Architecture Unplugged: The Teaching of the Principles, Needs and Calculation Procedures for Sustainable Housing Design

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ABSTRACT: The role of architectural education as a means of introducing new generations of architects to the principles and practices of sustainable architecture is becoming highly significant. There is a need, therefore, to effectively integrate sustainability considerations in the design education process. As early stages of the design process involve the assessment of a large number of design options in a short period of time, the potential for using detailed sizing and assessment methods in these stages is limited. Consequently, teaching methods that are both simplified and sufficiently accurate and that can be effectively integrated into these stages are greatly required. This paper describes an experimental method of introducing architecture students to the principles, needs, and calculation procedures for the use of on-site resources contributing to off-grid sustainable residential design. This bio-climatic approach to design targets reductions in loads, responds to solar geometry, incorporates passive solar systems, utilizes on-site water harvesting and photovoltaic technology, and, when needed, integrates high efficiency auxiliary mechanical systems. The method involved the development of six specialized booklets introducing students to the principles and calculation procedures for the proper design and sizing of various residential sustainable systems. The paper also describes the experimental application of the method in a graduate course in the department of Architecture, Texas A&M University and discusses the lessons learned from this.

Keywords: energy, housing, sustainability, solar geometry, passive solar, photovoltaic, water harvesting.

1. INTRODUCTION

Within the context of the increased realization of mounting environmental problems, the impact of the built environment in this regard, and the resulting growing sense of environmental responsibility of architects and other professionals, the role of architectural education as a means of introducing new generations of architects to the principles and practices of sustainable architecture is becoming highly significant. There is a need, therefore, to effectively integrate sustainability considerations, including issues of climatic design, passive strategies, resource efficiency, and reduction of environmental impact, in the design education process. As early stages of the design process involve the assessment of a large number of design options in a short period of time, the potential for using detailed sizing and assessment methods in these stages is limited. Consequently, teaching methods that are both simplified and sufficiently accurate and that can be effectively integrated into these stages are greatly required. This paper describes an experimental method of introducing architecture students to the principles, needs, and calculation procedures for the use of on-site resources contributing to off-grid sustainable residential design. This bio-climatic approach to design targets reductions in loads, responds to solar geometry, incorporates passive solar systems, utilizes on-site water harvesting and photovoltaic technology, and, when needed, integrates high efficiency auxiliary mechanical systems. The paper describes the methodology and content of the course and then presents an evaluation of its outcome.

2. LITERATURE REVIEW

Several studies have investigated different approaches for the integration of sustainability considerations, such as climatic, energy, and other environmental considerations, in the architectural design process. Earlier studies (e.g. Olgyay [1]; Milne & Givoni [2]; Watson & Labs [3]; and Lechner [4]) have all adopted the approach of developing design guidelines and/or expert rules of thumb for different climatic zones. In a different approach, Kreider [5] investigated the integration of the design of active and passive solar systems in different stages of the architectural design process, i.e. programming, schematic design, design development and construction documents, and presented calculations procedures for each stage, with increasing degrees of detail and accuracy. Kreider argued that the schematic design phase should include an estimate of building loads, the sizing of major system components, as well as initial attempts at system optimization. In a review of existing approaches, Morbitzer [6] categorized them into: design guidelines or rules of thumb, physical calculation methods, correlation based methods, and building simulation, and argued that rules of thumb do not offer any prediction of building performance and need to be adapted to specific building types and climates. On the other hand, physical calculation methods, either in the form of hand calculations or integrated into computer programs, aim to predict a certain physical process in a building, and can therefore be a better indicator of the performance of a specific design. A similar categorization is also offered by Shaviv et al. [7], who categorized existing approaches into rules of thumb, simplified procedural methods, and comprehensive simulation. All of the previous studies, however, recognize the need to integrate sustainability considerations into the early stages of the design process and that these considerations should play a role in the architectural form generation process. Many of them also argue for the need to develop methodologies for achieving this goal that go beyond the limitation of the generalized design guidelines and rules of thumb approach, while in the same time maintaining a level of simplicity, combined with sufficient accuracy, that allows them to fit within the time limitations of these early design stages.

3. COURSE OBJECTIVES

The purpose of the course was to identify the principles associated with bio-climatic design, to develop assessment methods for determining residential energy and resource needs, and to experiment with specific calculation methods for the proper design and sizing of the various sustainable systems. Further, it was important to realize the potential formal characteristics of design in supporting the efficiencies of the various systems. The focus on "off-grid" designs was to demonstrate through design the necessary impact required by these systems so that an understanding of the extremes required from completely unplugging from conventional sources and systems may be illustrated. Demonstrating the more radical architectural responses to accomplish off-grid housing will enable a better understanding for applying these principles and systems to larger residential developments, increased density and differing housing typologies. There were six prime learning objectives:

1. To identify the sustainable principles appropriate to the scale of skin-dominated residential design.
2. To become aware of the constraints and possibilities of the macro and micro climates;
3. To become aware of the constraints and possibilities offered by on-site analysis of resources.
4. To become aware of energy and resource needs required to render a design completely sustainable.
5. To develop an ability with the systems' designs, components and sizing calculations.
6. To become adept in the synergizing affects of the integration of systems and architectural form.

4. TEACHING METHODOLOGY

4.1 Overview

This graduate seminar was designed to combine technical information and quantitative analysis with the synthesis of design for a small residential project. Two differing climates were chosen – cold/temperate and hot/humid, although any climate can be used with the method. It was important to understand the normal building design process and the ways in which bio-climatic design considerations, particularly when generating quantifiable information, informed the design and become an integral part of the building form. A major course objective was to see, through these processes, the impact of all of the technologies, which utilize on-site resources and contribute to creating an *off-grid* or *unplugged* design.

The method developed for this course emphasized the relationships between climate and on-site resources; between on-site resources and environmental technologies; between environmental technologies and user needs; and between user needs and the resulting physical design response. By focusing on off-grid or utility-free systems, the approach clearly illustrated and emphasized the magnitude and importance of these systems choices and their impacts on design.

4.2 Structure of booklets

A number of booklets [10] were developed for the course each dealing with one of the various sustainable systems that impact the *unplugged* design. Each of those booklets started with definitions of key terms and concepts addressed in the booklet, followed by a summary of the system sizing procedures covered in subsequent sections of the booklets, which aimed to provide a quick-reference of students. Following that, background information, specific to each booklet, including system significance, main concepts and principles involved, system types, components, building integration methods, and other system design and performance considerations, are presented. A detailed description of the sizing calculation and procedures is then included combined with examples when necessary. Each booklet also included all the relevant data needed to perform its calculations (e.g. climate data, solar resources data, economic data, and product specifications). An example problem, representing an application of the booklet's calculation procedures to a specific design project, is then presented followed by a list of relevant references (e.g. [8], [9], [11]). Finally, some relevant articles or project descriptions are attached to some of the booklets.

4.3 Description of booklets

Heating and cooling loads - Residential heating loads (HL) and cooling loads (CL) vary in differing climate zones and patterns of use. Determination of these loads enabled the designers to select the various kinds and sizes of passive and active heating and cooling systems. The peak load equation was used to size auxiliary systems if 100% heating and cooling fractions were not achieved.

Students were asked to develop transmission losses/gains (UAΔT), to calculate infiltration losses, determine internal gains from lights, people and equipment, and calculate annual heating (1), cooling (2) and peak loads (3). To determine these load values, the following equations were used:

- •transmission losses/gains (Q_{trans})
- •air exchange infiltration losses/gains (Q_{inf})
- •internal gains (Q_{ig})

$$HL_{ann} = \frac{24\,[(Q_{trans} + Q_{inf})] - Q_{ig}]\ x\ Hydd}{1,000,000}\ \text{MBTU/yr} \quad (1)$$

$$CL_{ann} = (Q_{st} + Q_{glass} + Q_{inf} + Q_{occ} + Q_{app})\ x\ LF \quad (2)$$

$$Q_{peak} = Q_{tot}\ x\ (68^{\circ} - T_{design})\ \text{Btu/hr} \quad (3)$$

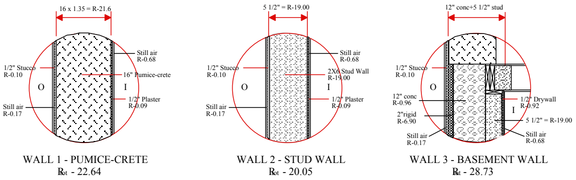

Figure 1: Fabric Wall Types

Students' heating and cooling load analysis varied from project to project. Typically, with their first runs, there was as much as 250% difference in the magnitude for annual loads – in cold climates, for example, these numbers varied from under 20 MBTU/yr to as much as 50 MBTU/yr. These differences occurred as a result of variations in envelope efficiencies, volume, amount of glazing area, and the presence of usable internal gains. The difficulty for students in this phase of the work was committing to a design, developing sufficient detail and providing necessary quantitative information for complete area and volume takeoffs. Students were often reluctant to make the necessary decisions about their project form, construction materials and wall section details at the early stage of the process. After first run load computations, students made appropriate adjustments to reduce them and/or bring them into acceptable levels.

Solar geometry - Solar geometry played an important role in the siting of buildings as well as the development of particular façade designs in response to various orientations, sun shading objectives, solar access and self-shadowing. In the cooler climates, solar access was important in order to protect the proper function of passive and active solar systems. In the warmer climates, solar control was important to reduce the deleterious effects of the sun, thereby reducing cooling loads.

Students were asked to create annual composite shadow patterns of adjacent coniferous and deciduous trees in summer and winter and to delineate self-shadowing caused by building design elements, such as roof overhangs, stepping forms and other protrusions. In addition they were asked to design proper shading devices for fenestrations on the south and west facades. To determine composite annual shadow patterns and solar shading devices (overhangs), the following equations were used.

- •solar window hour selection (Al)
- •building element height (H)
- •site slope analysis (Sa)
- •overhang design (Do)

$$D_{(distance)} = \frac{H\,(height)}{\tan Al_{(hour)} - (Sa\ x\ \cos B)} \quad (4)$$

$$D_{(overhang)} = {}^{H}\!/_{\cot Al} \quad (5)$$

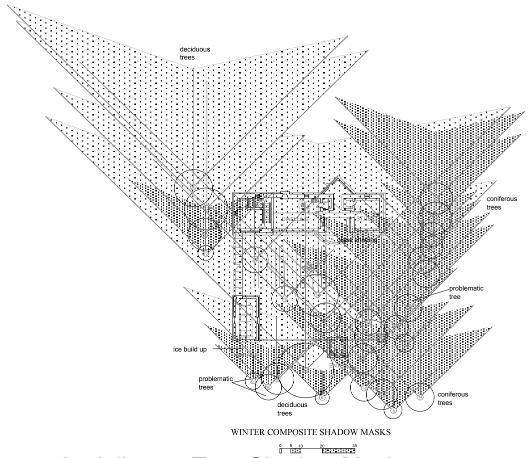

Figure 2: Adjacent Tree Shadow Masks

Students' solar geometry analysis impacted the building orientation, aspect ratios, varying façade treatments, landscaping, and shading device designs. As student designs gained more complexity of form, self-shadowing became more present. Necessary response to solar geometry varied drastically between cold and hot climates and between summer and winter seasons. Orientation responses to the cardinal directions acknowledged the differing ambient conditions and solar energy variability. For all solar energy systems in this project, 100% solar access was a goal of the program.

Passive solar heating & cooling - In the conceptual and schematic design phases it was important to gain an understanding of the magnitude of physical impact of passive solar systems' choices. Direct Gain, Thermal Wall, and Sunspace systems were available for analysis using the P-chart method of sizing developed by Dr. Jan F. Kreider. In more complex designs, hybrid or mixed systems were used. This usually produced added complexity to the computational methods and integrative design. Design responses for these systems focused on collection, distribution and storage of solar energy and the ways in which the architecture contributed to these functions.

The sizing procedure for passive solar heating systems determined the solar collector area and thermal mass requirements (6), the solar fraction (7) and optimized systems' cost. Students were required to choose actual grazing systems and windows in order to achieve net or usable glass areas. To calculate the area and storage requirements, and solar fraction, the following equations were used.

- •L, annual heating load requirement
- •F & H, fuel cost and inflation rates
- •C & G, passive systems' cost and interest rates
- •Ac, passive solar collector requirements
- •fs, solar fraction

$$A_c = \left[\frac{(\frac{F \times H}{N}) \times A}{(C \times G)} - \frac{1}{B} \right] \quad (6)$$

$$f_s = A \times \ln\left[1 + B \left(\frac{A_c}{L}\right)\right] \quad (7)$$

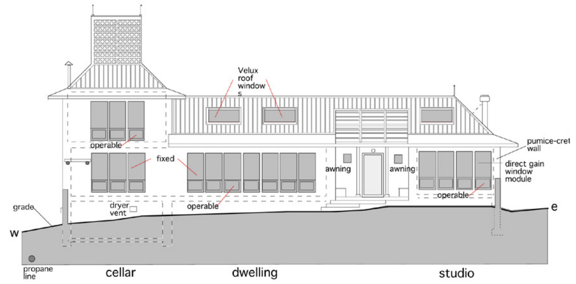

Figure 3: South façade passive glazing

Students' passive heating and cooling systems designs included the solar collector and thermal mass sizing and placement, internal zone coupling techniques, ventilation, shading and other cooling techniques. For the cold climate designs, students soon found out that passive solar collection area requirements were quite high and had a large impact upon the south facades and roofs. Thermal mass placement was initially undersized and lacked appropriate heat distribution characteristics.

Photovoltaic systems – here, student were introduced to the concept, principles and simplified sizing procedures of photovoltaic (PV) systems. Basic photovoltaic system types, components, and building applications were addressed and a number of factors that impact the design and performance of PV systems were discusses. The included sizing procedures introduced student to simplified methods of estimating the building's electric demand vs. the available solar resources. Subsequently, a PV system was sized (8) which utilizes the available resources to meet those demands. The main equation used for sizing the collector area (A_c) is:

- Wh/da, daily electric demand
- f & C, PV efficiency and conversion factor
- I & DL, solar insolation and no. of daylight hours

$$A_c = \frac{\text{Wh/da} \times 365\ \text{da} \times C}{f \times I \times DL} \quad (8)$$

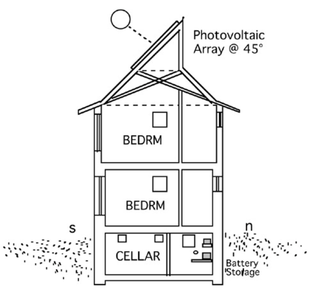

Figure 4: PV system building integration

Students were encouraged to investigate the design implications of the PV system size and the impact of reducing electrical demand on that size, and therefore on the design of the building. Students also investigated the impact of PV systems on building form, orientation, roof tilt, roof area, and other PV building integration requirements.

Water in architecture – here, students were introduced to the significance of water as a valuable resource and the need for, and methods of, increasing water efficiency. The basic types, components, and design considerations for a number of related building systems were then introduced, including rain water harvesting systems, solar domestic hot water (SDHW) systems, and grey water systems. Sizing procedures were then presented for both rain water harvesting systems and SDHW. Both systems were sized based on an estimate of the demand (of water in general or of hot water) and the available resource (rain water or solar energy). Sizing of SDHW systems used the P-Chart method, which provides an estimate of the available solar resource in a specific location in the form of two constants, A & B. The main equation used was:

- A_C, required collector area
- f_s, desired solar fraction
- L, annual thermal demand (MMBTU)

$$A_c = L\left[(\exp(f_s / A) - 1)/B\right] \quad (9)$$

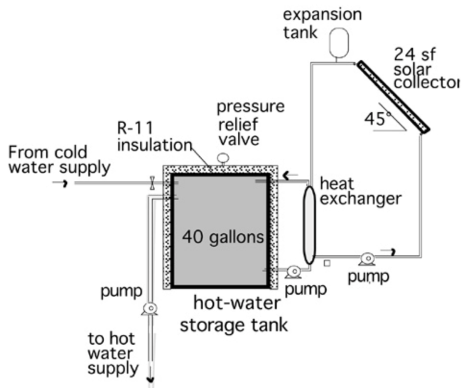

Figure 5: Diagram of SDHW system

After sizing these two systems, students were required to integrate the different system components into their designs and to investigate the implications of the system sizes on various design related considerations such as building orientation, roof tilt, roof size, selection of material, and space programming. The relationship between the size of the systems and the demand was also investigated.

Auxiliary systems – this booklet presents students with selected auxiliary heating, cooling and power systems suitable for small residential buildings, which are used both to supplement the passive heating and cooling systems or as a backup for them. Systems presented in booklet included: electric heating, stoves, baseboard heating, warm air systems, and heat pumps in the case of heating, and mechanical ventilation, including ceiling fans and whole-house fans, in the case of cooling. Simplified sizing procedures were included for electric heating systems, wood stove systems, baseboard heating systems, and whole-house fans. Sizing procedures for all of these systems use an estimate of the peak (heating or cooling) load, calculated previously, to size the system based on the available efficiencies.

For example, the following equation is used to size a boiler for the baseboard heating system:

- B_{cap} & E, boiler capacity & boiler efficiency
- SI, standby losses
- Q_{peak}, peak heating load (MMBTU)

$$B_{cap} = \frac{SI \times Q_{peak}}{E} \tag{10}$$

While the systems included in this booklet were not covered in depth, as this would lie beyond the scope of the course, sufficient information was presented to give students a sense of why an auxiliary system is needed, their selection criteria, and the positive and negative implications of their use. The impact of each of these systems on the design was also investigated as was the impact of reducing the peak load on the size of the auxiliary system and therefore on its design implications.

4.4 Design projects

Regardless of climate zone, each student worked from the same building program, in which the space requirements were approximately 1000 square feet (100 sq. meters) for an off-grid retreat. Two sites were selected – one outside of Austin, Texas and the other in southern Colorado. The program called for living, dining and kitchen areas, two-bedrooms, bathroom, storage, and systems' mechanical space. Systems to be analyzed included: passive heating and cooling, photovoltaic electric, water harvesting and solar hot-water, and auxiliary HVAC as required. The students were to achieve between 90% and 100% self-sufficiency with their designs.

5. EXAMPLES OF STUDENT WORK

Students were required to submit all calculations, performance-based analysis, systems' designs, and a full set of architectural drawings with a physical model. Figures 6 & 7 show examples of student projects for a hot and a cold climate zone respectively, which show the integration of various sustainable systems such as stack ventilation & whole house fans (figure 6), and envelope insulation & mechanical room requirements (figure 7).

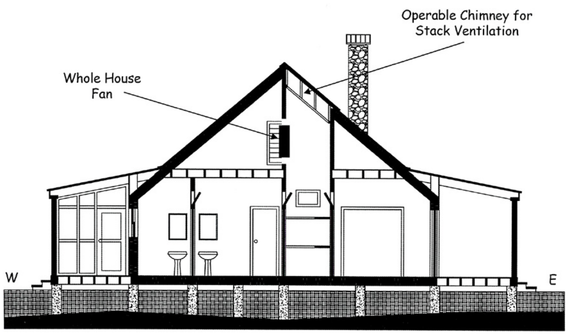

Figure 6: Student design example for hot climate

The conditioned spaces in the house in Figure 6 are surrounded by a protective porch and buffer space and the structure is lifted off grade to promote under-floor ventilation. The high ceiling helps promote the stack ventilation.

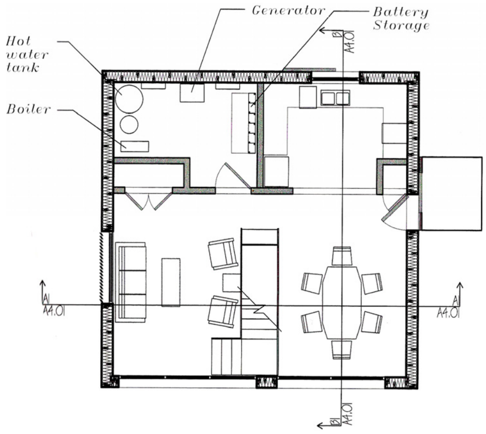

Figure 7: Student design example for cold climate

6. LESSONS LEARNED

7.1 Systems' impact upon the building design

Systems' requirements seriously impact building designs as climate zones become more severe and as the design approaches the 100% level of self-sufficiency. The impact of the various systems' area requirements and the need for thermal balancing for all interior spaces required careful planning and design. Being armed with performance-based information in the formative stages of design helps in assuring the appropriate technological response. The iterative process allowed students to make incremental adjustment to their evolving designs in response to the systems' needs.

- Off-grid sustainable technologies have a large impact upon students' designs, particularly the primary form, which is characterized by size, shape, aspect, orientation, complexity, levels of transparency, and materiality.

7.2 Achieving higher levels of efficiency

Once students gained an understanding of the systems' components and the computational requirements generating particular designs, they began to realize the difficulty in achieving the higher levels of self-sufficiency and the degree to which the systems' determinants affected their designs. In particular were the area requirements of passive solar collection, thermal mass storage, photovoltaic electricity production, and water harvesting. The mechanical room requirements increased in complexity with the storage, filtering and monitoring requirements. Several important lessons are summarized below:

- Certain technical considerations, such as size, orientation, location, etc., must be adhered to in order to render the systems operational. Many of the constraints associated with these systems cannot be compromised; and
- Area requirements for achieving the higher levels of self-sufficiency were quite significant, often competing with other design objectives.

7.3 Integrative Designs

The quality of integration was affected by the understanding of the physical impacts of the various systems. At first students simply added the technologies to their building forms. Often they appeared contrived, awkward and temporary. Better designs seemed to more fully integrate the systems and their constraints with more compatible and blended building forms. Using bio-climatic design principles helped in setting the stage for the integration of these systems.

- Creating an overall design unity, with these various systems, was difficult. Those designs that blended the technologies and building forms achieved higher levels of integration and produced more aesthetic results.

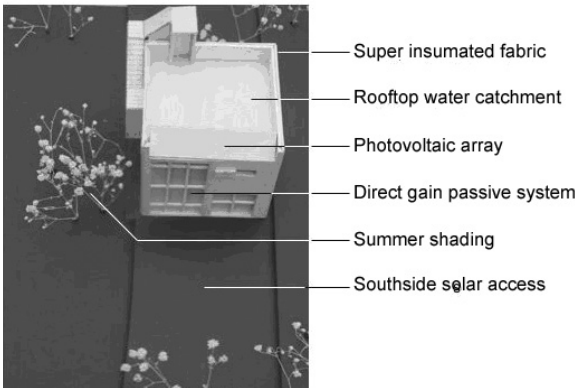

Figure 8: Final Project Model

7. SUMMARY AND CONCLUSIONS

8.1 Conventional course delivery methods

Application of environmental technologies to student designs is difficult given the normal methods of academic delivery – environmental controls lecture or survey courses and studio design projects. The lecture courses are often piecemeal and do not allow the student to fully engage in the integrative design process. Studio projects most often were too large and too complex to achieve a mature level of analysis and often had multiple design agendas. The comprehensive studio require by NAAB is one of few studios that typically requires evidence of knowledge in the areas of climate, energy, sustainability and environmental control systems. Following are the two primary shortcomings of these kinds of delivery systems:

- Overly detailed and piecemeal lecture courses
- Pluralistic and complex studio design agendas

9.2 Integrative learning outcomes

In between these two approaches was our method, which drew from the best of their inherent pedagogies – content and synthesis. This was the design/seminar where technical focus, detail and performance analysis were directly related to the integrative formal design process. Informed analysis and sustainable design principles were the prime objectives, and students were able to apply systems' thinking into the primary, secondary and tertiary form responses. Since student design work rarely evolves beyond the schematic design phase, this course provided ample material for an intelligent fusing of technology into the form and meaning of their designs expressed at that level.

- Technology and design - a necessary unity
- Performance-based decision-making

It is important to expose students to the cause and effect of systems' requirements and components upon the synthetic process of design. As students gain a greater understanding of this systems-building form integration process, their designs become more responsive and expressive of these important determinants. The learning outcomes are integral to their designs and, therefore, the learning process is both expressed and it gains valuable ownership by each student. A difficulty with this kind of course is its ability to be classified as a required course where it would reach all professional design students. The required interaction and feedback may be too difficult within a large class format. Architecture Unplugged is an experimental design pedagogy that would certainly benefit from further exploration and testing. Its application to multi-family housing typologies and larger community contexts would give the work greater applicability.

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