# Developing Architectural Tools and Curricula for Meaningful Energy Analysis

Sustainability and the design of sustainable architecture is an often promoted aspect of many architectural education curricula. In recent undergraduate admissions polls students have expressed that instruction in sustainable design is a core element they expect to receive in their education. Although many students have a sense and some experience in sustainable design, their ability to measure and quantify the sustainability performance of their designs is often weak. Given the three standard categories of sustainable design as economics, ecology and social equity, the quantitative aspects and analytical skills needed to make effective designs that impact economics and ecology are often the least understood and developed by students.

**DANIEL CHUNG**
Philadelphia University

To address this issue some architectural programs have integrated net zero and carbon-neutral building projects into their design studios and building technology courses. Net zero energy and carbon neutral buildings represent singular quantitative goals that most students can conceptually grasp even if they are not able to skillfully manipulate the design parameters. With a clear quantitative project goal such as carbon-neutral design, students can develop sustainable design skills over the course of a project to manage, measure and implement effective design parameters. Carbon-Neutral Buildings and their design pose a significant challenge to architecture students due to the technical and analytical process required to achieve carbon neutrality. This often benefits from a long-term strategy across multiple semesters of their education to meaningfully empower students to not only walk through the steps, analysis and accounting of energy and carbon in a project but to have the critical thinking ability to thoughtfully manage and integrate a process that leads to a carbon-neutral design into their overall design process. This paper explores the obstacles in implementing meaningful energy analysis in design and a potential curricular method to address the issue of empowering design students to make thoughtful, analytical, and well integrated sustainable designs via the topic of carbon-neutral design.

## TECHNICAL INTEGRATION AS A DESIGN OBJECTIVE

Architects today can rarely claim to have an expert grasp on the complete design, analysis and logistics for complex building projects. The more complex and multi-faceted a project the greater likelihood and increased necessity for collaboration with specialists and consultants. Thus the architect's role has shifted to that of the generalist and like a film director guides all the actors and technicians towards an overarching vision. But in the process of the architect transforming from the master builder to the role of the generalist one might question if control and crafting of the project's design vision has been compromised or diminished especially when building performance is often defined and measured by specialists and consultants with little integration into the conceptual design vision. Although the architect does not need to master all the specialists' domains, more time and ability in building performance analysis can greatly enhance both the quality and performance of the design. It is the unconscious acceptance of the generalist role that has limited the progress of technical curricular standards in architectural education. To advance technical standards such as carbon-neutral buildings to become a practical routine in education requires academics and professionals to design curricula where building performance analysis is not only taught as part of building technology courses but must be meaningfully integrated into the iterative process in the comprehensive design studios where students can critically evaluate the qualitative and quantitative impact of building science and sustainable designs decisions.

## MEANINGUL TECHNICAL SUPPORT OF STUDIO DESIGN

Much of architectural education in the minds of students is divided into two categories. These categories are design studios and support courses. Students are often passionate about their design studios and find creative outlets and innovative ideas within their studio work. On the other hand student often view support courses as perfunctory requirements towards their degree. These support courses span across multiple specialty concentrations from history and theory to building science and three-dimensional modeling. This approach in essence divides their curriculum between generalist and specialist experiences. The assumption here is that the experiences, skills and knowledge gained in seminars, lectures and specialist courses would of course support their studio design process (Banerjee 1996). There are two major obstacles to the transference of knowledge and its application in the student's design process. They are the lack of critical understanding of the support course material and the lack of integrated outcomes in cross-course curriculum design (Chung 2013). The second obstacle can be overcome by effective collaboration between coordinating faculty members in technical courses and design studios, where particular attention is given on mapping curricular objectives of the support courses to have directly correlated evidence in the studio courses. The first obstacle often requires instructional redevelopment of courses to specifically target the development of long term flexible knowledge that can be actively utilized in iterative studio design.

## A. ACTIVE LEARNING METHODS IN BUILDING TECHNOLOGY

Technical material related to building systems taught to design students is often taught in a lecture format that relies on rote memorization of facts. These courses frequently are designed to help students become familiar with a broad range of topics and pass the multiple choice questions anticipated on the Architectural Registration Exams. Thus they may not be effectively designed to enable technically proficient outcomes in design studios. To achieve critical understanding of technical material requires students to not merely be exposed to, memorize information about or understand a topic area, but requires them to integrate and apply the knowledge into their design experience through student-centered active learning methods (Bower 2007). Problem-based learning methods utilized in science and medical educational fields are proposed as a way to facilitate critical thinking skills and abilities for architectural students regarding technical analysis for building performance (Roberts 2007). Most often this requires the students to be posed with a technical problem that they lack the skills to solve so that they can first analyze their own abilities and create a mental context for future information. Once this is accomplished, faculty help facilitate the implementation of established analytical methods for technical solutions (Hmelo-Silver 2004).

### B. STRUCTURAL DESIGN AS A CURRICULAR PRECEDENT

Given the proposed curricular enhancements a pertinent question arises as to the appropriate level of technical education required for design students. Many architectural programs have rigorous and well developed structural design and analysis courses. Often this involves two or more courses with an expectation of not only qualitative understanding but demonstrated quantitative ability in structural analysis and architectural applications. Most architects can agree on the importance of a solid education in structural analysis, having conceded that the structure and building frame are integral physical elements of their projects. Thus structural analysis education in architecture is accepted even though a majority of architects utilize structural engineers as design consultants and in fact most projects require a licensed structural engineer. But when it comes to building energy use and environmental systems with a focus on net zero energy and carbon neutrality, few architectural programs even attempt to instruct students in the analytical process to achieve these goals. An education and early experience in building energy and systems analysis similar to structural analysis allows for greater understanding and confidence for design students to meaningfully integrate these technical elements into their design process. It is only by iterative methods of hands-on analysis and evaluation that students can quickly develop useful correlations between technical parameters and design outcomes (Chung 2013).

### C. TECHNICAL ANALYSIS TO ENABLE DESIGN AMBITIONS

Ultimately the instruction of technical analysis for the generalist architect is an attempt to enhance his/her understanding so he/she is better able to make design decisions related to technical parameters. Technical decisions that are often relegated to consultants can become integrated more fluidly into the design process and thus increase the opportunity for those parameters to be supportive rather than a hindrance to the overall design vision of the project. By practicing and experiencing technical analysis, designers are given the opportunity to develop an understanding of the relative leverage that individual technical parameters have in determining spatial outcomes that impact design goals. In most practices this would help architects to more effectively lead consultants in accomplishing the architectural design ambitions.

## STEPS TO CREATE MEANINGUL ANALYSIS IN STUDIO DESIGN

Having stated a case for technical analysis of building energy and systems as part of the architectural design education, the next question is how this type of analysis should be performed and taught. Similar to how structural design has benefited from advances in computerized analysis, three-dimensional modeling and simulations, building energy and systems analysis has had considerable development and increased software availability. With the integration of software technical analysis tools into design documentation software, such as Vasari into Revit, there is a now the ability for architecture students to have quick and common tools for iterative building energy and systems analysis (Jankovic 2012). The wide availability to this type of computerized technical analysis is both potentially an advantage and disadvantage.

### A. DEVELOPING AND UNDERSTANDING COMPUTERIZED ANALYSIS

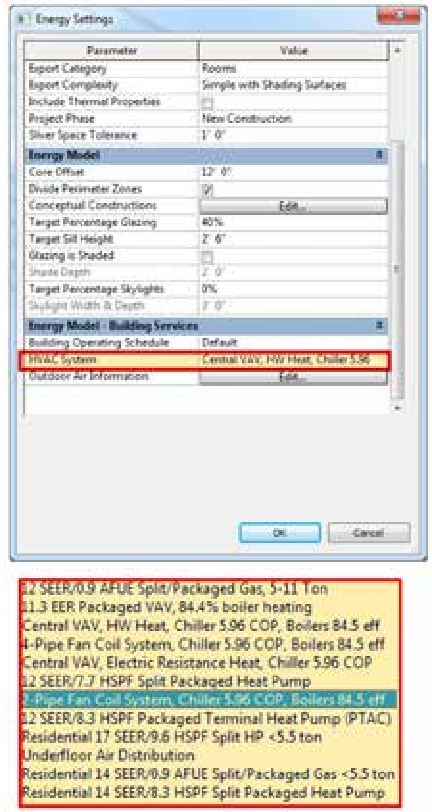
Technical analysis software tools, especially ones with well-developed graphical user interfaces such as Vasari offer students access to analysis and results that assume an understanding of the underlying physics and input parameters. Vasari utilizes the much researched and vetted DOE-2.2 analysis engine for building energy consumption. DOE-2.2 and its graphical interface eQuest have traditionally been too unwieldy for a majority of architects in professional practice and instead have been used by mechanical engineers and building envelope consultants in the service of architectural offices. Now with DOE-2.2 integrated into Vasari these tools are readily available but still not well understood by most architects. In an attempt to streamline the process, Vasari will automatically assume a number of key technical input variables without prompting the user to decide on whether they are appropriate for their project (see figure 1) and then quickly provide a graphical output (see figure 2). Thus the danger is that students and architects will use these analytical tools without properly knowing how to use them and thus making decisions based on erroneous inputs and results. Technical analysis for building systems and energy use must be first learned at the fundamental level of handwritten equations before using computer assisted analysis. It is the basic hand calculations that allow students to have firsthand experience in the inputs and outputs of analysis. Only after having practiced the fundamental analysis can students meaningfully navigate and utilize software analysis tools and avoid the engineering phrase “garbage in, garbage out,” which refers to the fact that automated software tools can only produce quality results if they have quality inputs.

Once students learn the fundamental calculations for analysis, the next step is to develop their own software tools to help them shorten the time for analysis and allow analysis to be an iterative tool. The most basic way to do this is to utilize a spreadsheet program where students can manually craft their own inputs, equations and outputs for the analysis (see figure 3). The benefit of having students develop their own spreadsheets rather than immediately working with prepackaged software solutions is that they continue to develop an understanding of the parameters that become influential to the design process. These spreadsheets can be linked with three-dimensional modeling programs (such as Revit) to update parameters and results in real time. By crafting their own iterative analysis tools, students enable themselves to develop tools that are appropriate to their own work and are not limited to the restrictions of prepackaged tools.

### B. INTEGRATING ITERATIVE ENERGY ANALYSIS

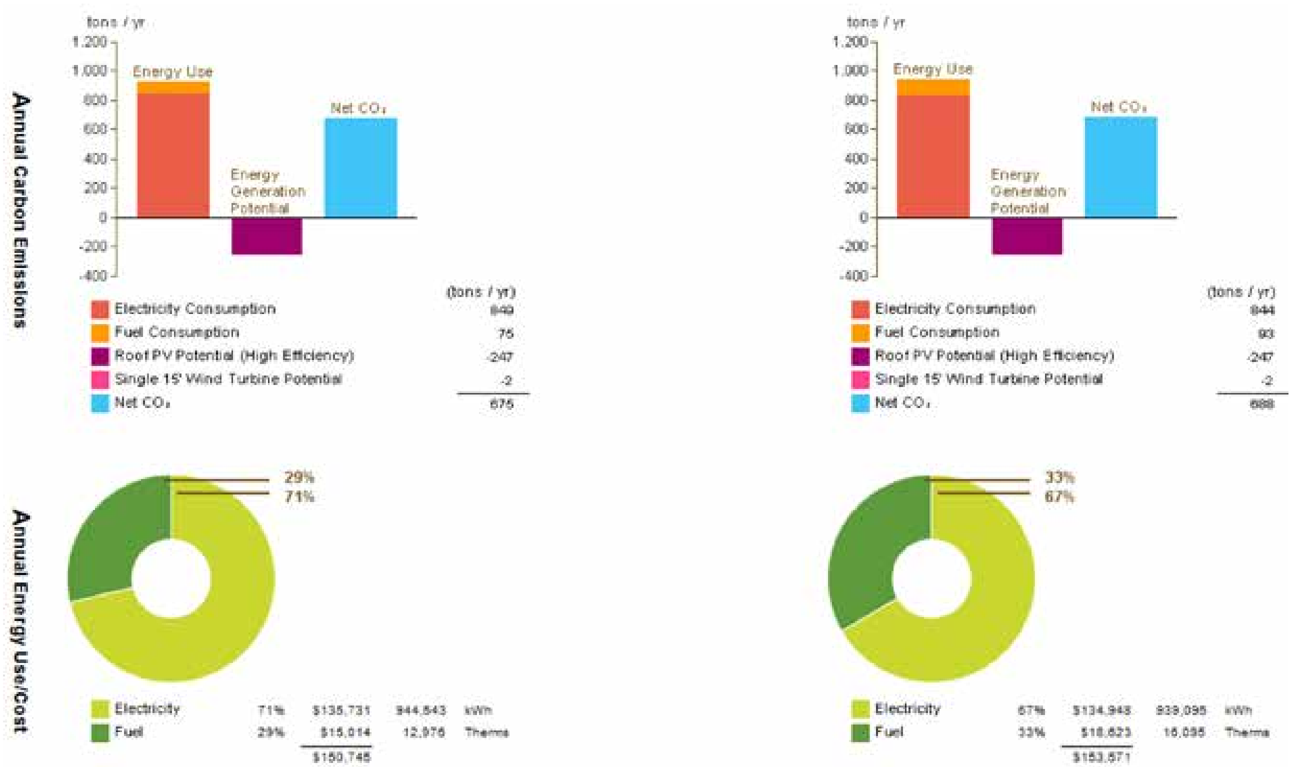
Once students are comfortable with their individually developed analysis software tools, they can compare and evaluate prepackaged tools to determine their relative merits. It is at this point of skill and understanding that prepackaged energy modeling and analysis tools such as those in Vasari become particularly useful in an iterative studio design process.

Projected energy consumption as a measure of building performance is increasingly incorporated into the building documentation process. In many cases, architects look to technical professionals to provide energy analysis services as



1

Figure 1: Example of Vasari Conceptual Energy Analysis Auto-selected Input Parameters (2013).




2

a post-design process, or perhaps as a permitting issue. In these instances, the analysis is completely removed from any iterative design process and lacks the ability to inform and empower the designers to make meaningful energy related design decisions. In some cases an energy analysis might be performed by a consultant at the end of major design phases (SD, DD and CD). Although somewhat more timely, this scenario still places responsibility and implementation on an outside consultant, which of course comes at a price. Each consultation and analysis performed by an outside specialist in effect reduces economic resources for the project's design team and thus limits the likelihood that the analysis will be used as a quick iterative tool to aid in daily design decisions. It is only when the primary design team within the architectural office becomes proficient in analytical tools that these parameters can effectively be leveraged and measured in day to day design decisions and thus have a more meaningful role in early conceptual and schematic designs.

### C. CRITICAL ENERGY ANALYSIS CATEGORIES

Being proficient in technical analysis and knowing how to integrating it into the design process are desired methodological goals. This leads us to the question of what type of analysis and which parameters can the architect as a generalist attempt to draw into his/her understanding of design moves. With the goal of net zero energy or carbon-neutral buildings, the parameters are relatively well established regarding which building design parameters carry the greatest impact on meeting these quantitative goals. The seven largest categories that impact energy consumption and carbon dioxide production due to commercial buildings in the United States are lighting, heating, cooling, ventilation, refrigeration, equipment and cooking (USDOE, USEIA 2001). The last three of these are related to appliance efficiencies, schedules and user behavior with little control from a building design standpoint. The first four of these categories though

Figure 2: Example of Vasari Conceptual Energy Analysis Outputs created for preliminary massing designs (2013).

**WEST WING**

**BUILDING PARAMETERS**

| | | | | |
|---|---|---|---|---|
| Program Area | 11,283 | SF | | |
| Circulation @ | 0 | % | Program @ | 100 |
| Floor Area (Program + Circulation) | 11,283 | SF | | |
| | | | Program | 1 |
| Ceiling Height | 12 | FT | | |
| Volume (Floor Area x Ceiling Height) | 135,396 | CF | | |
| Roof Area | 6,570.00 | SF | | |
| Exterior Wall Area | 7,356.00 | SF | | |
| Total Exterior Surface Area) | 13,926.00 | SF | | |
| Volume to Surface Area Ratio) | 9.72 | | | |

**HEAT LOSS**

| | Surface Area | | R-Values | U-Values | UA | |
|---|---|---|---|---|---|---|
| Roof Assembly | 6,570.00 | SF | 20 | 0.05 | 328.50 | |
| Wall Assembly | 5776.00 | SF | 12.83 | 0.07794 | 450.19 | |
| Glazing | 1580.00 | SF | 5 | 0.2 | 316.00 | |
| **Total** | 13,926 | SF | | Total UA(Skin)= | 1094.69 | (BTU\h-F) |

| | | |
|---|---|---|
| UA(Infiltration)=0.6ACH x volume x 0.018= | 1462.277 | (BTU\h-F) |
| UA(total)=UA(skin)+ UA (inf)= | 2,556.97 | (BTU\h-F) |

**HEAT GAIN**

| | | | |
|---|---|---|---|
| Solar Insolation (Texas) | 1008 | (BTU/dy-SF) | |
| Solar Gain) | 68,996.34 | BTU/hr | |
| Internal Activity Heat Gains | | | Assumptions for Activities |
| People | 1.9 | BTU/hr-SF | Health Clinic |
| Equipment | 0.6 | BTU/hr-SF | Hospital/Office Space |
| Lighting | 0.5 | BTU/hr-SF | Daylight Factor >4 |
| **Total** | 3 | BTU/hr-SF | |
| Operation Hours | 10 | hrs | |
| Average Heat Gain | 1.25 | BTU/hr-SF | |
| Heat Gains (Internal Activity) | 14103.75 | BTU/hr | |
| Total Heat Gain | 83,100.09 | BTU/hr | |

**BALANCE POINT**

| | | |
|---|---|---|
| Balance Point Temperature (Tb = Ti - Qi/UA) | | |
| Ti (Desired Internal Temperature) | 70 | F |
| BALANCE POINT TEMPERATURE | 38 | F |

**EAST WING**

**BUILDING PARAMETERS**

| | | | | |
|---|---|---|---|---|
| Program Area | 5,630 | SF | | |
| Circulation @ | 0 | % | Program @ | 100 |
| Floor Area (Program + Circulation) | 5,630 | SF | | |
| | | | Program | 1 |
| Ceiling Height | 10 | FT | | |
| Volume (Floor Area x Ceiling Height) | 56,300 | CF | | |
| Roof Area | 4,218.00 | SF | | |
| Exterior Wall Area | 5,257.60 | SF | | |
| Total Exterior Surface Area) | 9,475.60 | SF | | |
| Volume to Surface Area Ratio) | 5.94 | | | |

**HEAT LOSS**

| | Surface Area | | R-Values | U-Values | UA | |
|---|---|---|---|---|---|---|
| Roof Assembly | 4,218.00 | SF | 20 | 0.05 | 210.90 | |
| Wall Assembly | 4102.90 | SF | 12.83 | 0.07794 | 319.79 | |
| Glazing | 1154.70 | SF | 5 | 0.2 | 230.94 | |
| **Total** | 9,476 | SF | | Total UA(Skin)= | 761.63 | (BTU\h-F) |

| | | |
|---|---|---|
| UA(Infiltration)=0.6ACH x volume x 0.018= | 608.04 | (BTU\h-F) |
| UA(total)=UA(skin)+ UA (inf)= | 1,369.67 | (BTU\h-F) |

**HEAT GAIN**

| | | | |
|---|---|---|---|
| Solar Insolation (Texas) | 1008 | (BTU/dy-SF) | |
| Solar Gain) | 68,996.34 | BTU/hr | |
| Internal Activity Heat Gains | | | Assumptions for Activities |
| People | 1.9 | BTU/hr-SF | Health Clinic |
| Equipment | 0.6 | BTU/hr-SF | Hospital/Office Space |
| Lighting | 0.5 | BTU/hr-SF | Daylight Factor >4 |
| **Total** | 3 | BTU/hr-SF | |
| Operation Hours | 10 | hrs | |
| Average Heat Gain | 1.25 | BTU/hr-SF | |
| Heat Gains (Internal Activity) | 7037.5 | BTU/hr | |
| Total Heat Gain | 76,033.84 | BTU/hr | |

**BALANCE POINT**

| | | |
|---|---|---|
| Balance Point Temperature (Tb = Ti - Qi/UA) | | |
| Ti (Desired Internal Temperature) | 70 | F |
| BALANCE POINT TEMPERATURE | 14 | F |

3

are directly linked to architectural design decisions and have long term impacts (that are often difficult to alter) on the functional use, performance and economy of designed spaces. These four categories in commercial buildings account for approximately 80% of the total energy used (USDOE BTO 2012). Thus it is the deeper understanding and analytical ability related to these four energy use categories that are proposed as targets for meaningful engagements and investments for architects. The performance metrics associated with these design elements that greatly affect energy use can be incorporated into the design process within a semester long technical analysis course and then later integrated into a semester long design studio. In addition, technical analysis regarding energy production must also be added to reach a viable net zero energy and carbon-neutral building design (Jankovic 2012).

## D. METRICS FOR ENERGY & BUILDING PERFORMANCE

Lighting, Heating, Cooling, Ventilation and Energy Production are technical categories that architects have mostly relegated to MEP and lighting design firms but can be meaningfully and quantitatively integrated into the architectural practice and allow designers greater control and maneuverability in the early design process. For lighting the analysis is focused on evaluating the recommended lighting levels for programmatic functions and how to efficiently meet those needs with

Figure 3: Example of undergraduate student-created spreadsheets for the use of building performance analysis in the comprehensive design studio (2013).

daylighting and electric lighting. This helps architects determine how many light fixtures and windows are needed and where they should be placed. For lighting the most common performance metrics are Watts/SF, lux (or footcandles) at the work surface and annual $/SF (Grondzik 2010). For heating, cooling and ventilation the analytical issues are focused on thermal loads and air quality. This helps determine the size and type of mechanical systems but also can critically inform the material assemblies of the building envelope and perhaps more importantly can significantly impact the size, location and function of spaces. For heating, cooling and ventilation, the most common metrics are kBTUs/SF/year and the annual $/SF (USEIA 2001). For energy production the analysis should focus not only on the system type and capital costs but the location and size of the energy systems employed and their spatial impact on the site. For energy production the common metrics are the Watts/SF generated and the annual $/SF saved. In each of these categories the amount of energy used/generated and carbon dioxide produced/saved can be quantified, tabulated and tracked through design iterations (Jankovic 2012).

### E. BENCHMARKS AND COST

These metrics are not only meaningful for designers to test the progress of their designs but they can also be compared to both national and international energy use databases such as the Commercial Building Energy Consumption Survey (USEIA 2003). Designers can also compare their results to code required minimums and develop baselines and strategies for energy efficient buildings. These internal and external comparisons and benchmarks can help designers quickly realize if design goals are in line with their project budgets. As part of the educational process of utilizing technical analysis it is critical for students to wrestle with project cost analysis and life cycle analysis. A total project cost analysis allows students and designers to see the capital cost impacts related to their design decisions and the life cycle cost analysis gives them a long term view of how these costs are related to the maintenance and operation of their buildings. Energy and cost analysis allows for more informed design decisions for both the designer and the owner.

### F. COMPARITIVE ANALYSIS THROUGH ITERATION

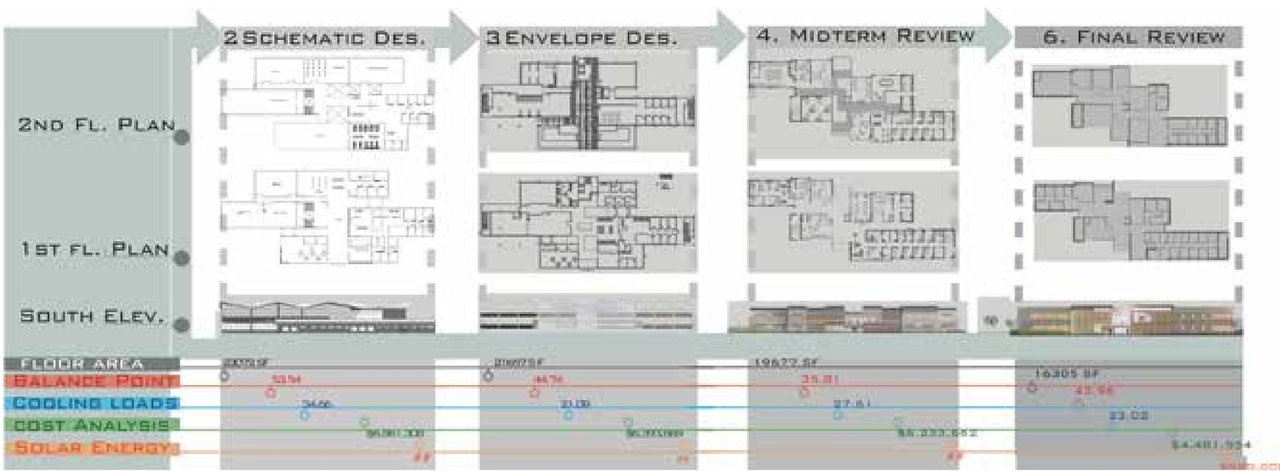
A key aspect of creating meaningful energy analysis in the architectural design process is to utilize the analysis as part of the iterative design process. Just as parametric and digital design techniques have allowed designers to explore a large number of possibilities in relatively short period of time, technical analysis is most beneficial when it is utilized as a comparative analytical tool that helps compare and contrast the merits of various design decisions (Jankovic 2012). This is where tools such as Vasari are well poised to help designers in the early stages make comparative analytical design decisions based on energy analysis.

## CASE STUDY IMPLEMENTATION

To study the pedagogical outcomes of using iterative technical analysis in architectural design, I implemented a two-year case study within my own building technology and architecture studio design courses at Philadelphia University. I teach and coordinate two interrelated courses within the required curriculum of a five-year NAAB accredited undergraduate architecture program. These two courses at Philadelphia University are the third-year environmental systems building technology course and the fourth-year comprehensive design studio. Each year, approximately sixty to seventy students complete these courses. The

| 2. Presently, I can... | 1:not applicable | 2:not at all | 3:just a little | 4:somewhat | 5:a lot | 6:a great deal | Mean | N |
|---|---|---|---|---|---|---|---|---|
| 2.1 Effectively diagram and incorporate schematic structural systems into my studio design process. | 0% | 0% | 8% | 17% | 67% | 8% | 4.8 | 12 |
| 2.2 Effectively incorporate and diagram building systems meaningfully into my studio design process. | 0% | 8% | 8% | 42% | 33% | 8% | 4.2 | 12 |
| 2.3 Effectively analyze and draw material assemblies related to the building envelope in regards to structure, climate and constructability | 0% | 0% | 8% | 50% | 33% | 8% | 4.4 | 12 |
| 2.4 Effectively determine and discuss the intent and character of my studio project. | 0% | 0% | 0% | 17% | 58% | 25% | 5.1 | 12 |
| 2.5 Develop logical arguments in regards to design decisions and concepts | 0% | 0% | 0% | 25% | 58% | 17% | 4.9 | 12 |
| 2.6 Write documents in discipline-appropriate style and format | 0% | 0% | 8% | 33% | 42% | 17% | 4.7 | 12 |

4




5

first objective was to use the third-year technology course to establish basic analytical skills through precedent studies and discrete quantitative analysis exercises in the form of hand calculations for lighting and MEP systems. The second objective was to use the fourth-year comprehensive studio as the curricular target for active implementation and demonstrated ability of technical analysis and simulation within a week by week iterative studio design process. Over the two academic years of 2011-2012 and 2012-2013 surveys have been conducted in each of these classes to track intentions and outcomes related to technical analysis and meaningful design integration. Surveys have been conducted at the beginning, midpoint and ends of the courses to track changes over the semester and over the two-year period. Figure 4 is an excerpt from the 2013 survey used in the comprehensive design studio.

## A. THIRD YEAR SYSTEMS COURSE

In the third-year environmental systems course the students are instructed in the use of approximate analytical methods used by their consultants to obtain early technical evaluations of building designs for lighting, MEP and energy production systems. This is most often accomplished through hand calculations and student generated spreadsheets on predefined common (in terms of CBECS performance) building designs. This helps them understand the metrics and analysis related to typical buildings and gives them a sense of scale and magnitude of

Figure 4: Survey questions completed by students gauging their perceived skills related to course material (2013).

Figure 5: Abridged student graphic of metrics from iterative quantitative analysis in studio design (2013).

the quantitative parameters. For lighting, the Lumen Method and Zonal Cavity Methods are employed. For thermal analysis, ASHRAE-based balance point temperatures and degree day methods are used. Most of the calculations used in the course are readily found in the 11th edition of *Mechanical and Electrical Equipment for Buildings* by Grondzik, Kwok, Stein and Reynolds.

### B. FOURTH-YEAR STUDIO

In the fourth-year comprehensive studio the students utilize these same analytical methods for their own individual design projects. This often starts with hand calculations but quickly evolves to spreadsheets that are tied to BIM models. During this studio they also begin to utilize prepackaged computer simulation tools such as Vasari and Ecotect to help them perform analysis on multiple design iterations. Over the course of the semester, metrics are mapped and presented to track the changes in design and their impact on the projects' cost and energy performance (see figure 5).

### C. CASE STUDY RESULTS

The results of the two-year study have shown a sharp increase in the integration of analytical tools in the students design process leading to more thoughtfully considered technical solutions within their designs for economically viable attempts at net zero and carbon-neutral building designs. Perhaps more importantly surveys have indicated that students, when finishing the two-course sequence, highly rank their confidence in the use of technical analysis and expect to integrate it into their future design work outside of the requirements of the design courses (Chung 2013). Many students expressed in the surveys that the design profession can and should be capable of utilizing analytical tools within the day-to-day design process to achieve net zero and carbon-neutral buildings.

## CONCLUSION

This paper presents some of the perceived and real difficulties of incorporating energy analysis into an iterative architectural design process and offers a two course implementation method for education programs to provide students with the means to build technical skills so that they can meaningfully utilize energy analysis toward viable carbon-neutral designs. Early educational application of fundamental building science analysis through hand calculations (before the regular use of prepackaged software) on a student's own design project is a highly effective method of creating a curriculum where students are empowered to use energy analysis as a supportive and meaningful design tool.

## REFERENCES


Banerjee H.K. and De Graaff E. 1996. Problem-based Learning in Architecture: Problems of Integration of Technical Disciplines, *European Journal of Engineering Education* vol. 21, No. 2.

Bower, A., Ashley, J., Buchanan, G., Dispensa, J., Pierce, J., Ross, F. 2007. Fostering Science Literacy: Non-science Majors Discover the Science behind National Public health Issues. *Science Education & Civic Engagement*: Winter 2007 vol 1, issue 1, pages 25-40.

Chung D and Harnish C. 2013 Methods for Developing Flexible Technical Knowledge in Architectural Education. *Architectural Research Centers Consortium Spring Research Conference* 2013, pp267-272.

Grondzik, W., Kwok, A., Stein, B., Reynolds, J. *Mechanical and Electrical Equipment for Buildings*, Hoboken, New Jersey: Wiley, 2010.

Hmelo-Silver, C. 2004. Problem-Based Learning: What and How Do Students Learn? *Educational Psychology Review*, Vol. 16, No. 3.

Jankovic, Ljubomir. *Designing Zero Carbon Buildings Using Dynamic Simulation Methods*. New York: Routledge, 2012.

Roberts, A. 2007. Problem Based Learning in Architecture. *Centre for Education in the Built Environment Briefing Guide Series*.

US Department of Energy Building Technologies Office (2012), "Commercial Building Basics." http://www1.eere.energy.gov/buildings/commercial/about.html.

US Energy Information Administration (2001), "Commercial Office Buildings" http://www.eia.gov/emeu/consumptionbriefs/cbecs/pbawebsite/office/office_howuseenergy.htm.

US Energy Information Administration (2003), "Energy Use in Commercial Office Buildings" http://www.eia.gov/energyexplained/index.cfm?page=us_energy_commercial.