Open Access

Advances in Environmental and Engineering Research

LIDSEN Publishing Inc.

Original Research

On Net Zero Energy Building Design Methodology: A Case Study Examining Learning as Measured by Interdisciplinary Knowledge Acquisition

Luis A. Martínez [1,*], Lizeth Rodríguez [2], Carlos M. Flores [1], Carlos A. Cisneros [2], Mario W. Chávez [1], Idis A. Lemus [1], René I. Ariza [1]

1. Departamento de Ciencias Energéticas y Fluidicas, Universidad Centroamericana "José Simeón Cañas", Antiguo Cuscatlán, El Salvador; E-Mails: lamartinez@uca.edu.sv; cmflores@uca.edu.sv; mchavez@uca.edu.sv; 00097313@uca.edu.sv; rariza@uca.edu.sv
2. Departamento de Organización del Espacio, Universidad Centroamericana "José Simeón Cañas", Antiguo Cuscatlán, El Salvador; E-Mails: lrrodriguez@uca.edu.sv; acisneros@uca.edu.sv; ORCID of Lizeth Rodríguez: 0000-0003-2890-0433

* **Correspondence:** Luis A. Martínez; E-Mail: lamartinez@uca.edu.sv; ORCID: 0000-0002-6553-8819

Academic Editor: Zed Rengel

Special Issue: Advances in Environmental and Energy Economics

Adv Environ Eng Res
2023, volume 4, issue 1
doi:10.21926/aeer.2301001

Received: August 28, 2022
Accepted: December 27, 2022
Published: January 03, 2023

Abstract

Net zero energy building design methodologies include integrative approaches and numerical tools to provide optimal performance and cost-effective results. Team integration, characterized by knowledge transfer between disciplines, has yet to be quantified for the design processes of these buildings. This article proposes a specific methodology for designing net zero energy buildings, tested through a case study design process conducted in an academic setting at Universidad Centroamericana in El Salvador, with the participation of students and faculty members. Through a survey, interdisciplinary knowledge transfer between team members was measured. We found that, without additional instruction, team participants outperformed a control group without project involvement by 16.4% ($P < 0.002$, t-test) in terms of interdisciplinary knowledge. This result implies that designers acquire new knowledge from other disciplines by interacting and solving design problems, although such acquisition is not uniform between disciplines. Remarkably, results show that the disciplinary groups that acquired the most knowledge about each other are Mechanical Engineering students and Architecture students. These results help us understand how to improve the design process, limit boundaries for disciplinary interactions, and determine which specific knowledge gaps to target per discipline in engineering and architecture education.

Keywords

Net zero energy; case study; design; methodology; interdisciplinary teams; interdisciplinarity

1. Introduction

Net zero energy buildings (NZEB) are being implemented worldwide [1-3]. The design process of these buildings is a collaborative effort that requires appropriate methodologies and tools. Traditionally, a new building design process gathered a team of experts in various disciplines, such as architecture, civil engineering, mechanical engineering, and electrical engineering, to work together and develop each component and system of the building sequentially. This multidisciplinary work lacked a more detailed understanding of how each discipline affects the overall design. In recent times, building design approaches have improved, and a push for an integrative design process encourages all specialists to participate in the design process from the initial meetings, assessing opportunities and challenges collaboratively, as advocated by the United States Green Building Council (USGBC) [4].

Additionally, design tools [5] help guide the design teams on design decisions' practical and quantitative outcomes. Tools such as energy modeling and optimization software have become prevalent [6-8]. The design process of an NZEB generally includes energy modeling and optimization techniques to achieve the net zero energy balance within the design constraints. Design teams generally adopt a quantitative definition of NZEB [9] and invest significant time to meet that quantitative goal. The challenge is finding the optimal combination of features and strategies to achieve the desired result. Several works have investigated optimization approaches; for instance, Harkouss [10] presented a simulation-based multi-criteria optimization of NZEBs, including four steps: building simulation, optimization process, multi-criteria decision-making (MCDM), and testing the solution's robustness.

On the other hand, Kapsalaki [7] developed a methodology for optimizing NZEBs from the economic standpoint, considering the influence of local climate, energy resources, and local economic conditions. He found that the difference between an economically efficient and economically inefficient NZEB can be over three times in terms of initial and life cycle cost, which underpins the importance of optimization. Genetic algorithms can effectively evaluate the energy and thermal performance of building envelopes and other systems [11]. Attia [12] found that simple genetic and evolutionary algorithms are easily adaptable, and the limitations in integrating these tools into the design practice have been examined. However, the difficulty of use and a steep learning curve continues to be a challenge for their widespread use. Another aspect to consider is the changing climate, which forces designers to consider the variations caused by climate change, as advocated by Robert [13]. Recently, with the emergence of data-driven technologies such as the Internet of Things (IoT), Machine Learning (ML), and Smart Grid applications, even better integration and optimization are needed, as discussed by Bellatreche [14], who shares a data-driven methodology for designing net zero energy public buildings.

Team integration is one key component for the effective design process of high-performing buildings. It is generally assumed that design team integration is key to achieving successful building designs, but such integration is generally considered abstract and challenging to quantify. A theoretical concept that helps visualize the integration is interdisciplinarity. Interdisciplinarity can be defined as the integration of different disciplines working on a common problem [15]. This approach incorporates new integrative qualities not inherent to each isolated discipline [16-18]. The key difference between interdisciplinarity and multidisciplinarity is integration. Interdisciplinarity implies more integration and invites a more involved conversation between disciplines to solve common problems from different perspectives and knowledge. Within the building design context, few studies have empirically looked at the design process of an NZEB from the participants' perspective [19]. Attia [20] studied the integrated design process of high-performing buildings to propose a map that attempts to guide and describe each stage of the process, including team competencies and expert assistance required. The proposed map was discussed with design practitioners and analyzed through process modeling software to gain feedback. The result concluded that actual design practice differs from recommended design methodologies, remarking on the non-sequential process, selective use of analysis tools, and using external expertise only when needed. It is common for design teams to use design charrettes, defined as intensive participatory workshops for brainstorming different schemes for a project or aspects or areas within a project [21]. The interdisciplinary design charrettes were the object of inquiry by Sutton [22], who examined three design charrettes involving students and faculty from various disciplines, including architecture, urban design, community planning, history, and social work, and members of the community benefitted from the designs. The paper found evidence of new knowledge acquired by team members due to the combination of technical and practical knowledge through team member communication. However, the study also indicated that disciplinary communication tools need to be adjusted to include another discipline's members in the conversations. Additionally, some case studies reveal an interest in improving engineering design education for undergraduate students, introducing interdisciplinary design and sustainability [23-27].

Nevertheless, it is not well understood how effective the interactions between team members in the NZEB design process are. Particularly, it is not known how knowledge is transferred during the process. Knowing how those interactions work can help improve design methodology, design practice, and engineering and architecture education. For instance, a structural engineer with knowledge of mechanical engineering and electrical engineering is more capable of proposing a structural system that is more synergistic with the building's mechanical and electrical systems than another engineer with limited or no knowledge of those disciplines. We argue that a necessary condition for a team member who belongs to one discipline to bridge the gap with other disciplines is acquiring knowledge from other disciplines.

This paper aims to shed light on the interdisciplinary interactions that occur throughout the design process of an NZEB. Particularly, we want to present a design methodology for NZEB buildings and assess the transfer of knowledge between disciplines due to participants' interactions throughout a case study design process. The article provides the following contributions: i) An NZEB design methodology was synthesized and adapted from the literature (Section 2.2) and was used as a guideline in the present case study. ii) We measured interdisciplinary knowledge acquisition at the end of the design process through a survey and identified the need for additional training in specific areas for each discipline (Section 3.2). iii) Interdisciplinary interaction during the design process is discussed, and lessons learned are presented (Section 4.7).

2. Methods

This research project included the design of a new NZEB building and analyzing team interactions and knowledge transfer between disciplines during the design process. To conduct the activities, it was necessary to define a) net zero energy building design process methodology and b) Survey methodology to measure knowledge transfer during the design process. In this section, we present each specific methodology in detail.

2.1 Design Process Methodology

An NZEB design methodology was developed for the present case study using approaches found in the literature [12, 28-30]. The proposed methodology is a synthesis of design approaches explicitly aimed at achieving NZEB considering measurement and verification of performance. We believe it can be used as a guideline for designing high-performance NZEB in contexts not limited to the present case study. The case study consists of the design of an NZEB at Universidad Centroamericana "José Simeón Cañas" (UCA) in Antiguo Cuscatlán, El Salvador. The building to be designed is a 100 m^2 laboratory with mixed-used space for a research laboratory, classroom, technology showroom, and office space. A multidisciplinary group of professors and students from UCA conducted the design. In this paper, we will refer to the professors as faculty. The disciplines involved were Architecture (ARC), Civil Engineering (CE), Mechanical Engineering (ME), and Electrical Engineering (EE). The designing timeline was from October 5th, 2017, to April 10th, 2018.

Early in the process, all design team members were briefed on the design methodology developed by the researchers. No training was provided to team members about disciplines other than their own and the design tools and software needed within their discipline. The methodology guided the design process, and all design meetings were documented for further review. The documentation included meeting minutes, status reports, photographs, and audio interviews with selected team members.

From the holistic approach, a building is a set of systems that interact with each other to respond as a unit throughout its useful life. Therefore, each system has a function and performance that can affect all other systems. It is the case of the interaction between systems such as; electrical, HVAC, hydraulic, envelope or façade, structure, and circulations, among others. Therefore, in the design process of a building, the intervention of a team of professionals is required, whose experience must be accrued to respond to the challenges posed by the design project.

Otherwise, in traditional practice, an architect generates a first project draft called a "preliminary project" that is the starting point for the development of the engineering applied to the building; however, for the design of high-performance buildings, it is necessary that the beginning of the project is generated by a team of experts in each of the building systems, interacting in an interdisciplinary way.

In this sense, the design process of the NZEB El Salvador laboratory began with charrette-type team meetings, according to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), in which both collaborating students and faculty from the different areas worked in an integrated manner [30], as shown in Figure 1 and Figure 2.

Figure 1 Student design charette.

Figure 2 Design team interaction (faculty and students).

In the case of the NZEB building designed at UCA, the process lasted seven months. Three months were invested in the site analysis and initial research, as well as the evaluation of construction technologies. The remaining four months were dedicated to implementing the integrative design methodology. The design team met regularly to discuss progress and make design decisions. The use of collaborative resources such as Building Integration Modeling software was included throughout the process [31]. The follow-up of the planning and the revision of the design products were conducted weekly. This allowed for completing the design documents (executive project) and information required for obtaining the construction permits within the expected time frame. The design process included three phases, schematically shown in Figure 3.

- Phase I: Generation of Initial model;
- Phase II: Iterative optimization process;
- Phase III: Generation of technical and legal documents.

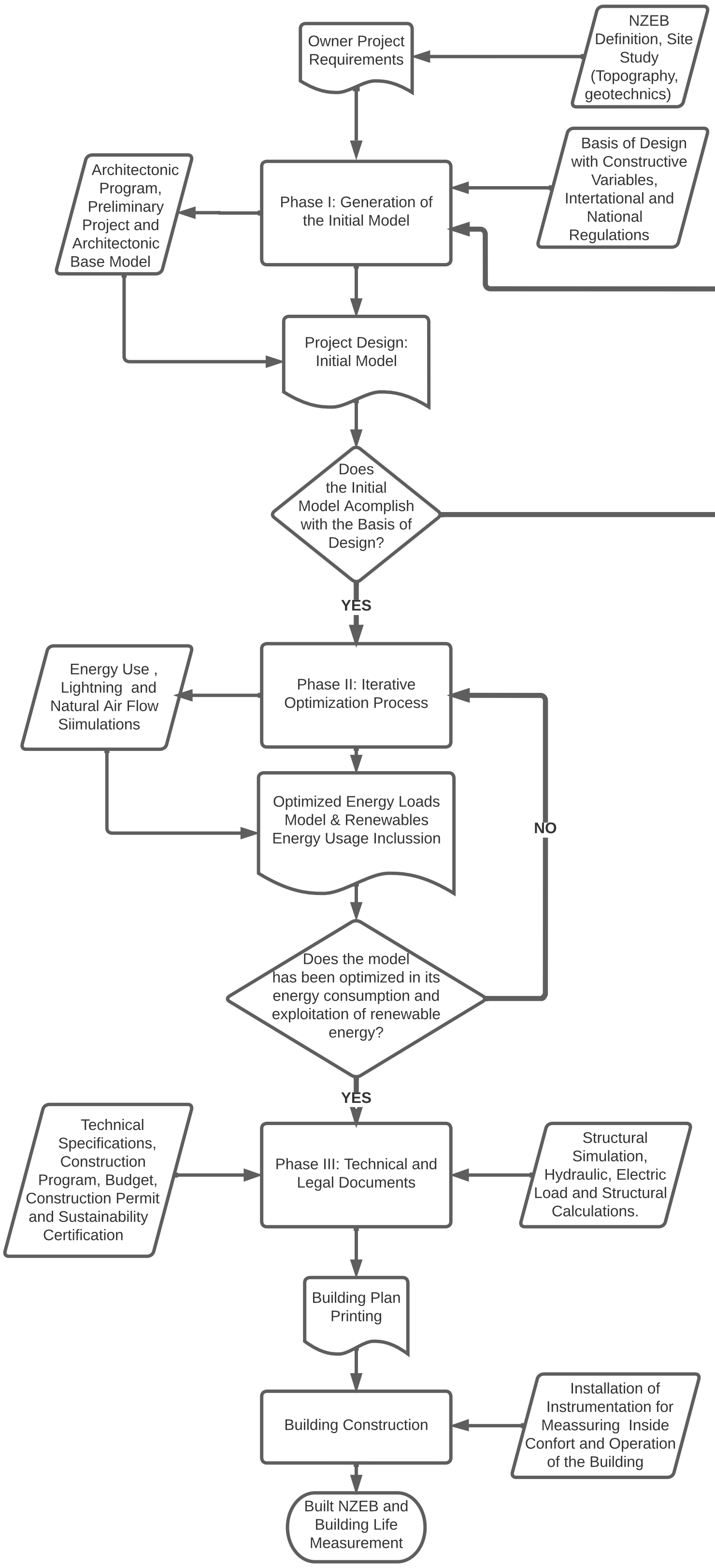

Figure 3 Interdisciplinary design methodology adopted for NZEB design.

Phase I: Generation of Initial model: It is summarized in the following sub-processes from 1 to 6, and if step 5 is not fulfilled, it should iterate to step 4 and, if necessary, to step 3.

1. Establishment of the Owner Project Requirements (OPR), which are the requirements for the use of the building [30].
2. Study of the environment and the site through geotechnical and topographic studies.
3. Architectural Program (AP). This is the systematization of spaces and their characteristics.
4. Base model, first volumetric sketch for solar incidence analysis, and verify the location of the building on the site.
5. Establishment of the Basis of Design (BOD), including the technical assumptions, calculations, revisions of codes, equipment selection, and system design assumed to satisfy the OPR and validation of the base model. The BOD is given by standards of energy efficiency and comfort conditions such as the ASHRAE 90.1 [32].
6. Establishment of architectural base model validated with BOD.

Phase II: Iterative optimization process: Through energy simulation, annual energy consumption is estimated for the architectural base model with the specifications defined in the OPR and BOD. Phase II is summarized in the following sub-processes from 7 to 11. In case of steps 7 to 9 are not fulfilled, they should be iterated, if necessary, to step 6 of the previous phase I to validate step 10, giving way to the sub-processes 11 and 12.

7. Energy simulation. Required inputs are the thermal characteristics of the building envelope systems (facades and roof), the number of users, assumed electric loads, and schedules. The outputs are the thermal load and energy consumption [12, 33].
8. Lighting simulation, requiring as input the type of luminaire and the type of natural lighting input or percentage of fenestration, has as output the load and consumption by lighting [12, 33].
9. Airflow simulation, which has as input the percentage of fenestration and has as output the load and consumption by ventilation.
10. Generation of optimized energy loads model. This is the result of an iterative process, as many times as necessary, to comply with the required energy performance or improvement over ASHRAE 90.1 standard [12, 33].
11. Potential renewable energy use simulation will depend on the location of the building, its surroundings, its geometry, and the definition of net zero Energy for which the building was designed [12, 33].
12. Structural simulation guarantees that the proposed structural system complies with the structural safety parameters and verifies that the stresses and the deformations comply with admissible values.

Phase III: Generating technical and legal documents: this is required to manage construction processes. It is summarized in the following sub-processes from 13 to 19, and if step 16 is not fulfilled, the following steps 17 to 19 cannot be performed.

13. Calculation of electric loads according to equipment demand.
14. Calculating hydraulic installations according to the pressure delivered and the sewage and rainwater collection systems.
15. The structural calculation, according to the structural simulation process and validated architectural model.
16. Building plan printing. Required for applying for legal construction permits.

17. Technical specifications, which complement the construction plans, including a detailed report of the building technologies applied, gather evidence for compliance with certification requirements [19].
18. Construction program. This is constituted by the planning document of the construction works and foresees the duration of the activities of execution of works taking into account the financial resources and the management of human talent.
19. Budget. Obtained from the detailed work volume of the supply plan and the direct unit cost per work, as well as the indirect cost derived from the works program.

The design team formed by professors and students worked collaboratively and followed the methodology step by step. Synergies were created for the effective transfer of knowledge that is required in an integrative design process. In this case, twelve design iterations were needed to complete the optimized load model, achieving a net zero energy balance within the Bases of Design BOD and Owner Project Requirements OPR.

Upon completion of the design process, all environmental and Construction licenses and permits were obtained, followed by the commissioning stage, prior to the installation of measuring instruments [29].

2.2 Survey Methodology

A survey was developed for design team members at the end of the design process. The purpose of the survey is to assess design team members' experiences through the design process and knowledge about the disciplines involved in the project. The idea of measuring the benefits of project-based learning has been explored in the literature [34, 35]. This approach showcases how students acquire new understandings, knowledge, and attitudes regarding the issues under investigation [36], often using standardized test averages [37]. Previous studies emphasize the need for controlled experimental studies, such as the one conducted in this paper. Since all researchers participated in the design process, the lead researcher prepared the survey using a group of questions suggested by the UCA faculty. The survey was administered to team participants from July 27th, 2018, to October 4th, 2018. The period was extended due to multiple commitments of students and faculty at the end of the semester, which complicated administering the survey to all participants within a short time frame. The lead researcher did not take the survey to avoid affecting the outcome.

The survey contained fifteen qualitative questions regarding the experiences of team members through the design process and sixty questions that explored fundamental and practical knowledge in three areas: I) Construction (CO), II) Electrical Systems (ES), and III) Energy (E) (including energy modeling and HVAC systems). Twenty questions were designed for each knowledge area, ten focused on fundamentals, and ten on practical knowledge obtained during the design process. The knowledge questions were multiple choice and qualitative; it was opted not to include quantitative or calculated questions in order not to bias the results due to the different mathematical backgrounds within the participating disciplines. Three knowledge areas were defined, which would encompass all disciplines involved. The definition of the knowledge areas was based on simplicity. Out of the four disciplines involved in the design process, the ones more closely related, from the disciplinary standpoint, are architecture and civil engineering. Both disciplines work on different perspectives of building construction but are generally subject-related, especially on a fundamental basis. A knowledge area named Construction (CO) would focus on the knowledge associated with building construction, including structural and architectural considerations. The second knowledge area under analysis is Electrical Systems (ES), including power and control systems. This area is in the domain of electrical engineering. One final knowledge area would focus on Energy (E), more specifically, energy efficiency, simulation, and HVAC systems. Although Energy is a broad area closely related to Electrical Systems, the third knowledge area focuses on the thermal and modeling aspects of energy use in buildings. These areas are traditionally within the domain of Mechanical Engineering. Hence, three knowledge areas are matched with three disciplinary groups: Architecture/Civil Engineering (ARC/CE), Electrical Engineering (EE), and Mechanical Engineering (ME). It should be noted that Architecture and Civil Engineering are two separate disciplines, but the purposes of the present study are grouped due to their focus on construction. For each knowledge area, twenty questions were prepared, ten fundamental testing knowledge and ten evaluating practical project-related knowledge.

In parallel, a random group of faculty and students who were not involved in the design process were asked to complete the survey but only the fundamental questions (30 questions). The random group of faculty and students, i.e., the control group, was chosen to be as academically similar as possible to the design team members, i.e., the experimental group. Surveys were administered to all participants on campus under controlled conditions. Survey responses are the basis for the analysis presented in section 3. All survey questions are presented in Annex A.

The determination of the survey groups was based on the following considerations. The case study design process was conducted by a team of leading faculty and third, fourth, and 5th-year undergraduate students; therefore, this particular group is the one in which interdisciplinary interactions occurred and is the subject of this study. The experimental group comprises the design team members, leading faculty, and students. In order to contrast the experimental group results, there is a need for a similar group of people without the experience of working together through a design process and without the experience of interacting with students or faculty from other disciplines. This group would be our control group. The criteria for selecting the control group were the following: 1) Professors from the same field and experience, determined by the university tenure track system (i.e. an associate professor in the experimental group would have an equivalent associate professor from the same field but without involvement in the design process), 2) Students from the same majors and academic year, taking similar courses and with Grade Point Averages within a given range (7.0/10.0 or above), 3) Within the possible control group candidates, final control group participants were chosen randomly. Table 1 summarizes the experimental and control groups whose answers have been analyzed in the present study. A larger student sample was chosen for the control group since the experimental group was limited by the number of students and faculty who were part of the case study design process. The design process participants limit the small sample for the experimental group. A larger control group sample makes statistical results more representative of the faculty and student bodies within those disciplines.

Table 1 Summary of Experimental Group and Control Group.

Discipline	Experimental Group[a]		Control Group[d]	
	Students[b]	Faculty[c]	Students[e]	Faculty[f]
Architecture/Civil Engineering	5	2	6	2
Electrical Engineering	5	1	10	1
Mechanical Engineering	3	1	8	1
Totals	13	4	24	4

[a] The experimental group consists of the team of students and faculty who participated in the design process.

[b] Students who participated in the study are 3rd, 4th and 5th year undergraduate students with no previous experience in design processes.

[c] Faculty who participated in the study have some experience in building design processes but their experience in integrative design is limited. They were mainly junior level faculty.

[d] The control group consists of a random sample of students and faculty who did not participate in the design process.

[e] Students in the control group were randomly selected from a list of students who are classmates with experimental group students, take similar classes and are 3rd, 4th and 5th year undergraduate students which at the time had no prior experience in design processes.

[f] Faculty in the control group were selected on the basis of experience and disciplinary similarity with experimental group faculty.

Participation in the survey for experimental and control groups was entirely voluntary. Most students and faculty involved in the design process agreed to complete the survey. Finding students who agreed to take the survey was challenging for the control group, and two calls for volunteers from the list of peers were required. For the survey administration, a research assistant was responsible for proctoring students and faculty in a computer lab. Flexible testing schedules were made available for the control and experimental groups to complete the survey. Individuals taking the survey were prohibited from using any devices or material during the test. All participants signed a consent form, and their answers and scores were kept anonymous. The experimental group survey consisted of sixty knowledge questions and ten questions regarding their experiences in the design process. Participants were allowed a maximum of eighty minutes to complete the survey. Both the control and experimental group answered the same set of thirty fundamental knowledge questions. Control group members had a time allowance of forty minutes for completing the survey.

3. Results

In order to present the case study in full, results for the design process and survey are presented separately in the following sections.

3.1 Final Design

The outcome of the design process is briefly presented here. The detailed design is provided in a different publication [38]. The building is a laboratory for studying the energy efficiency of buildings in tropical climates. The laboratory (Figure 4) has an area of 100 m^2, featuring a 1 ½ story, which includes a research laboratory, office space for researchers, and a showroom for students and visitors. The laboratory is a permanent construction, containing multiple instrumentation devices for measuring surface temperature, air temperature, and air velocity. In addition, a building automation system monitors and controls lighting and HVAC and measures the power and energy consumption of main energy users in real-time. The building is located at the main University campus in Antiguo Cuscatlán, El Salvador.

Figure 4 Final design of NZEB.

It is well documented that to reduce the operation energy demand of a building, both passive and active measures should be implemented, such as roof insulation, translucent skylights, and ventilation louvers, which effectively lower operation phase energy requirements; active measures include the use of lighting and an efficient air conditioning system [8, 39, 40]. The building structure consists of wood studs and beams, which allow for implementing materials with high thermal insulation levels. Materials with low volatile organic compounds with low environmental impact were considered as a strategy to promote environmentally friendly products, which is a practice in other latitudes [41]. For the roof, R-25 polyurethane foam insulation was included. On top of the roof, a 14.175 kW PV solar array was installed, consisting of 45 solar modules with a maximum power of 315 W each and module efficiency of 16.23%, which, combined with 4 PV inverters, provides electric power and energy to the building and electric vehicle. The roof is tilted 13° towards the south. Although the building is grid-connected, the system includes a 10 kWh lithium battery energy storage system for research and load optimization purposes. Table 2 presents building system definitions and the thermal properties and loads of the building.

Table 2 Building systems definition and thermal properties and loads of proposed building.

System-technology		Thermal properties	
Foundations	Concrete slab	Floor area	100 m^2
Walls	Wood frame, thermo-acoustic insulation	Footprint	9.15 m × 6.12 m
Mezzanine	Wooden beams and boards	Exterior Wall U-value	0.30 W/m^2K
Staircase	Wood system	Roof U-value	0.067 W/m^2K
Trusses	Wooden trusses	Windows U-value	2.3 W/m^2K
Roof structure	Wooden structure	Windows SHGC	0.31
Roof	Metal sandwich panel, thermo-acoustic insulation	Equipment type	Inverter VRF
Hydraulic installations	Two sanitary units	Cooling Efficiency /(COP)	3.85
Electrical installations	Electrical supply network and energy generation	LPD	7.73 W/m^2
Mechanical installations	VRF inverter system, automated with sensors and actuators	Miscellaneous load	11.60 W/m^2
Floor finishes	Polished slab on the first level and vinyl on the second level		
Wall finishes	Drywall painted		
Doors	Glass and wood		
Windows	Insulation, low-energy windows		
Energy generation	45 photovoltaic panels, inverters, and batteries		

The air conditioning system is a 17 kW (5.83 tons of refrigeration) cooling capacity inverter system with two cassette units and a fan coil. The inverter system modulates refrigerant flow and controls the temperature while saving energy. The system has a Coefficient of Performance (COP) of 3.85. The lighting system consists of dimmable LED panels. Overall, the lighting power density (LPD) is 7.73

W/m^2. The air conditioning and lighting systems are controlled by a building automation system that optimizes energy use. The building is all-electric, and it also has the capability of powering an electric vehicle. The electric vehicle chosen has an 88 kW electric motor with a rated torque of 295 Nm, equipped with a lithium battery of 28 kWh storage capacity. The rated combined efficiency is 15.4 kWh/100 km. The vehicle is expected to be used for experimental purposes and maintain a regime of at least 10,000 km per year. The expected occupancy schedule is Monday through Friday from 8:30 am to 6:30 pm and Saturday from 8:30 am to 12:30 pm.

In order to model the energy performance of the proposed building design, a commercial interface of the EnergyPlus^{TM} energy simulation engine [42] was used. Model inputs include building geometry, electric loads, building envelope properties, and schedules. Typical meteorological year weather (TMY2) data from San Salvador/Ilopango was used for modeling local climate. Results for the annual energy performance are presented in Figure 5. The main energy uses for the building are air conditioning and miscellaneous equipment, which includes computers, servers, and other electric devices used in the building. The annual predicted energy consumption is 10,262.60 kWh, equivalent to an annual energy metric of 108.28 kWh/m^2/year. Using open-source software, monthly and annual energy generation can be estimated for the PV system. When comparing monthly consumption with monthly PV generation, it is clear that an energy surplus can be obtained every month, estimated at 42.0% annually. This was designed for flexibility; an oversized system was specified since the laboratory may change its energy use patterns to investigate different building Energy uses for research purposes.

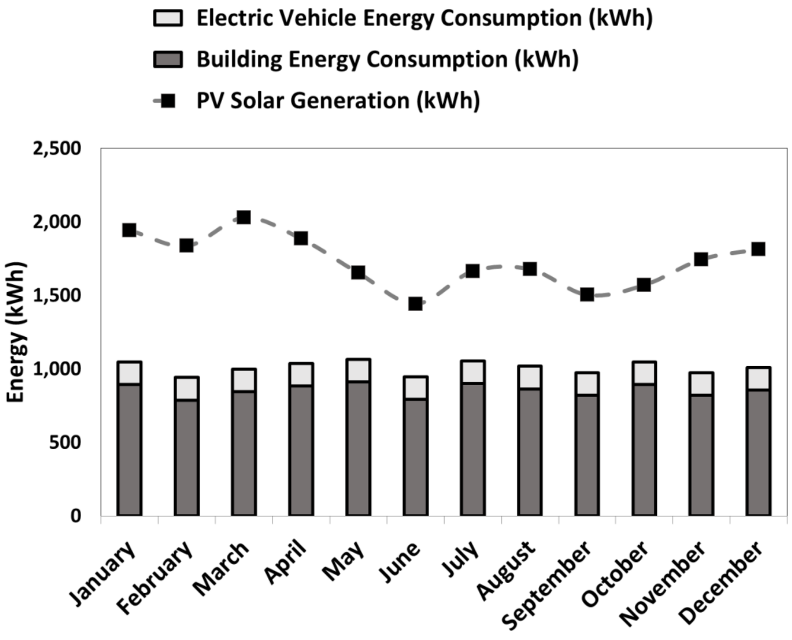

Figure 5 Monthly energy balance for NZEB, including electric vehicle.

The building energy model for the proposed building was compared with a base case scenario, defined by the ASHRAE 90.1-2013 Energy Standard for Buildings, except for Low Rise Residential Buildings [32]. Figure 6 compares the proposed building and the base case scenario. According to modeling results, the proposed building exceeds the base case building energy efficiency in all energy use categories, except for miscellaneous equipment, which was kept intact as suggested by ASHRAE 90.1 Standard methodology. Annual energy reductions observed in the proposed case compared with the base case are 32% for interior lighting, 48% for air conditioning and ventilation fans, and 86% for exterior lighting. The largest energy savings are within the air conditioning category. A summary of different key features in both models is presented in Table 3. The comparison shows that the most impactful improvements are on building envelope materials, ranging from 19% to 75%. This is accomplished by using highly insulated construction and high-performance windows. The only feature where a decrease in efficiency was noted is the solar heat gain coefficient. The improvement in air conditioning equipment efficiency (12%) does not explain the magnitude of savings observed in that category.

Table 3 Comparison of thermal properties and loads for proposed case and base case building.

Model	Proposed Case	Base Case	Improvement
Area	100 m^2	100 m^2	N/A
Footprint	9.15 m × 6.12 m	9.15 m × 6.12 m	N/A
Envelope Features			
Exterior Wall U-value	0.30 W/m^{2}K	0.50 W/m^{2}K	40%
Roof U-value	0.067 W/m^{2}K	0.270 W/m^{2}K	75%
Windows U-value	2.30 W/m^{2}K	2.83 W/m^{2}K	19%
Windows SHGC	0.31	0.25	-24%
Equipment type	Inverter VRF	Constant volume	
Cooling COP	3.85	3.45	12%
LPD	7.73 W/m^2	9.00 W/m^{2}K	14%
Miscellaneous Load	11.6 W/m^2	11.6 W/m^2	N/A

Therefore, improving the building envelope's thermal properties is key to saving annual energy consumption. Lighting Energy is also reduced significantly due to optimizing the lighting distribution and selecting high-efficiency LED panels, which decreases lighting power density. The proposed building also considers savings due to the building automation system.

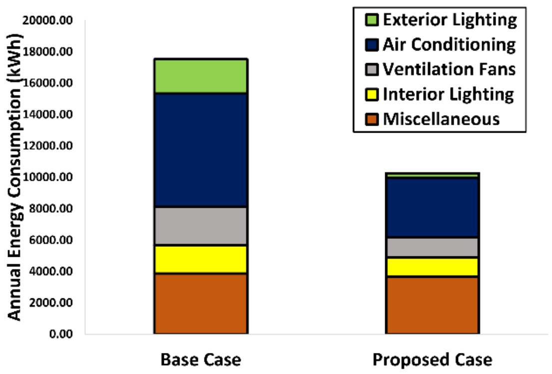

Figure 6 Energy balance distribution for proposed and base cases.

3.2 Survey Results

The survey explored how much each team participant knows on a fundamental and practical basis regarding all disciplines involved in the design process. It also asked some qualitative questions about the process, aiming to understand their perceptions. Due to the small sample size within the experimental group (17 people), reliability analysis is not recommended, although the calculated Cronbach Alpha was calculated as 0.56 [43]. However, when combining the control and experimental groups (45 people) for the common questions, the calculated Cronbach Alpha resulted in 0.71, generally accepted as a statistical indicator of internal reliability.

3.2.1 Fundamental Questions Scores

Quantitative scores for the 30 fundamental questions are presented in Figure 7, showing mean scores for the combined experimental group (E) and control group (C) and student and faculty scores for the experimental and control groups. Scores are the number of correct answers transformed linearly to a 10-point scale.

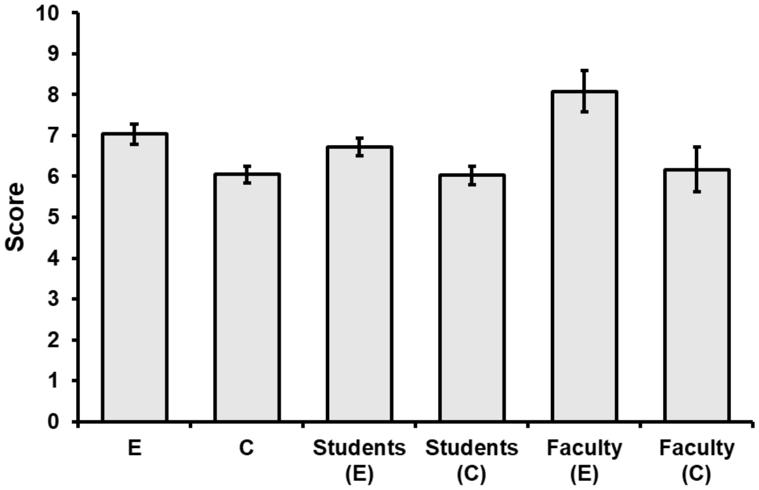

Figure 7 Mean scores of fundamental questions for Experimental (E) and Control (C) groups.

The first result to analyze is whether the experimental group got statistically higher scores than the control group. Also, it is interesting to determine which discipline improved the most compared to its control group counterparts. Results show an overall improvement of 16.4% for experimental group scores compared to control group scores (P < 0.002, *t*-test). Students in the experimental group performed 11.5% better than students in the control group (P < 0.03, *t*-test), whereas faculty in the experimental group outperformed faculty in the control group by 31.1% (P < 0.03, *t*-test). Analyzing student results, focusing on discipline, Mechanical Engineering students in the experimental group performed 34.3% better than their control group counterparts (P < 0.004, *t*-test).

In contrast, the experimental group of Architecture/Civil Engineering students improved their scores over their control group counterparts by 20.0% (P < 0.006, *t*-test). On the other hand, Electrical Engineering students in the experimental group scored 6.5% lower than Electrical Engineering students in the control group. However, that difference is not statistically significant (P

= 0.19, *t*-test). As for the faculty, no reliable statistical analyses were possible due to the small number of faculty involved in each discipline. However, we choose to present faculty scores for illustration purposes. Mechanical Engineering faculty in the experimental group got scores 47.1% higher than their control group counterparts, Electrical Engineering faculty in the experimental group outperformed EE faculty in the control group by 20.0%, and ARC/CE faculty in the experimental group performed by 9.8% better than their control group counterparts. As an initial result, it should be highlighted that the experimental group performed better in the test than the control group, observing a higher difference in the students of the Mechanical Engineering and Architecture disciplines.

By analyzing areas of knowledge, Construction fundamentals (CO F) did not show statistically significant differences between disciplines for control group students ($F = 0.5$, $P = 0.6$, one factor ANOVA), but it did show statistically significant differences for experimental group students ($F = 9.0$, $P < 0.005$, one factor ANOVA), with ARC/CE students performing best. When comparing CO F scores between control and experimental groups, statistically significant differences were found, with ARC/CE scoring 8.8% higher ($P < 0.04$, *t*-test) and ME students scoring 46.2% higher ($P < 0.007$, *t-test*) than their control group counterparts, no statistically significant differences were found for EE students in that category.

In the Electrical Systems fundamentals (ES F) category, statistically significant differences between disciplines were observed for both the control group students ($F = 8.1$, $P < 0.003$, one factor ANOVA) and the experimental group ($F = 5$, $P < 0.04$, one factor ANOVA). EE students did best for both groups in this category, and ARC/CE did worst. When a comparison is made between experimental and control group scores in this category, no statistically significant differences are found.

Within the Energy fundamentals (E F) category, no statistically significant differences were found between disciplines for both the control group students ($F = 0.56$, $P = 0.58$, one factor ANOVA) and experimental group students ($F = 2.62$, $P = 0.14$, one factor ANOVA). A comparison between experimental and control group scores in this category only shows statistically significant differences for the ME Students, with a 63.4% improvement ($P < 0.006$, *t*-test). A summary of average scores for fundamental questions is presented in Table 4.

Table 4 Summary of average fundamental questions scores for control and experimental groups (only students).

	Discipline	CO F	ES F	E F	Average	Improvement (%)
Control	ARC/CE	7.2	5.8	3.8	5.6	
	EE	7.2	8.3	4.1	6.5	
	ME	6.5	6.8	3.9	5.7	
Experiment	ARC/CE	8.6	7.0	4.6	6.7	20.0%
	EE	6.0	9.0	3.4	6.1	-6.1% *
	ME	8.7	8.0	6.3	7.7	34.3%

*Not statistically significant.

3.2.2 Experimental Group Scores by Knowledge Category

Another question of interest is how each discipline scored in each area of knowledge. This would help identify which knowledge areas could be strengthened for each discipline. Figure 8 and Figure 9 allow visualization of experimental group student and faculty scores in each of the six knowledge categories: Construction Fundamentals (CO F), Construction Applications (CO A), Electrical System Fundamentals (ES F), Electrical System Applications (ES A), Energy Fundamentals (E F) and Energy Applications (E A). The contour tagged as PS represents a perfect score in all categories and is shown for comparison purposes.

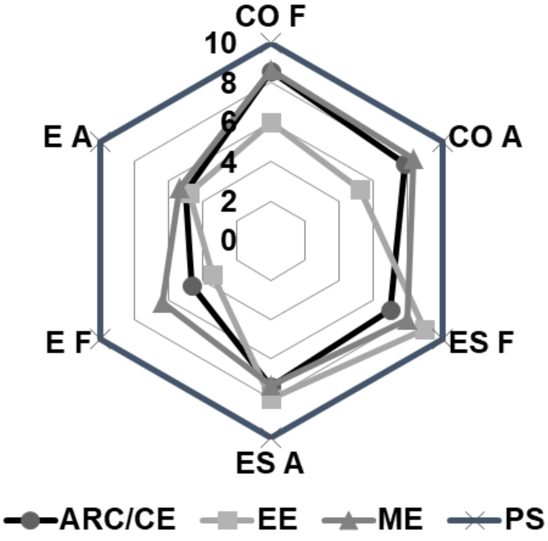

Figure 8 Visualization of experimental group student scores in six knowledge subcategories.

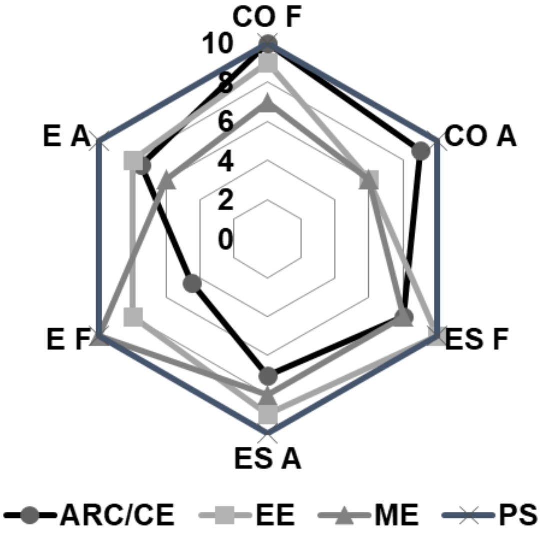

Figure 9 Visualization of experimental group faculty scores in six disciplinary subcategories.

A combination of fundamental and application question scores allows for comparing knowledge categories. This comparison considers fundamental and practical project-related aspects of each knowledge category. This comparison is only possible for experimental group students because control group students took fundamental questions only. Table 5 presents a summary of global average scores for experimental group students. Within the Construction (CO) category, EE students performed 18.2% worse than ARC/CE students ($P < 0.001$, *t*-test), with no statistically significant differences found between ARC/CE and ME students. In the ES category, ARC/CE students scored 15.3% lower than EE students ($P < 0.05$, *t*-test). ME and EE students had no statistically significant differences in ES scores. Finally, within the E category, EE students obtained scores 42.3% lower than ME students ($P < 0.01$, *t*-test), with no statistically significant differences between ARC/CE and ME student scores. As expected, each disciplinary group performed best in their disciplinary questions. The area where scores were lowest is Energy Systems (E).

Table 5 Summary of average knowledge questions scores (combined fundamentals and applications) for experimental group students.

Discipline	CO	ES	E	Mean
ARC/CE	8.2	7.2	4.8	6.7
EE	5.6	8.5	4.1	6.1
ME	8.5	7.7	5.8	7.3
Mean	7.4	7.8	4.9	

3.3 Qualitative Survey Results

3.3.1 Perceptions of Knowledge Acquisition

Experimental group participants were asked about their experiences through the design process. One question was whether they felt they had learned new things about other disciplines. Sixteen of 17 team members agreed or strongly agreed that they had acquired new knowledge about other disciplines during the design process. When asked whether they felt more capable of interacting with professionals from other disciplines, 12 out of 13 students agreed or strongly agreed they felt more capable of interacting with other disciplines after their work in the design process.

3.3.2 Perceptions of Design Process Experience

Most case study participants expressed that the work environment of the design process was comfortable for them, except for one team member who strongly disagreed and one who expressed a neutral perception of the work environment. The things that participants liked the most about the process were the opportunity to interact with people with different academic backgrounds and knowledge, the dynamics of the process, which encouraged feedback from other disciplines with their views and perspectives, and the possibility of a real work experience for the students.

However, case study participants also expressed several things they disliked about the design process experience. One of the respondents mentioned that sometimes, senior designers wanted to make design decisions without consulting with students. Another recurring theme was the heated discussions between senior team members when defending their ideas for the design. One respondent felt there was a lack of communication between disciplines, with some disciplines making changes without informing other disciplines about those changes. One student mentioned that the beginning of the design process had been difficult because the work dynamics proposed by the research team required much interaction with other disciplines, which was not easy to do without experience in integrative design processes. One respondent mentioned that the lack of a student CE team had reduced the ability to exchange ideas with that discipline since the most involved CE team member was a faculty member.

3.3.3 Perceptions of Interdisciplinary Interaction

Survey respondents were asked to rank ease of interaction with other disciplines from highest to lowest. Table 6 presents the results, indicating what each respondent ranked as the easiest discipline to interact with (with a "+" sign) and the most challenging discipline to interact with (with a "-" sign).

Table 6 Experimental group preferences based on ease of interaction with other disciplines, "+" means easiest to interact with and "-" most difficult to interact with.

	Disciplines			
Team members	ARC	CE	EE	ME
ARC Faculty 1		+	-	
ARC Student 1	+		-	
ARC Student 2	+			-
ARC Student 3	+		-	
ARC Student 4	+			-
ARC Student 5	+	-		
CE Faculty 1		+	-	
EE Faculty 1	-		+	
EE Student 1			+	-
EE Student 2	-		+	
EE Student 3			-	+
EE Student 4			+	-
EE Student 5			+	-
ME Faculty 1			+	-
ME Student 1		-		+
ME Student 2		-		+
ME Student 3		-		+

Respondents were asked whether disciplinary boundaries should be respected. Nine out of 17 respondents believe such boundaries can be crossed or express a neutral position on the issue. However, one thing most respondents agreed on was the idea that studying other disciplines' subjects can help communicate more effectively with other disciplines. Eleven out of 17 respondents believe that acquiring knowledge about another discipline can allow them to suggest how to solve problems of that discipline to professionals in that discipline.

4. Discussion

4.1 Final Design Results Benchmarking

A comparison was made between the simulated results for the energy performance of the final design and other buildings and guidelines in comparable climate zones, as presented in Table 7. The building is a mixed-used laboratory, office, and educational building; therefore, the comparison is not straightforward with other published works. One thing to discuss is that the simulation assumed occupancies higher than seen in reality (full use of the whole building from 8:30 am to 6:30 pm from Monday to Friday and 8:30 a.m. to 12:30 p.m. on Saturdays). In reality, activities for the first year of operation were less frequent since classroom and laboratory use was not continuous. The overcalculation of energy consumption was assumed to ensure the building met the net zero energy criteria under more frequent occupancy. The measured energy consumption lies below other net zero energy buildings reported in the literature. However, a more thorough analysis of measured results and the difference between simulated and measured results in practice under equivalent occupancy conditions will be conducted in the future. For this article, it is worth indicating that the simulated and measured results show that the design process and methodology produced a building that performs within expectations for a high-efficiency building in its climatic context.

Table 7 NZEB El Salvador Results Benchmarking.

NZEB Benchmark	**ASHRAE Climate Zone**	**Location**	**Building Type**	**Energy Consumption (kWh/m2-year)**	**Avg Solar Radiation (kWh/m2)**	**Ref.**
NZEB El Salvador Simulated	1A	San Salvador, El Salvador	Laboratory/Office/Educational	108.28	5.79	
NZEB El Salvador 1 Year Measured	1A	San Salvador, El Salvador	Laboratory/Office/Educational	55.39	5.79	
DPR Construction Phoenix Regional Office	2B	Phoenix, USA	Office	80.00	5.79	[44]
Ilet du Centre-offices	1A	Reunion Island, France	Office	66.00	5.72	[45]
ENERPOS	1A	Reunion Island, France	Educational	16.00	5.72	[45]
ASHRAE Advanced Energy Design Guide for Small to Medium Office Buildings-Achieving Zero Energy	1A	-	Office	73.82	-	[46]
	2B	-	Office	71.92	-	[46]

[a] The average solar radiation was calculated according to ASHRAE Climatic Design Conditions 2021 [47].

4.2 Fundamental Questions Scores

Mean scores of fundamental questions, which lie within the range of 6-8 out of 10, reflect that the difficulty level was intermediate, with the survey being neither too easy nor too difficult to answer. Results show that experimental group respondents got better scores on the fundamental questions than control group respondents. This would indicate that, through participation in the present case study design process, design team members acquired new fundamental knowledge about the disciplines involved. This knowledge acquisition is more evident for faculty members than for students. According to the survey, 12 out of 13 students agreed that participation in the design process allowed them to gain new knowledge through interacting with other disciplines and self-studying their discipline. When discussing design options, each discipline had to present facts and explain the principles involved in their suggestions. It was mainly through this interaction and discussion based on fundamentals that new fundamental knowledge was acquired. However, statistical analysis reveals that disciplines did not acquire new knowledge evenly. EE students in the experimental group got statistically equivalent results to their control group counterparts, whereas ME and ARC/CE students obtained scores significantly better than their control group counterparts. In the experimental group, ME students got 34.3% better scores than the control group ME, students. They were involved in modeling energy performance and had to obtain information from other disciplines to build their models. Since building energy modeling is a holistic process, ME students had the opportunity to interact in more detail with other disciplines, which would explain the clear increase in scores in part.

Analyzing fundamental questions scores by knowledge area, trends are not as clear as overall scores. In the Construction fundamentals (CO F) category, scores within the control group do not appear to differ between disciplines. This is an interesting result since it was expected that ARC/CE students would perform significantly better than the other disciplines. The experimental group observed statistically significant differences between disciplines, with ARC/CE students performing best. One possible explanation is that for many ARC/CE students within the experimental group, this case study was their first real-life design experience and allowed them to solidify fundamental knowledge through practice. A clear trend is observed when comparing the experimental and control group students' scores for the ME and ARC/CE disciplines. ME students in the experimental group scored 46.2% higher ($P < 0.007$, *t*-test) than their control group counterparts. Again, this seems to reveal how the energy modeling work developed by ME students forced them to interact strongly with other disciplines, particularly ARC/CE. Interestingly, EE students in the experimental group got statistically equivalent scores to control group EE students, which would reveal that they acquired limited new fundamental knowledge of Construction through the design process.

The Electrical Systems fundamentals (ES F) category results show that EE students have a better domain of the fundamentals than the other disciplines, which was expected. It was also revealed that ARC/CE students performed worse than the other disciplines in both groups. However, group comparisons do not reveal statistically significant changes in scores, which means that any discipline acquired no significant new knowledge in this category. This result shows that interaction was poorer in this knowledge area and that EE students relied on their expertise to conduct their design with little interaction with the other disciplines. The Energy fundamentals (E) category scored lower for all disciplines and groups. A lack of fundamental knowledge in energy is prevalent, even for ME and EE students. No statistically significant differences were observed between disciplines for both groups. However, ME students improved fundamental knowledge substantially in this knowledge category, with a 63.4% ($P < 0.006$, *t*-test) improvement, although their mean score is relatively low (6.3). Although energy topics are within mechanical engineering and electrical engineering studies, survey questions focused on energy efficiency, energy modeling, and HVAC topics, which would be more closely related to mechanical engineering. However, at UCA, energy efficiency courses are elective courses for EE students and ME, and HVAC is an elective for ME students. Therefore, no significant coursework on energy efficiency is mandatory for ME and EE students, and a lack of fundamentals is evident, even for experimental group ME students. Overall, experimental group scores improvements are driven by knowledge acquisition by ARC/CE and ME students in Construction fundamentals (CO) and by ME students in Energy fundamentals (E).

4.3 Experimental Group Scores by Knowledge Category

In addition to the fundamental questions, a set of application questions were included for the experimental group. Such questions were based on practical aspects of building design in each knowledge category and information and details discussed during the design process, which were included in the final design. Comparing disciplinary results concerning knowledge subcategories, Figure 8 and Figure 9 allow visualization of how some disciplines perform better than others, with better scores observed in the knowledge sub categories more closely related to their discipline. Figure 8 also contrasts with Figure 9 in how faculty got higher scores, nearly perfect scores in their more closely related category, except for ME on Energy Applications (E A). However, due to the small number of faculty involved in each discipline, statistical analysis would be unreliable, and this discussion focuses on students. When fundamental and application scores are added, a combined score per knowledge category is obtained (Table 6). Results show that within the combined Construction (CO) category, EE students need more reinforcement in both fundamental and practical aspects. Surprisingly, ME students performed statistically equivalent to ARC/CE students, considering both fundamental and application questions. Analysis of the combined Electrical Systems (ES) category reveals that ARC/CE students got statistically lower scores than EE students, with ME and EE students performing statistically the same. Interestingly, when considering practical and fundamental aspects combined, ME students match the scores of EE students. Because of ME students' involvement in energy modeling, practical knowledge of the electrical system control, loads, and operations was required, which could explain this result.

Finally, within the combined Construction (CO) category, EE students obtained statistically lower scores than ME, with ARC/CE and ME students obtaining statistically equivalent scores. This, combined with the statistically equivalent scores of ME students and ARC/CE students in the combined Construction (CO) category, would indicate that in the present case study, ME students and ARC/CE students integrated the most in knowledge acquisition.

4.4 Perceptions of Knowledge Acquisition

From the qualitative standpoint, survey respondents felt new knowledge about other disciplines and their own was gained through the design process. The perception of a higher capability of interaction with other disciplines was also documented. However, it must be noted that knowledge acquired during the design process mainly occurred through interaction with other disciplines. This is not a perfect knowledge acquisition method, especially for fundamental principles. Interaction with other disciplines should not replace knowledge acquisition through coursework or guided self-study. However, we argue that some knowledge is acquired through interdisciplinary interaction, as our results show. It should also be recognized that knowledge is one of several cognitive levels required for interdisciplinary competencies and should be complemented with the other levels (i.e., comprehension, application, analysis, synthesis, and evaluation), according to Bloom's taxonomy theory [48].

4.5 Perceptions of Design Process Experience

For the present case study at UCA, interdisciplinary design is not usually part of student's academic experiences. Some survey respondents mentioned that this design process was their first experience working with other disciplines. Creating a comfortable work atmosphere for all participants was a challenge, given the majority of the design team's lack of integrative design experience. One of the interesting issues brought up by student respondents was the perception that although students participated actively in the design process, final design decisions were made by team leaders (i.e., faculty). This observation was probably true with some of the decisions, but as a methodological guideline, the discussion of ideas was encouraged, with students having a seat at the design table (Figure 2). Five out of 17 respondents disliked the heated discussions held by some design team members over technical aspects of the design. Attempts were made to keep civility in the discussions, although, at times, passionate arguments were held, which was probably a new experience for some students.

As in many projects, mistakes were made, and some lack of communication occurred, which one student respondent noted, which obliged some disciplines to work without knowing that other disciplines had changed assumptions or technical details, which affected their work. Interdisciplinary design processes require constant communication and interaction, with most decisions affecting all disciplines and the necessity of coordination and interdisciplinary participation in the decision-making process. For administrative reasons, the design team relied on only one CE team participant (a faculty member), and no CE student team was formed. One respondent noted that this limited the opportunities for interaction with the CE discipline.

4.6 Perceptions of Interdisciplinary Interaction

Table 7 shows how each response ranked the ease of interaction with other disciplines. A clear trend shows that it is easier for most team members after the case study design process experience to interact with team members of the same discipline. Additionally, most EE respondents find it most difficult to interact with ME team members, and all ME respondents find it most difficult to interact with CE team members. The latter trend may be because ME participants had fewer interactions with CE team members as a discipline. Of course, there is a level of subjectivity in perception and personal relationships, which are generally varied, may play a role and do not reflect generalizable ease of interaction trends.

Survey respondents expressed mixed opinions regarding the role of each discipline concerning disciplinary boundaries. Although 4 out of 17 respondents believe that disciplinary boundaries may be crossed and a professional in one discipline may do some work within the domain of another discipline, 8 out of 17 respondents believe otherwise, with 5 out of 17 respondents expressing a neutral position. The survey further explored this issue to get an answer regarding what they would see as a limit to disciplinary crossing. Interesting responses were obtained; one respondent shared a view in which regulations and codes set limits that untrained people should not cross because of severe safety consequences if a design does not consider them. However, this respondent believes that interdisciplinary crossing should be encouraged in other decisions not related to safety or code compliance. Another respondent expressed that the responsibility for calculating and interpreting results should be left to specialists, and other disciplines should not intervene. One team member responded that although solutions can come from any discipline, in the end, within the expertise of one discipline, a specialist in that discipline should assess the feasibility of each solution proposal. The experience was cited as a prerequisite of interdisciplinary crossing and a strong domain of fundamental principles of the other discipline. What was agreed by most (15 out of 17) was the benefit of acquiring knowledge about other disciplines in order to foster better communication, collaboration, and interaction.

4.7 Lessons Learned

Although most respondents expressed favorable opinions about the design process, valuable suggestions were made. It was suggested that it would have been beneficial to set up induction sessions regarding design process methodology and fundamentals of each discipline relevant to the project. Our results strongly recommend strengthening the Energy Systems (E) knowledge area (including energy efficiency, modeling, and HVAC systems) for all disciplines. As other priorities, attention should be paid to providing Construction (CO) training to Electrical Engineers and Electric System (ES) training to Architects. This seems logical, given the results, which show that knowledge of fundamentals is limited, especially about other disciplines. Aligned with the previous suggestion, developing more interdisciplinary workshops would be beneficial. Interdisciplinary workshops (Figure 1) allowed students to work in groups of different disciplines, developing design ideas to be proposed to the team. Creativity, teamwork, and interdisciplinary knowledge acquisition were fostered during these workshops. It was also suggested that more time for interaction would be good for the process. Due to the project dynamics involving students and faculty from different disciplines, finding time for the team to come together was challenging. In professional settings, time availability for one project is limited as well. However, perhaps some activities could benefit more from an increase in the time of interaction. For instance, a review and revision of the work of each discipline by all disciplines would allow for the easier identification of interference problems and factors not considered which could affect other disciplines.

As a social endeavor, the success of a design process also depends on developing a civil work atmosphere where ideas are debated with facts. At times, one respondent noted that heated discussions and some level of inflexibility or preconceived design solutions may have affected the process. Improving the dialogue, both on the personal level and the information technology level, was suggested as necessary. For instance, encouraging a more committed use of building information modeling software, a tool with a highly graphical interface that enables designers to simulate building performance from the earliest stages of conceptual design [49, 50], offers the potential for more agile interaction and fewer mistakes. Interdisciplinary design processes require strong leadership and managerial skills to avoid missing deadlines and motivate all team members.

5. Conclusion

This paper presented an NZEB design process methodology developed by the researchers from the literature and tested through a case study design process at Universidad Centroamericana in El Salvador. The methodology allowed for interdisciplinary team integration, characterized by knowledge transfer between disciplines measured by a survey. The design outcome also met expectations regarding optimizing energy performance for the building within the design goals and constraints. Overall, we found evidence that the design team members acquired new interdisciplinary fundamental and practical knowledge due to project interactions. This was measured by conducting a test of fundamental questions on three knowledge areas to the design team members (experimental group) and a control group, composed of same-level students and faculty with no project involvement. All disciplines did not evenly acquire this fundamental knowledge; some acquired more knowledge about certain disciplines, and some did not. ME students, who were involved in energy modeling efforts and had to gather data from other disciplines, acquired more new fundamental knowledge than the other disciplines. It was found that ARC/CE students and ME students increased their fundamental knowledge of Construction (CO) but did not increase their fundamental knowledge of Electrical Systems (ES). All disciplines did poorly on the fundamental knowledge of the Energy (E) category, and only ME students improved their fundamental knowledge of that category as a result of participating in the design process. This form of knowledge acquisition through interdisciplinary interaction is valuable but should not replace appropriate coursework or guided self-study. Team members expressed that new knowledge had been acquired and that better interaction would be possible through additional study about other disciplines' fundamental and practical knowledge. We believe it is easier for some disciplines to interact with specific disciplines. For instance, for our case study, ME and ARC students learned new fundamental and practical knowledge about each other, which was not the case for EE students. We believe this is partly because of the nature of each discipline; for instance, ME students performed energy simulation and had to interact with ARC majors to obtain parameters; likewise, ARC majors received feedback on materials and shapes from energy simulation. From the responses obtained in the survey, ME and ARC students were more hesitant to intervene and cooperate in electrical systems because of the codes and regulations related to safety and the inherent responsibilities associated. This discouraged interaction and let EE team members do their job more unidisciplinarily.

By understanding better how this knowledge transfer through team interaction works and the gaps for specific disciplines, the NZEB design methodology can be optimized to enhance interdisciplinary interaction. If this interaction is inadequate, the final product can be negatively impacted by a lack of synergy between systems, which eventually translates into higher building operational costs. Also, we found that by limiting the disciplinary boundaries to decisions that do not impact safety, which should be left to a specialist, a higher level of trust can be achieved, which leads to better design outcomes. This design methodology and survey are encouraged in other contexts outside academia. We believe that larger sample sizes, strictly professional settings, and different NZEB building topologies and cultural realities would help generalize the results to improve design practice and engineering and architecture curricula. Design practitioners with more knowledge about other disciplines can lead to better design outcomes, which would impact global decarbonization goals in the context of sustainable construction.

Acknowledgments

This work was supported by The United States Agency for International Development (USAID) [grant number 0214405-G-2018-001-00] and the Universidad Centroamericana "José Simeón Cañas". We appreciate our industry partners, who provided additional donations of equipment and materials for the construction of the NZEB: MP Service, INCO, EuroAire, Enersys Solar, Sherwin Williams of Central America, Dissetti. We are grateful to our international advisor, Prof. Ty Newell, Professor Emeritus of Mechanical Engineering from the University of Illinois at Urbana-Champaign for his guidance. We thank all the students who participated in the present project, especially our undergraduate research assistants. Dr. Dora López is thanked for providing feedback to our manuscript. We thank Prof. Humberto Molina for helping us set up the computer-based survey.

Author Contributions

Dr. Luis A. Martínez, Project Administration, Conceptualization, Methodology, Data curation, Investigation, Supervision, Writing-original draft, Writing-review and editing. Lizeth Rodríguez, Conceptualization, Investigation, Methodology, Writing-review and editing, Validation, Visualization. Carlos M. Flores, Conceptualization, Investigation, Methodology, Resources, Validation, Data curation. Carlos A. Cisneros, Conceptualization, Investigation, Methodology, Resources, Validation. Mario W. Chávez, Conceptualization, Investigation, Formal analysis, Data curation, Resources, Validation. Idis A. Lemus, Data collection, Resources, Software, Visualization. René I. Ariza, Data collection, Resources, Software, Formal analysis, Visualization, Writing-review and editing.

Competing Interests

The authors have declared that no competing interests exist.

Additional Materials

The following additional materials are uploaded at the page of this paper.

1. Part I: General Information.
2. Part II: Experience in the Project.
3. Part III: Knowledge questions in Area: Construction (CO).
4. Part IV: Questions about knowledge in Area: Electrical Systems (ES).
5. Part V: Questions about knowledge in Area: Energy (E).
6. Part VI: Open questions.

References

1. D'Agostino D, Mazzarella L. What is a Nearly zero energy building? Overview, implementation and comparison of definitions. J Build Eng. 2019; 21: 200-212.
2. Wu W, Skye HM. Residential net-zero energy buildings: Review and perspective. Renew Sustain Energy Rev. 2021; 142: 110859.
3. Kapsalaki M, Leal V. Recent progress on net zero energy buildings. Adv Build Energy Res. 2011;

5: 129-162.
4. Council UG. LEED v4 for building design and construction. USGBC Inc.; 2014.
5. Attia S. State of the art of existing early design simulation tools for net zero energy buildings: A comparison of ten tools. Louvain La Neuve, Belgium: Architecture et climat; 2011; 01/2011.
6. Ferrara M, Fabrizio E, Virgone J, Filippi M. A simulation-based optimization method for cost-optimal analysis of nearly zero energy buildings. Energy Build. 2014; 84: 442-457.
7. Kapsalaki M, Leal V, Santamouris M. A methodology for economic efficient design of net zero energy buildings. Energy Build. 2012; 55: 765-778.
8. Abdul-Zahra AS, Al Jubori AM. Potential evaluation and analysis of near-to-net zero energy building in hot and dry climate. Energy Convers Manag. 2021; 12: 100146.
9. Marszal AJ, Heiselberg P, Bourrelle JS, Musall E, Voss K, Sartori I, et al. Zero energy building–A review of definitions and calculation methodologies. Energy Build. 2011; 43: 971-979.
10. Harkouss F, Fardoun F, Biwole PH. Multi-objective optimization methodology for net zero energy buildings. J Build Eng. 2018; 16: 57-71.
11. Yu J, Tian L, Xu X, Wang J. Evaluation on energy and thermal performance for office building envelope in different climate zones of China. Energy Build. 2015; 86: 626-639.
12. Attia S, Hamdy M, O'Brien W, Carlucci S. Assessing gaps and needs for integrating building performance optimization tools in net zero energy buildings design. Energy Build. 2013; 60: 110-124.
13. Robert A, Kummert M. Designing net-zero energy buildings for the future climate, not for the past. Build Environ. 2012; 55: 150-158.
14. Bellatreche L, Garcia F, Pham DN, Jiménez PQ. SONDER: A data-driven methodology for designing net-zero energy public buildings. In: International conference on big data analytics and knowledge discovery. Cham: Springer; 2020. pp. 48-59.
15. Larivière V, Gingras Y. On the relationship between interdisciplinarity and scientific impact. J Am Soc Inf Sci Technol. 2010; 61: 126-131.
16. Klein JT. Interdisciplinarity: History, theory, and practice. Detroit: Wayne state university press; 1990.
17. Choi BCK, Pak AWP. Multidisciplinarity, interdisciplinarity, and transdisciplinarity in health research, services, education and policy: 2. Promotors, barriers, and strategies of enhancement. Clin Invest Med. 2007; 30: E224-E232.
18. Tamayo M. El proceso de la investigación científica. Editorial Limusa, 2004. ISBN 968-18-5872-7
19. Wang N, Esram T, Martinez LA, McCulley MT. A marketable all-electric solar house: A report of a Solar Decathlon project. Renew Energ. 2009; 34: 2860-2871.
20. Attia S, Walter E, Andersen M. Identifying and modeling the integrated design process of net zero energy buildings. In high performance buildings-design and evaluation methodologies conference. 2013. Available from: https://hdl.handle.net/2268/164039.
21. Kelbaugh D. Design Charrettes. Urban Plan Des J Univ Michigan. 2010; 4: 29-34.
22. Sutton SE, Kemp SP. Integrating social science and design inquiry through interdisciplinary design charrettes: An approach to participatory community problem solving. Am J Community Psychol. 2006; 38: 51-62.
23. Viswanathan S. Implementation of effective capstone projects in undergraduate manufacturing design engineering program. Am J Eng Educ. 2017; 8: 45-60.

24. Price JM, Robinson M. Developing future engineers: Case study on the incorporation of sustainable design in an undergraduate civil engineering curriculum. J Water Resour Plan Manag. 2015; 141: A5015002.
25. Nae HJ. An interdisciplinary design education framework. Des J. 2017; 20: S835-S847.
26. Vemury CM, Heidrich O, Thorpe N, Crosbie T. A holistic approach to delivering sustainable design education in civil engineering. Int J Sustain High Educ. 2018; 19: 197-216.
27. Bedoya-Valencia L, Palacio KS, Spencer-Workman S, Correa-Martinez Y. An exploratory study on the contextual challenges and barriers of introducing sustainability to first-year engineering students. In: 2014 ASEE annual conference & exposition. Indianapolis, Indiana; 2014. pp. 24-160.
28. Deng S, Wang RZ, Dai YJ. How to evaluate performance of net zero energy building–A literature research. Energy. 2014; 71: 1-16.
29. Sartori I, Napolitano A, Marszal AJ, Pless S, Torcellini P, Voss K. Criteria for definition of net zero energy buildings. International conference on Solar heating, cooling and buildings; 2010; Graz, Austria. EuroSun 2010.
30. ASHRAE. ASHRAE laboratory design guide: Planning and operation of laboratory HVAC systems. 2nd ed. Atlanta: ASHRAE; 2015.
31. Hollberg A, Genova G, Habert G. Evaluation of BIM-based LCA results for building design. Autom Constr. 2020; 109: 102972.
32. ASHRAE S. Standard 90.1-2013, energy standard for buildings except low-rise residential buildings. Am Soc Heat Refrig. 2013; 278.
33. Building Research Institute. LCCM (Life Cycle Carbon Minus) houses as advanced energy-efficient housing for a low-carbon society [Internet]. Japan: Building research institute; 2013. Available from: http://www.kenken.go.jp/english/contents/lccm/lccm-01.html#gaiyou.
34. Condliffe B. Project-based learning: A literature review. New York: MDRC; 2017; ED578933.
35. Kokotsaki D, Menzies V, Wiggins A. Project-based learning: A review of the literature. Improv Sch. 2016; 19: 267-277.
36. Holubova R. Effective teaching methods–project-based learning in Physics. Online Submiss. 2008; 5: 27-36.
37. Schneider RM, Krajcik J, Marx RW, Soloway E. Performance of students in project-based science classrooms on a national measure of science achievement. J Res Sci Teach. 2002; 39: 410-422.
38. Martínez LA, Romero CM, Castellanos FA, Chávez MW, Flores CM, Rodríguez L, et al. Energy simulation of proposed net zero energy laboratory building in Central America. In: 2018 IEEE 38th Central America and Panama Convention (CONCAPAN XXXVIII). San Salvador, El Salvador: IEEE. 2018. doi: 10.1109/CONCAPAN.2018.8596534.
39. Tulevech SM, Hage DJ, Jorgensen SK, Guensler CL, Himmler R, Gheewala SH. Life cycle assessment: A multi-scenario case study of a low-energy industrial building in Thailand. Energy Build. 2018; 168: 191-200.
40. Saidur R. Energy consumption, energy savings, and emission analysis in Malaysian office buildings. Energy Policy. 2009; 37: 4104-4113.
41. Mungkung R, Sorakon K, Sitthikitpanya S, Gheewala SH. Analysis of green product procurement and ecolabels towards sustainable consumption and production in Thailand. Sustain Prod Consum. 2021; 28: 11-20.
42. Crawley DB, Lawrie LK, Pedersen CO, Winkelmann FC. Energy plus: Energy simulation program.

ASHRAE J. 2000; 42: 49-56.
43. Bujang MA, Omar ED, Baharum NA. A review on sample size determination for Cronbach's alpha test: A simple guide for researchers. Malays J Med Sci. 2018; 25: 85.
44. Reeder L. Net zero energy buildings: Case studies and lessons learned. New York: Routledge; 2016.
45. Donn M, Garde F. Solution Sets and Net Zero Energy Buildings: A review of 30 Net ZEBs case studies worldwide. 2014.
46. ASHRAE. Advanced energy design guide for small to medium office buildings – Achieving 50% energy savings toward a net zero energy building. 2019.
47. ASHRAE. Ashrae climatic design conditions 2009/2013/2017/2021 [Internet]. 2022. Available from: http://ashrae-meteo.info/v2.0/#.
48. Sharunova A, Butt M, Qureshi AJ. Transdisciplinary design education for engineering undergraduates: Mapping of Bloom's taxonomy cognitive domain across design stages. Procedia CIRP. 2018; 70: 313-318.
49. Azhar S, Carlton WA, Olsen D, Ahmad I. Building information modeling for sustainable design and LEED® rating analysis. Autom Constr. 2011; 20: 217-224.
50. Somboonwit N, Sahachaisaeree N. Healthcare building: Modelling the impacts of local factors for building energy performance improvement in Thailand. Procedia Soc Behav Sci. 2012; 50: 549-562.