengths and weaknesses of systems from a real world perspective. Both the architecture and engineering students could be paired with local professionals to talk about their experiences with different systems design. The professionals could also consult with the students on systems alternatives and various HVAC integration strategies for their projects. Ideally, the students would be talking to groups or pairs of architects and engineers simultaneously to hopefully gain insight into the or presence or lack of integrated design.

Section 2.4.5 Energy-Charrette

The Pre-Design Phase of the curriculum culminates with an all-day Energy-Charrette focusing the design on the evidence and data presented from the previous collection phases. In this step of the process, the students will apply all of the goal setting, climate analysis, performance criteria, and HVAC systems research toward solving their design problem. The charrette is also an opportunity to get multiple other disciplines involved with the students’ projects. The local building community and students from other programs could become involved and distributed within the student teams. This group could include a wide arrange of disciplines such as intended users, financial managers, building construction managers (and even students), landscape architects, civil engineers, interior designers, contractors, etc. This charrette structure also works extremely well in this particular fast paced studio format, which prevents the tedious cycle of autonomous formal ambition. In contrast, the charrette forces design decisions to be made quick and early with an emphasis on integrating with the building simulation methodology that will be carried throughout the design process.

The structure of the charrette should not be organized into different sections that disaggregate envelope from HVAC systems and climate analysis from program usage. Rather, the structure of the charrette should revolve around integrated design and high performance building concepts such as “the elimination of mechanical cooling” and “using the climate and earth as a resource”. The emphasis should communicate that solutions rely in holistic concepts that traverse individual building components or systems. The goal of the charrette will be to create multiple broad stroke building forms and parti diagrams used as fodder for simulation in
the next phase of the curriculum. Creating form ‘types’ or simplified “shoebox models” will reflect design attitudes such as “tall and skinny”, “doughnut”, “broken H”, and “atrium” schemes. Additionally, multiple HVAC strategies should be chosen based upon appropriateness for each model while identifying opportunities for integration in each design scheme. Both building designs and HVAC systems should be chosen based upon sensitivity towards previously researched performance criteria and climate analysis performed earlier in the course. By the end of the day, students should have clear roadmaps of how they will test their freshly created designs using building simulation as a tool for high performance building analysis.

Section 2.5 Conceptual Design

The conceptual design phase marks the first usage of building simulation software in the curriculum. This phase looks to analyze the multiple large scale design moves created in the energy charrette and analyze their maximum potential for deep energy savings. Consequently, absolute energy consumption values are not the goal, rather the process elicits a relative comparison between different design decisions to create a “worse and better” type output for different energy or performance characteristics.

Figure 7-Four different “shoebox model” design schemes created during a charrette process. These four design schemes were then run through daylight and energy simulation to create data which was used to discern which design held the highest potential energy savings.

This phase should begin with a workshop dedicated toward this scale of this type of building performance analysis. This initial phase of analysis looks at zone level loads of the building, which do not require the complicated specification of an HVAC system. Here the primary loads will be analyzed using an “ideal” HVAC system, which is 100% efficient, does not impose any loads on the spaces, and allows for the specific analysis of building form and basic envelope parameters. The short term goal is to reduce the building loads and energy consumption as much as possible through architectural means (orientation, form, etc.) before modeling HVAC systems. This modeling effort will take place mostly with the architectural students leading the analysis, while the engineering students will use the time to begin testing the effects of different systems on a simplified single zone. The engineering students will start to learn the process of defining simplified HVAC systems through a series of exercises to prepare them for to include more complex systems in the later design iterations. The consideration of HVAC systems and strategies during the Pre-Design Phase of the curriculum and Energy-Charrette should still allow for integration and synergies in the future.
Section 2.5.1. Building Shape, Form, and Orientation Analysis

The intent of this first stage of building simulation looks to limit that number of design variable to large scale notions of building shape, form, and orientation. This level of modeling still requires the students to input occupancy schedules, lighting schedules, ventilation rates, etc. Additionally, all the envelope assemblies of the different models will have to be defined according to the minimum ASHRAE 90.1 or IECC requirement, which will further reference the students’ initial research. To start the process, daylighting simulation should be performed on the simplified “shoebox” models to ascertain the different design scheme’s potential for daylighting and energy savings. The students will test the schemes’ daylight illumination levels while simultaneously simulating daylight harvesting photocontrol systems to quantify energy savings. This building simulation strategy will also test effect that daylighting has on not only electrical energy savings and visual comfort, it will also show daylighting’s connection to cooling and heating energy consumption and peak demand. Through preliminary passive design strategies concurrently considered throughout the process, the students will also be able to understand the synergies between a well-daylit building form and potential natural ventilation and other passive strategies. For example, passive strategies such as natural ventilation tend to lend themselves to thin and open building plans that are also desirable for daylighting. Simple hand calculations using accepted formulas will help students to quantitatively analyze the effectiveness of these strategies prior to their inclusion in a holistic building simulation.

Figure 8 – Examples of the different daylight modeling outputs that show both vertical and horizontal illumination levels for the four different design schemes.

Next, energy modeling software should be used to analyze the different design schemes through the creation of annual energy use statistics along with peak demand charts. Both of these statistics can be disaggregated into their constituent load contributions to further understand the performance of the building. For example, a peak cooling pie chart can be broken into the heat gain contributions from solar, conduction, ventilation, infiltration, people, lights, and equipment contributions. Some of the design schemes might show a high peak cooling demand according to the solar component, which might suggest a problem with the glazing ratio, orientation, or shading design. The previously mentioned hand calculations will also need to be taken into account all throughout this phase of design to analyze passive strategy potential through the modeling process.
Students can also use disaggregated load contributions to plot annual load profiles. This information can be useful to understand times of the year when the building may be both heating and cooling and may present opportunities to move BTUs within the building throughout the day or spatially to other parts of the building. The goal is for the students to come away with a method of analyzing both the peak and annual demand profiles of a building for heating and cooling to be able to recognize opportunities for load reduction.

The same type of charts can be created for annual energy use and can be broken apart into their constituent heating, cooling, electrical, and miscellaneous components. At this level of analysis, energy use trends can be extrapolated from the data to decide upon which design schemes should be pursued in the next phase of the curriculum. However, this selection also requires the synthesis of different criteria that might not be strictly energy based. For example, a building with slightly higher energy use might be chosen based upon its potential for daylighting or its potential to integrate with passive design systems.

Section 2.6- Schematic Design

The structure of schematic design in this curriculum focuses on developing one of the previous schemes explored in the Conceptual Design Phase. This section also introduces an ASHRAE 90.1 baseline model which serves as a benchmark for comparison the proposed design’s energy efficiency measures. In addition to learning about the current industry standard students will also evaluate methods to show savings beyond the scope of appendix G such as building shape, glazing area, and programmatic efficiency. The students will learn about the standards as well as some of their current weakness as outlined by Baker\(^5\). At the beginning of this phase, another energy modeling workshop should be administered to teach students about how to define HVAC templates, a simplified form of fully developed HVAC systems. The definition of an HVAC system not only allows a system of comparison for the student’s proposed models, but it provides insight into how the system can affect loads and energy consumption dynamics. The workshop would also need to focus on more advanced data outputs.
and post processing methods that relate to different energy efficiency measures. The goal of schematic design is to focus on a high performance envelope, optimized daylighting, control systems such as occupancy sensors, and passive design analysis to reduce loads as much as possible. HVAC systems design and integration will be covered in the next section of Schematic Design.

This phase of the curriculum will also challenge the integrated studio groups. Some of the design ideas tested during this phase will have had their inception during the Energy Charrette. However, new design opportunities will present themselves and students will have to learn how to design and model simultaneously. This synchronized movement will force the students to deeply collaborate to push the project forward through this phase of the curriculum.

Section 2.6.1 Load Reduction Strategies

This section of the curriculum utilizes building performance simulation to analyze multiple iterations of a previously selected design scheme to drive down building loads. These strategies can range from envelope shading strategies to the manipulation of comfort criteria in thermostat objects defined in energy modeling software. Daylight modeling will be incorporated again throughout this phase of the design to optimize daylighting details such as exterior shading, daylight versus viewing glazing parameters, surface brightness, interior furnishings, light shelves, interior shading, skylight geometry, etc., in an attempt to reach certain illumination levels. Regardless of the design strategies tested using this type of building simulation, results and outputs should always be compared against the student’s performance criteria for illumination levels within the building to guide and influence the design.

Figure 10 – This daylight data represents a small section of data analysis that was conducted for each of the different iterations tested during schematic design. The resultant outputs looked at a range of different factors including horizontal illumination grids, vertical illumination grids in section, false color glare analysis imagery, and both regular and fisheye luminance renderings.

These optimized glazing and shading parameters should influence the exterior design of the energy model before the creation of the baseline ASHRAE 90.1 model and the application of
the next set of energy efficiency measures. This type of energy modeling can be used to explore many different design strategies and following sections describe only some of the specific approaches that the curriculum could emphasize.

Section 2.6.1.1 Illumination Analysis Strategies

There are two major types of daylight simulation, single point in time analysis versus annual dynamic simulation. The former refers to the fact that most daylight simulations and metrics are created for one point in time, at multiple times of the day, throughout different times of the year, and under different sky conditions. Understanding daylight performance under this wide range of single points in time can start to create a better idea of the annual performance of the building’s daylight design. Figure 11 above represents this type of analysis and its illumination grids represent data from noon, September 21, during a sunny sky condition. However, annual dynamic simulation refers to the usage of annual daylight metrics such as daylight autonomy that allow the analysis of daylight patterns throughout the entire year. This form of simulation uses annual weather files to simulate the building’s daylight performance under an entire year of climate data.

Figure 11 – This daylight autonomy illumination grid uses different contours of color to represent the percentage of time the space receives 25 footcandles of daylight. Most of the space is around the 80% range, meaning that these spaces receive the defined daylight criteria during almost the whole year.

Section 2.6.1.1 Shading and Daylight

Shading device heights, widths, and cutoff angles are typically defined by rule of thumb calculation procedures which attempt to take climate specificity into account. However, only building simulation can accurately model the heating and cooling impact that a particular shading device has on the energy efficiency of the project. The simulation will take into account the building’s balance point and accurately reflect whether a net heating or cooling gain
occurs using actual climate data, which can have a large impact on peak cooling or direct gain systems. Consequently, an iterative modeling approach should be taken to optimize the design of the shading device to ensure the proper balance between daylight, heating, and cooling is achieved according to the projects climate. Students will have to constantly mediate the balance between these different performance parameters as their building evolves through design.

Building simulation performance can also specifically quantify energy savings from daylight, which can serve as another metric to evaluate the effectiveness of a daylighting strategy. This type of software can help quantify lighting power density reduction over code standards, while also simulating the savings accrued from a daylight harvesting and photo-control systems. This simulation approach takes into account the interrelated aspects of lighting and its impact on energy not associated directly with lighting. This process is not only invaluable toward the understanding of holistic systems design, but also it provides a quantifiable argument for the value of daylighting in an energy and cost metric. However, there are still technological limitations to this type of analysis. While daylight analysis through energy simulation software can be a valuable exercise, it has been shown that greater accuracy and a finer understanding of the quality of light should be calculated using a combination of outputs from daylight software as inputs in energy modeling. For example, different outputs from daylight simulation software can be spliced into energy modeling programs to quantify energy reduction based upon this more accurate lighting data.

Figure 12 – This chart shows the monthly kilowatt consumption of a building after simulating three different skylight to floor area ratios integrated with a continuous dimming photocell control system. The kilowatt savings can then be relegated to a dollar amount for cost comparison analysis.

Section 2.6.1.2 Insulation Optimization

The students will also have to make decisions about how much additional insulation to add to the envelope over the ASHRAE 90.1 standards. Building simulation can iteratively test different insulation schemes to determine their exact impact on the HVAC system’s heating energy consumption. This method can be used to determine the point of “diminishing return” for the insulation when its energy savings level off and it becomes cost ineffective to invest in this
efficiency measure. Additionally, different window performance specifications, such as the glazing’s U-value, solar heat gain coefficient, and external shading strategies can also be tested in this section of the curriculum.

*Figure 13* – Different energy consumption statistics used to analyze each iteration tested during the schematic design phase of building simulation. The design case includes a high performance envelope with increased insulation, added thermal mass, and a continuous dimming daylight harvesting system.

### Section 2.6.1.3 Passive Design Analysis

Passive design calculations can be used in conjunction with energy modeling to determine both if the design strategy is appropriate and how much energy it will save. First, simplified hand calculations can quickly determine cooling or heating capacities of a basic system. This capacity can then be compared to the simulated peak loads of the model to conjecture if further analysis is appropriate and will lead to significant energy savings. For the specific example of a thermal mass and night flush ventilation system, cooling energy savings can easily be calculated by incorporating concrete material in one of the proposed iterations of the energy model. Simulations tools can then simulate natural ventilation schemes by using climate data and intelligent window objects that open or close based off of a temperature difference between the interior and exterior. The result is simulated passive system that can output quantifiable effects on annual cooling energy. Indoor temperature profiles of the zones can also be created to understand the strategy’s impact on comfort. Both student groups will need to work through a sophisticated understanding of the climate and the critical parameters of the passive system and controls to ensure the successful execution this building simulation strategy.
Figure 14 – Daily temperature profile on the peak heating design day before and after the incorporation of a thermal mass and night flush ventilation system. The simulations were ran in a “free floating” mode without an HVAC system.

At the end of the schematic design process, this phase of the curriculum will require the expression of an energy use consumption breakdown of all the different energy efficiency measures tested by the students. This type of graphic displays each of the iterative design strategies of the proposed model in an additive manner to show a design package that achieves the deepest energy savings. These different iterations are shown in comparison to the ASHRAE 90.1 baseline to understand their performance above and against this standard. The chart expresses a clear connection between the design strategy and its energy use as it relates to the entire dynamic of the building. The final iteration shows the opportunities for HVAC optimization and energy targets for the next round of building simulation and systems analysis.

Figure 15 – Final – This final energy modeling output shows additive energy efficiency measures applied to an office in Eagle, Idaho.
Section 2.6.2 HVAC Systems Design and Analysis

The schematic design phase of this curriculum encompasses two parts. The first section analyzes building envelope upgrades, use patterns, and passive design measures to lower the buildings loads. The next step involves the modeling of different HVAC and distribution systems to achieve deeper energy savings. This phase of the curriculum will build upon previously developed proficiency from the systems design exercises conducted by engineering students from the schematic design phase.

The engineering students’ background and technical skills will undoubtedly provide critical guidance to this section of the curriculum. However, the architectural students still have a key role in the collaboration between the two parties. Not only will they gain large amounts of knowledge concerning HVAC systems throughout this process, but they will need to collaborate to ensure that architectural intent is not lost. This becomes increasingly important when dealing with passive systems to ensure that mechanical systems can interface and integrate with specific design strategies between the building and its climate. Refering back to figure 2 in this paper, the architectural involvement during this phase of building simulation is at its lowest point. However, the decreased involvement of the architecture students on the building simulation side of the project can free up time to focus on the final presentation of the building as a design project including graphic diagrams of passive systems and renderings of final building design.

This section of the schematic design phase largely follows the same methodology applied to the architectural design process. Similar to the building orientation, shape, and form exercise, the students will already have an idea of what systems they will test by referencing their initial research and EnergyCharrette. At first, multiple systems should be modeled to evaluate the most energy efficient option between air-based, water based, and fuel source choices. Next, the chosen system should undergo multiple iterations that test the different parameters inherent within the system that affect its energy efficiency and comfort. These parameters include system concepts such as distribution oversizing fan motor placement, and premium performance equipment. The students will focus on using building simulation to explore strategies that address the reduction of system-imposed peak loads such as fan heat, pump heat, reheat, duct/piping losses, etc. Other issues explored could pertain to the elimination of simultaneous heating and cooling, the impacts of equipment and thermostatic setpoint temperatures, and the use of different thermal comfort models to address performance. As with all other phases in the process comfort analysis will also be conducted using a variety of different methods such as the Fanger comfort model. These alternative considerations will broaden the students sensibilities toward what defines a successful HVAC system. Some methods only look toward HVAC set points not met, where some of the more comprehensive thermal comfort models attempt to predict the subjective comfort of the occupants based off of multiple environmental variables such as radiant surface temperature, air speed, air temperature, and humidity.

The following example illustrates some of the ways that building performance process can be utilized to make decisions and optimize performance.
Section 2.6.2.1 Radiant Systems

If students chose radiant heating as the HVAC system for their building, the next step in this methodology involves an iterative analysis of the different internal parameters that affect the system’s performance. For instance, the decision of how much insulation to include under the slab can affect the performance of a radiant system dramatically. There are also many different types of radiant distribution systems including concrete embedded tubing and above floor systems using wood, tile, masonry, etc. Building simulation can even be utilized to create an operation schedule of the system’s different setpoint strategies. The modeling of constant temperature setpoints, time sensitive setbacks, and intelligent thermostatic systems can all lead to an increased knowledge of how these options relate to the energy consumption of a building.

Figure 16 – This chart shows the result of an analysis of the internal system factors affecting the performance of an in-slab radiant system. The energy modeling strategy tested different insulation amounts, locations, and different thermostat setpoint strategies. By the end of the analysis, the data was used to specify certain system control options and ensure that the architectural insulation strategy of the slab supported the HVAC system and vice versa.

Section 2.6.2.2

Section 2.6.2.1 Rightsizing HVAC Systems

Building performance analysis can also perform sophisticated loads analysis that lead to a deeper understanding of how zone level loads correspond to HVAC system imposed loads. The software can output the daily peak load of a building before and after energy efficiency measures have been added during the heating or cooling season. This load reduction will reflect passive design measures that traditional forms of sizing calculations do not take into account. However, the power in this process lies in the fact that the simulation will show the “actual” loads of the
building and how they correspond to HVAC performance capacity. Building performance simulation can output the zone level peak loads, the HVAC sizing factors associated with the equipment type, and the actual HVAC load capacity of the system. The equipment can then be sized to the extreme value of the actual HVAC system’s output, rather than relying on sizing factors and peak day judgments. Without the quantification of this data, it would be irrational to argue for smaller or right-sized HVAC systems.

Figure 17 – This energy modeling output shows different strata of information concerning the load and HVAC outputs of a building before and after a thermal mass and night flush ventilation system has been incorporated. The gray bars represent the work of the HVAC system before the passive system was applied, while the blue bars show the actual HVAC output over the five month cooling season. Since the chart shows the actual HVAC output versus the zone design load and traditional HVAC sizing factors, a more informed decision can be made about the size of the system.

Section 2.7 - The Final Project Document

In terms of grading, one inclination is to evaluate the student teams on if they achieved their initial proposed energy use goals derived from the beginning of the course. Although this approach would be the most cut and dry method of grading, it would be irrational to hold the students accountable to their initial energy savings ambitions which were made with limited experience of energy modeling and integrated design. Additionally, if the students felt that the achievement of their energy goals were the basis for their grade, this would discourage experimentation and rigorous approaches. For the proposed course, a more “checklist” oriented method of grading would be more appropriate. The students would mainly be graded upon the process of their analysis and if they performed the required amount of iterations per design. This way, the students learn an approach and design methodology that will hopefully lead to higher energy savings.
Additionally, the final for the course entails the completion of the students’ final building simulation report/book. The report would document each phase of the design process and be graded upon completeness and format. In general, the document would elaborate upon why certain decisions were made, as well as all the final design ideas, modeling assumptions, results and conclusions, and proposed future work as applicable. Each different phase of the course will have its own requirements and some may even require graphic outputs such as renderings, charts, or drawings depicting architectural and engineering concepts. At the end of each section of the curriculum students will be required to turn in a “draft” form of each section of their report, which will help the students structure their analysis and tailor their simulation outputs to allow a feedback loop for the design process and instructor guidance. The concluding sections of the report could include reflections on the integrated design team structure, the building simulation performance model, lessons learned, and future approaches. This final assignment and deliverable should fully document the students’ process and serve as both a portfolio piece and guideline for future curriculum improvements.

Section 3 Conclusion and Discussion

Section 3.1 Empowerment

This proposed course intends to empower students with the skills and knowledge to tackle real problems facing the building design profession. The most fundamental of which is the challenge of working as an integrated team across professional disciplines and specializations. Aggressive energy goals of the future certification programs and energy codes will require highly skilled technical experts with specialized knowledge to respond to the increasing complexity of building systems. However, for this knowledge to become effective and useful toward holistic sustainability and energy reduction concepts, it must be appropriately applied during the design process. For this integration to be successful, the process of communication between disciplines needs to be emphasized in academia, where students can then pave the way for an integrated professional setting. Utilizing building simulation throughout the design process can serve as an anchor for communication between the disciplines. When utilized for this purpose, building simulation transcends its typical role as a verification tool and becomes something that both leads to more sustainable design while facilitating the integrated design process.

Section 3.2 The Barriers to the Proposed Course

The momentum of the status quo in both the professional world and academia prevent, rather than support, the level of cross communication required for the integrated design process. Tight budgets, fast-paced project delivery timelines, adversarial contractual arrangements, shortsighted economic mindsets, and the complexity of modern buildings all act as barriers toward integrating project teams in the professional setting. This illustrates the quintessential need to address these process-based barriers in the academic realm and redefine its structure to support more integration across building design disciplines. However, the academic world is not without its barriers to this type of integration as well. Kiel Moe describes this problem in his book, Thermally Active Surfaces in Architecture, by saying, “…in the current context of building production and education, approaches to the topics of energy, material, sustainability, construction, history, and formalism, while intimately connected in actuality, are too often disparate realms of theory and practice3.” Even in academia these approaches are theorized and
taught by separate entities within universities and even within colleges of architecture or engineering. This division of knowledge may be convenient for the logistics of teaching and the individual pursuit of one particular field, but it stifles colleges’ ability to integrate its curriculums. Although professional precedent after precedent shows the challenge and success of integrating project teams to achieve high performance buildings, teaching integrated courses is not the priority of most architecture and engineering curriculums. To make restructuring even more difficult, this endeavor is not always well supported by university compensation, tenure and promotion practices, and accreditation requirements.

Section 3.3 The Potential for Broader Course Integration

In order to realistically achieve the goals set forth herein within a single semester course of 5 to 6 credit hours it is necessary to draw clear boundaries and set limits. It may be tempting to aspire to a fully-integrated curriculum and include all of the design disciplines such as landscape design and civil engineering. While these would be productive pursuits in theory, there is only so much that can be absorbed in a single semester. Although these disciplines will be given cursory attention in the completion of the final design, we propose to focus on the integration of the primary energy efficiency and human comfort aspects normally executed by the electrical and mechanical engineers and architects. We believe that the time needed to reach a proficient level of skill with the previously mentioned tools and techniques will require a great deal of attention, would benefit from several perquisites, and even potentially require intensive workshops throughout the semester. In order to be broadly applied at multiple institutions, alternative models could be explored such as co-taught elective courses to expand the credit hours available from 5-6 to as many as 9-12 over the course of a semester.

With the limitations of the course in mind, the next step toward a broader integration of student disciplines should target the economic side of the building industry. Not only does building simulation create a better mode of communication between architects and engineers, its quantification of energy/fiscal savings opens up a dialogue about cost analysis. While construction management students could be involved throughout the proposed course’s design process to provide traditional cost estimation, building simulation also provides the opportunity to look at return on investment timelines, life cycle cost analysis, and alternatives to first-cost dominated investment strategies. Ideally, the building simulation strategy could even cater to the economic factor of the curriculum. The final building simulation report could propose multiple energy efficiency upgrade strategies segregated according to basic and advanced design packages that reflect different levels of economic risk and life cycle cost analysis. The extent of this financial analysis could cover a range of issues including: upfront costs, durability issues, maintenance fees, operational energy costs, equipment life cycles, and other energy efficiency related economic factors.

Section 3.4 Future Work

This paper is intended to serve as a catalyst for an academic curriculum with an emphasis on promoting energy efficiency by integrating the design disciplines throughout the design process. The concept for the proposed course is informed by several years of integrated design activity in both professional and academic spheres. Much of the example work displayed was conducted by graduate students working as research assistants, whom worked closely with a diverse range of professionals on real projects. After nearly a decade of informal project-based
learning, there is a great need to formalize this pedagogical model and deliver it to a broad student population. While we have employed many aspects of the course described above in academic studios, we have yet to implement the full extent of the proposed course. We have almost reached the realization of this idea between not only different student disciplines, but different universities as well. The proposed plan is currently being developed for full incorporation into a graduate level architecture and engineering curriculum. Once the course is implemented and completed, the next step involves measuring the results of student performance in the delivery of low energy and high comfort buildings, as well as monitoring student growth in areas of interdisciplinary collaboration. Future papers will follow up on the successes, challenges, and lessons of delivering this interdisciplinary project-based education centered on building performance simulation.

Section 4 Acknowledgments

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Section 5 Bibliographic Information


