EDUCATIONAL EFFECTIVENESS OF A VIRTUAL DESIGN STUDIO ON ZERO-ENERGY BUILDING DESIGNS: THE CASE OF THE U.S. SOLAR DECATHLON DESIGN CHALLENGE

Jeehwan Lee[1,*] and Myoungju LEE[1]

ABSTRACT

Ongoing global architectural agendas span climate change, energy, a carbon-neutral society, human comfort, COVID-19, social justice, and sustainability. An architecture studio allows architecture students to learn how to solve complicated environmental issues through integrated thinking and a design process. The U.S. Department of Energy's Solar Decathlon Design Challenge enables them to broaden their analytic perspectives on numerous subjects and strengthen their integrated thinking of environmental impacts, resilience, sustainability, and well-being. However, the unprecedented impact of the global COVID-19 pandemic transformed the physical studio-based design education system into an online-based learning environment. Mandatory social distancing by the global COVID-19 pandemic restricted interactive discussions and face-to-face collaborations for the integrated zero-energy building design process, which requires features of architecture, engineering, market analysis, durability and resilience, embodied environmental quality, integrated performance, occupant experience, comfort and environmental quality, energy performance, and presentation.

This study emphasizes the educational effectiveness of virtual design studios as a part of the discourse on architectural pedagogy of zero-energy building (ZEB) design through integrated designs, technological theories, and analytic skills. The survey results of ten contests show educational achievement with over 90% of the highest positive tendency in the categories of embodied environmental quality and comfort and environmental quality, whereas the positive tendency of educational achievement in the categories of integrated performance, energy performance, and presentation were lower than 70%. The reason for the low percentage of simulation utilization and integrated performance was the lack of a proper understanding of and experience with ZEB simulations and evaluations for undergraduate students. Although VDS is not an ideal pedagogical system for the iterative design critique process, it can support the learning of the value of architectural education, including integrative design thinking, problem-solving skills, numerical simulation techniques, and communicable identities through online discussions and feedback during the COVID-19 pandemic.

1. College of Architecture, Myongji University, Republic of Korea (***Corresponding author:** Jeehwan Lee, College of Architecture, Myongji University, Republic of Korea, Email: jeehwanlee@mju.ac.kr)

KEYWORDS

Educational Effectiveness, Virtual Design Studio, Solar Decathlon Design Challenge, Zero-Energy Building Design, COVID-19 pandemic

INTRODUCTION

Importance of ZEB Design Education

With the adoption of the 2015 Paris Climate Change Convention (Paris Agreement) to cope with climate change, countries have been strongly implementing various policies to save energy and reduce greenhouse gas emissions. The U.S. has been establishing zero-energy building policies for all residential sectors by 2020, all new commercial buildings by 2030, and all commercial buildings by 2050. The global ZEB market size in energy security, building energy efficiency, renewable energy, and energy monitoring will grow from about 363 billion dollars in 2017 to about 1,351 billion dollars in 2024 [1–2]. Therefore, architectural education focusing on ZEBs is necessary to foster professional ZEB designers and technologists for future generations. The integrated ZEB design process of architecture studios is the key for linking passive architecture, active system technology, renewable energy, and energy management [3]. It is a critical element for students to learn about comprehensive performance-based design processes for dealing with designs, technologies, and analytical evaluations on ZEB.

Virtual Learning Process on ZEB Design

The virtual design studio (VDS) became a predominant pedagogical tool for architecture design studios under the global COVID-19 pandemic despite the reluctance of implementing VDS instead of the existing design critique process. Although VDS is not an ideal pedagogical system for the design critique process, it can serve to teach the value of architectural education, including integrative design thinking, problem-solving skills, social characteristics, and communicable identities through peer connections and a diversity of tools [4,5]. Online architectural design learning requires the instructor and students to adapt and adjust to new technological tools such as video conferencing, shared white-boarding, annotating for interactive communication; both a VDS and a physical design studio have the same educational goals and design process [5,6]. One study found that students expressed overall satisfaction with VDS due to their higher comfort level at home. Most students expressed an understanding of the critiques, communication, and information from peers and instructors through the VDS medium similar to the level with a physical design studio (PDS) [7–9]. The positive potential and challenges associated with online learning in architectural education are enumerated in Table 1 below [10].

Figure 1 shows the potential of VDSs with regard to discussing design agendas and collaborating on individual design works as part of the U.S. Department of Energy Solar Decathlon Design Challenge by sharing audio and video information on the VDS system.

Team Members

The project known as CRK35 targets a sustainable community through ZEB design with passive & active strategies, renewable energy applications, water management, and indoor

TABLE 1. Potential and challenges of online learning in Architectural Education [10].

Potential	Challenges
• Efficiency: Online learning offers an opportunity for the better delivery of lessons and instructions beyond what textbooks may offer. • Innovations: Online learning engages with software tools such as videos and PDFs, which are being improved continuously to cater to learning and teaching requirements. • Accessibility/Diversity: Time and geographical location are not barriers and as such schools are able to teach students across the globe. • Flexibility: Ability to have sessions even during times of uncertainty • Suits different learning styles: those with different preferences—audio and visual, for instance. • Improved Student Attendance: Because online learning is without boundaries, it is possible to have full attendance. • Cost Effective: Online learning reduces financial costs and increases affordability, especially where such education is being sponsored. • It is less intimidating and fosters better class participation, particularly amongst those with mental health issues. • Requires new reforms and changes of curriculum in architecture education • Promotes instructor accessibility and availability • Online learning promotes life-long learning and offers instant results and reviews of lectures.	• Technology Issues: irregular internet speeds and connections • Lack of in-person collaboration and peer learning • Inability students to manage or focus on screens for long periods and to remain attentive • Online courses make it easier for students to procrastinate • Requires the retraining of teachers to understand the applicability of using digital forms of learning in many cases • Mental health concerns and loneliness • Difficulty in accessing special software for specific architectural learning • Online courses make students responsible for their learning and time management. This reduces the responsibility and role of teachers to mentor, guide and encourage their students. • Sense of isolation and loneliness • Increased concerns for data security, security compliance, and unethical activities related to, for instance, privacy • The integrity of assessments of students

environmental quality to prepare for the post-COVID era. The proposed project is designed for the underprivileged, including children, young single people, newly coupled families, and the disabled, to ensure a safe, comfortable, pleasant dwelling unit at a riverside area of a traffic island.

The student members of CAMU consist of 15 students from the Departments of Architecture, Interior Architecture, and Traditional Architecture in Figure 2. During the COVID-19 pandemic, the team shared and discussed diverse agendas, including a carbon-neutral society, net-zero technologies, spatial transformation for the post-COVID era, the integration of the fourth wave of technology into architecture, human rights, and social justice through virtual learning platforms. External partners from the government and industry sectors have supported the team with energy policies, housing & land policies, renewable energy technologies, structure simulations, and ZEB designs.

FIGURE 1. An interactive process of performance-based design on the VDS system.

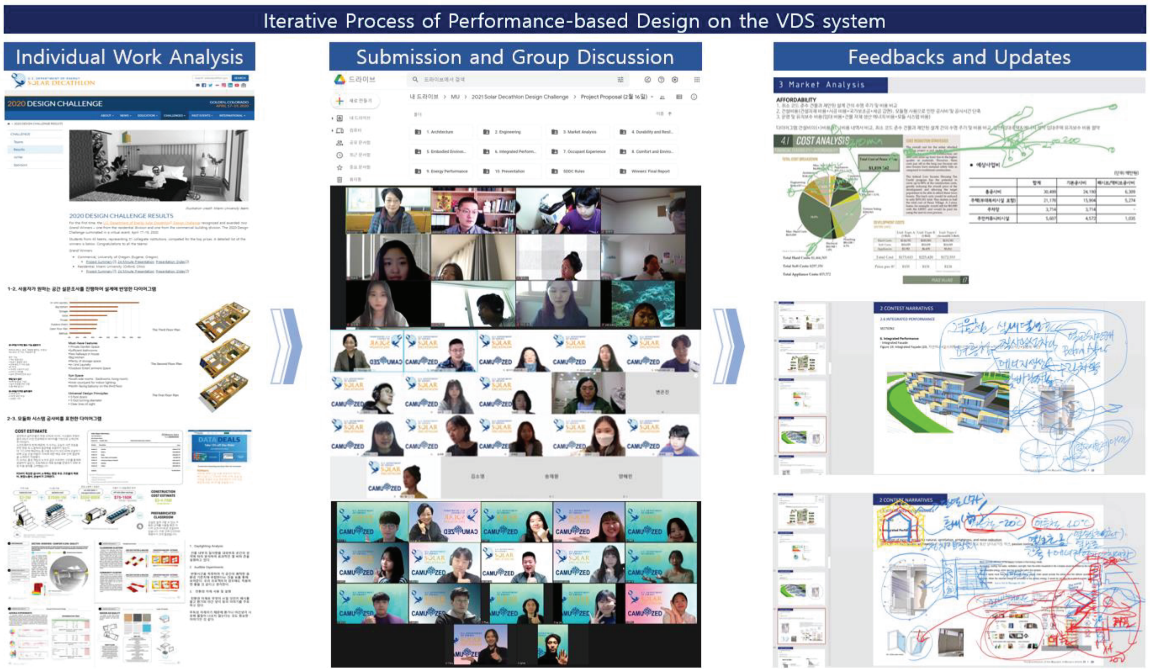


FIGURE 2. Team members on the VDS system.

PROJECT OVERVIEW

Architecture

The team proposed an affordable mixed-use housing complex for low-income families on abandoned land to solve the lack of housing supply in the Seoul, South Korea, metropolitan area. The proposed prototype is a testbed for expansion to the other remaining 15 traffic islands located on the Han River as the core community connecting the surrounding communities. The aim of the CRK35 project is a sustainable community through the ZEB design concept with passive and active strategies, renewable energy applications, water management, and ensured indoor environmental quality to prepare for the post-COVID era. The underprivileged, including children, young single people, newly coupled families, and the disabled, are provided with a

TABLE 2. Project overview.

Category	Details
Location	Seoul, South Korea
Climate	Hot & humid (summer) and cold & dry (winter), Similar to Climate Zone 4A
Number of units	105 units (30 studios, 45 one-bedroom, and 30 two-bedroom units)
Total floor area and unit area	11,092m^2
Unit module area	60m^2 + extra m^2 per dwelling unit
Ratio of residential to non-residential space	84.5% (9,372m^2) to 15.5% (1,719 m^2)
Space use and occupancy	Retail shops, a children's library, a kindergarten, startup service center, dwelling units, community service center, roof garden

safe, comfortable, pleasant dwelling unit at a riverside area of a traffic island, as noted above. Living in the community upgrades their human rights and dwelling quality at an affordable cost as shown in Table 2 below.

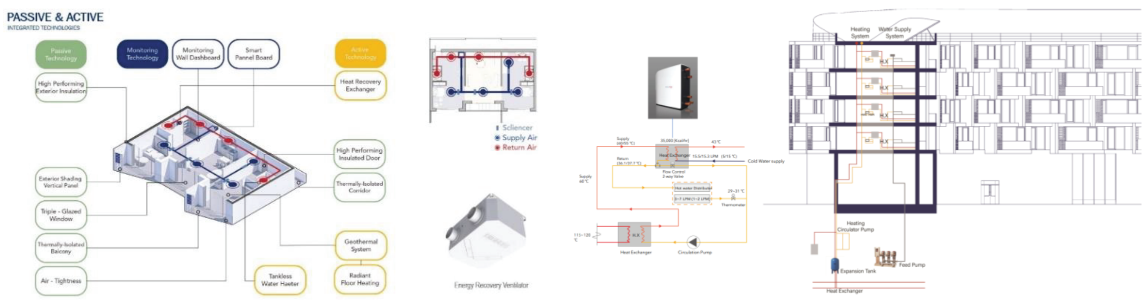
South Korea is located in the mid-latitude climate zone with four distinct seasons, which is similar to ASHRAE Climate Zone 4A. Owning a high-rise apartment lined up along the Han River crossing the center of Seoul is considered a symbol of wealth in Korea. The under-privileged, such as low-income families, young people, and newlyweds, are being driven out of Seoul's central areas due to the sudden increase in Seoul's house prices. The proposed site is located on the traffic island at the northern end of a half-cloverleaf interchange in Figure 3.

Engineering

Three main strategies of passive and active technologies and monitoring technologies are embedded into each unit in Figure 4. For energy savings, passive technologies include high-performance exterior insulation, exterior shading vertical panels, triple-glazed windows, thermally isolated balconies, and high airtightness. An energy recovery ventilator (ERV), tank-less water heater, and radiant floor heating in each unit can reduce the energy demand even more from the

FIGURE 3. Site perspective of the CRK35 project (left) and site plan (right).

FIGURE 4. Passive, active, and energy monitoring integration (left) and integrated piping system (right).



geo-thermal system. Air ducts supply fresh air and contaminated air returns through a return duct, indicated in red. A silencer reduces mechanical noise from the ERVs. The five primary energy usage sources of heating, cooling, hot water, ventilation, and lighting are measured by numerous electric flow meters and calorimeters. The amount of energy usage is also visualized on an energy dashboard (e.g., wall pad) for proper energy control by occupants.

The integrated piping system in each unit is connected to a single piping network ranging from the main heat exchanger, pump piping, an expansion tank to water treatment devices, a calorimeter, a hot water distributor, and floor heating coils. Hot water at approximately 60°C from the geo-thermal system flows to the unit's heat exchanger. After the heat exchange inside the unit's heat exchanger at about 5 to 15°C from a cold water supply, hot water at 43°C and warm water at 37°C are then distributed for showers and radiant floor heating.

Market Analysis

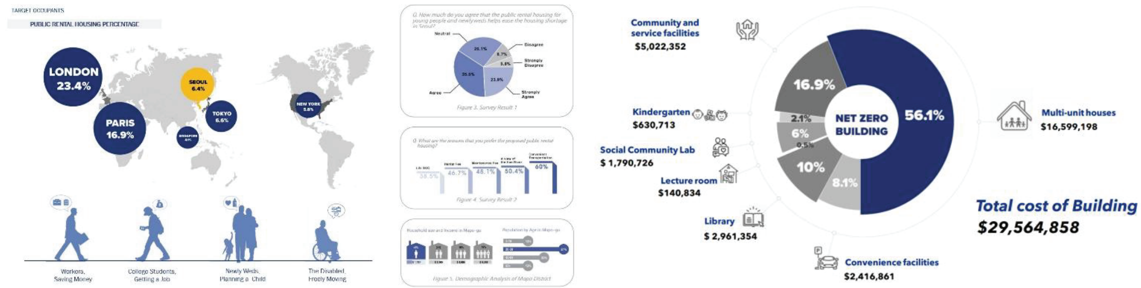
Due to soaring housing prices, low-income families, newlyweds, and newcomers to Seoul are increasingly being driven to the outskirts of Seoul to avoid the rising house prices. Our team aimed to reduce the economic gap and stabilize dwelling quality levels by providing affordable housing. The site belonging to the Mapo district has a high proportion of young people, with 41 percent of people there aged 20 to 39. The average income for single-person households, accounting for 45 percent of the single to five-person households in the Mapo district, was the lowest at $1,715.

The demand for zero-energy buildings is inevitable as we strive toward a carbon-neutral society. Despite the fact that high-performance building materials, active systems, and renewable systems increase the total construction cost by about 20 to 30% relative to conventional construction costs, the CRK25 project can serve as a footprint to drop the global temperature by 2°C given its low CO_2 emissions. Based on a cost analysis, the total construction cost of the CRK35 project is about 29 million dollars, and the cost per square foot is about 242 dollars in Figure 5. However, environmental benefits that the CRK35 project offer have a value that exceeds the numerical value.

Durability and Resilience

The environmental value of the CRK35 project depends on the cycle of the ecosystem. Repetitive heavy rains during the summer season cause flooding of the Han River, which requires more

FIGURE 5. Target market analysis (left) and construction cost breakdown (right).



efficient water management for the community area. During the rainy season, rainwater is collected in a bio-swale, bio-slope, tree box, and on a green roof. Filtered greywater can be reused for flushing, gardening, and for other purposes and leads to annual water savings for the cycle of the ecosystems as shown in Figure 6. The mechanical flow of the Han River is transformed into extra electricity using micro-hydroelectric power systems. With other renewable energy sources such as solar and geo-thermal energy, CRK35 maximizes the possibility of clean power generation from nature.

Tenants can use the buffer space by relocating (e.g., sliding, rotating, and folding) non-bearing flexible walls for home offices, a fitness center, a playroom, a workroom, home gardening spaces, and other studios for the post-COVID era. This buffer space is designed to promote better life quality for a family as well as diverse lifestyles.

Embodied Environmental Impact

The carbon footprint and other environmental impacts should be considered within a life-cycle approach because buildings cause 35% of global carbon emissions. The CRK35 project considers durable materials for building envelopes, passive façade designs, the use of local and recycled materials, and prefabrication of wall parts. The use of local building materials such as high-performance exterior insulation, thermal break blocks, triple-glazed windows, non-toxic paint, modular components, and precast concrete panels can reduce the environmental impact of the materials and their embodied carbon emissions as shown in Figure 7.

FIGURE 6. Water management diagram (left) and spatial modularity (right).

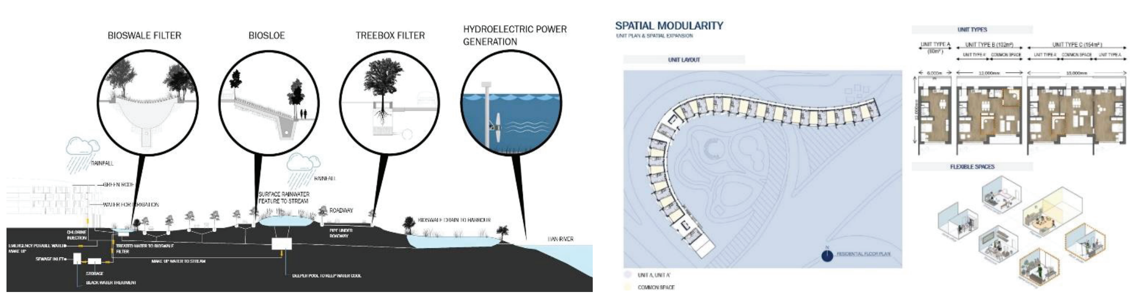


FIGURE 7. LCA-oriented local material utilization (left) and low impact development (right).

Integrated Performance

The dynamic façade of the CRK35 project is equipped with a PV-integrated perforated shading panel, which is patented by Myongji University. The functions of the shading panel are for daylight control, noise transmission loss, solar energy generation, and privacy protection. The perforated part of the panel scatters the direct solar radiance, and the remaining parts block outdoor noise transmission to the indoors in Figure 8. A sliding 17% efficient vertical photovoltaic panel can generate extra solar power with roof photovoltaics.

Occupant Experience

The IoT-based IEQ control system improves the dwelling quality of the residents. A registered tenant can access real-time visual data pertaining to the indoor environmental quality through the CRK35 app, allowing them to control room temperatures, relative humidity levels, and the indoor air quality (e.g., CO_2, PM2.5, and PM10 levels). Residents can also remotely control thermometers, gas valve breakers, smart door locks, smart wall pads, smart switches, and lights through IoT-based IEQ control systems. The smart wall pad visualizes each unit's amount of energy consumption by day, month, and year for the energy use patterns of occupants. The building energy monitoring (BEM) system of the CRK35 project spans energy management, home networking, services, safety, parking, and other features in Figure 9. Measured (or collected) data pertaining to home networking, remote monitoring, energy use, and automatic control are sent to an integrated database system through the gateway. Unit occupants, community monitoring managers and energy monitoring researchers access these data through their own user interfaces in different spaces simultaneously. The IoT-based BEM system is a type of networking for the optimization of the IEQ and energy factors.

FIGURE 8. Integrated active system (left) and multi-functional perforated panel (right).

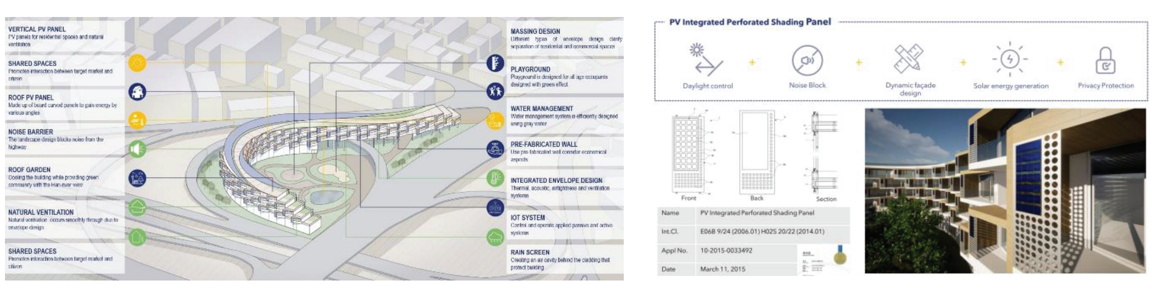
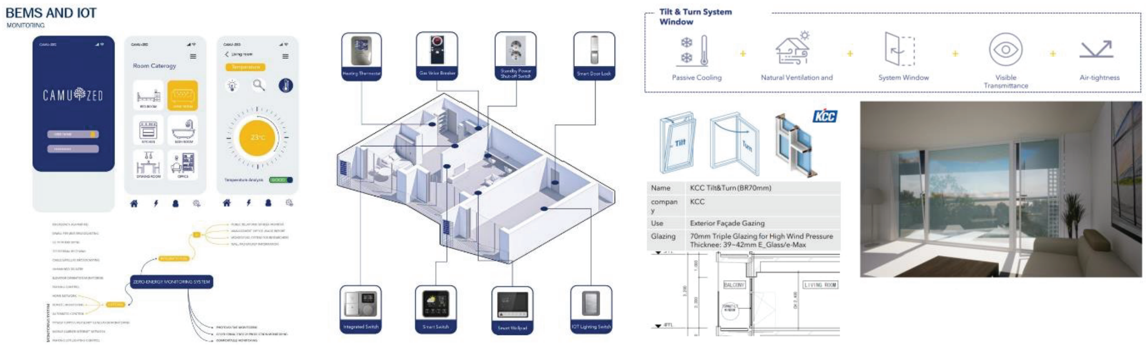


FIGURE 9. IoT-based IEQ control systems (left) and tilt-turn window system (right).



Tilt-and-turn window systems are integrated into the façade of the CRK35 structure, which connects to the Han River, enhancing natural ventilation and passive cooling during intermediate seasons. The tilt-and-turn window system improves airtightness for energy savings during extreme outdoor temperature swings, blocks traffic noise transmission to the indoors, and keeps children safe when the windows are open.

Comfort and Environmental Quality

Each unit faces south, maximizing the potential for daylight to reach deeper spaces. The entire triple-glazed façade of each unit is equipped with an automated horizontal shading louver that controls the amount of illuminance and visual connection to the outdoors. Based on a Sefaira daylighting analysis, 75% of the annual time achieved 300 lux of the recommended illuminance as shown in Figure 10. The sensor-embedded artificial lighting for the rest spaces where only 25% of the annual time reached 300 lux helps to maintain the lighting quality and energy savings requirements.

Each perforated vertical shading panel and automated horizontal shading louver collaborate to block excessive solar radiation to minimize indoor cooling loads during hot summers. The integration of electric heat pumps (EHPs), radiant floor heating, and a geo-thermal heat pump provides occupants with comfortable temperatures during hot and cold seasons. Energy recovery ventilators with silencers help reuse 84% of wasted energy, maintain required indoor air quality levels, and diminish noise annoyances by mechanical noise. Air-tightened envelopes by

FIGURE 10. Daylighting analysis (left) and indoor comfort diagram (right).

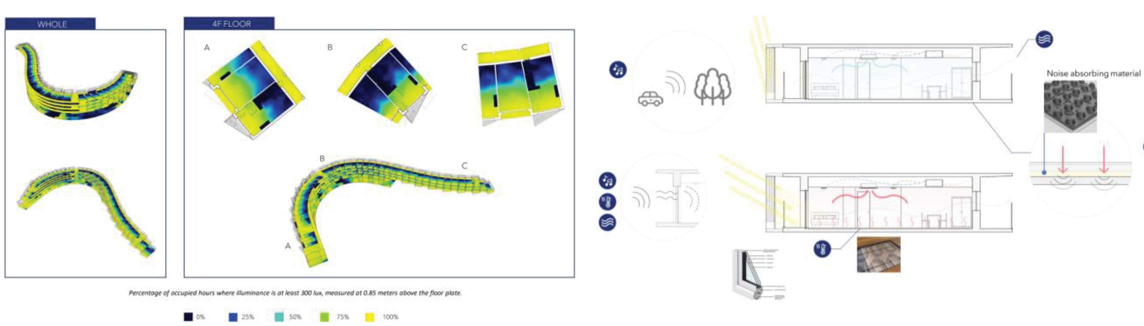
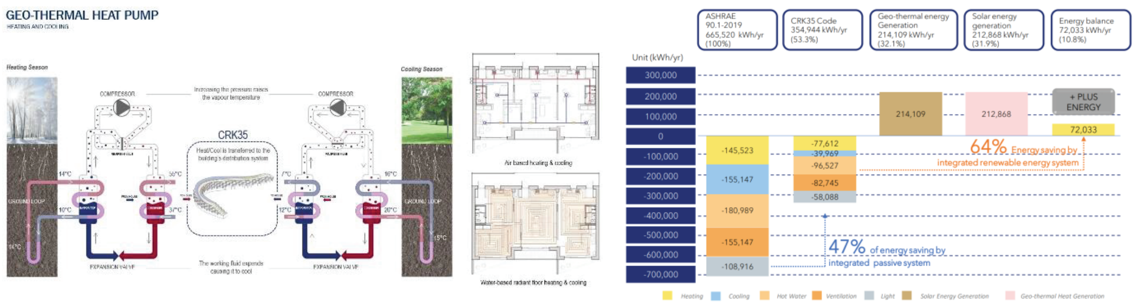


FIGURE 11. Geo-thermal heat pump (left) and energy flow (right).



triple-glazed windows and high-performance insulation can reduce the transmission of outdoor traffic noise. Thicker concrete slab layers and sound-absorbing floor materials minimize floor transmissions of vibration and noise for a family with children.

Energy Performance

The CRK35 project targets a site EUI of 32kWh/m^{2}yr (10kBTU/ft^{2}yr) and a source EUI of 88 kWh/m^{2}yr (28kBTU/ft^{2}yr) for the five primary energy end uses of heating, cooling, hot water, ventilation, and lighting in Figure 11. Compared to ASHRAE 90.1-2019, the high standards applied to the CRK35 project can reduce energy consumption by 46.7% due to the use of the passive techniques of high-performance thermal envelopes, airtightness, triple-glazed windows, and lighting efficacy. Moreover, 64% of renewable energy (e.g., 32% of electricity from solar panels and 32% of heat energy from the geo-thermal system) provides the CRK35 project with sufficient annual energy. Each scenario shows the process of the energy-saving strategies in a preliminary simulation study by Sefaira. The integrated process is critical to achieving the zero-energy CRK35 goal. Compared to ASHRAE 90.1-2019, the applied CRK35 codes improve the energy performance due to the thermal envelopes, airtightness, lighting efficacy, active systems, and renewable energy. As a result, energy consumption was reduced by 47% with the integrated passive and active system compared to ASHRAE 90.1-2019. The remaining energy consumption was then offset at a rate of 64% by the integrated renewable energy system.

EDUCATIONAL ACHIEVEMENT ON VDS

Survey Procedure and Responses

Students who participated in the Solar Decathlon Design Challenge conducted a survey of the educational effectiveness through ten contests related to architecture, engineering, market analysis, durability and resilience, embodied environmental impact, integrated performance, occupant experience, comfort and environmental quality, energy performance, and presentation, as shown in Table 3 [11]. Each question consists of a five-point Likert scale and a descriptive question for responses of the degree of agreement and disagreement for each question. The Google Forms online survey tool lasted for about three weeks from April 19 to May 7, shortly after the final announcement.

TABLE 3. Survey questions and responses.

Student's Achievements of SDDC Contest Criteria	Response
SDDC. 1 Architecture A respondent learned about the building's architecture for creativity, learning about the overall integration of the systems, and the ability to deliver outstanding aesthetics and functionalities. (e.g., aesthetics with sound building science, energy efficiency, natural ventilation, energy production, and resilience)	Strongly Agree: 40% Agree: 46.7% Neutral: 13.3% Disagree: 0% Strongly Disagree: 0% **Positive Tendency: 86.7%**
SDDC. 2 Engineering A respondent learned about effective designs of high-performance engineering systems, technologies, and techniques through the use of energy efficiency and renewable energy. (e.g., heating, cooling, water, and ventilation system types and design should reflect different technologies)	Strongly Agree: 46.7% Agree: 40% Neutral: 13.3% Disagree: 0% Strongly Disagree: 0% **Positive Tendency: 86.7%**
SDDC. 3 Market Analysis A respondent learned about the building's appeal, affordability, and attainability by its stated target market; this includes the likelihood of adoption by intended occupants and the construction industry for an impactful, cost-effective design. (e.g., financial capabilities of the target market and overall affordability)	Strongly Agree: 40% Agree: 40% Neutral: 20% Disagree: 0% Strongly Disagree: 0% **Positive Tendency: 80.0%**
SDDC. 4 Durability and Resilience A respondent learned about the building's long-term abilities to endure local environmental conditions and to anticipate, withstand, respond to, and recover from disruptions. (e.g., the ability of the building envelope to maintain long-term performance despite routine environmental conditions)	Strongly Agree: 33.3% Agree: 53.3% Neutral: 13.3% Disagree: 0% Strongly Disagree: 0% **Positive Tendency: 86.6%**
SDDC. 5 Embodied Environmental Impact A respondent learned about the full life cycle of a building, from 'cradle to grave'. (e.g., reclamation, refurbishment, repair, reuse, and recycle)	Strongly Agree: 46.7% Agree: 46.7% Neutral: 6.6% Disagree: 0% Strongly Disagree: 0% **Positive Tendency: 93.4%**
SDDC. 6 Integrated Performance A respondent learned how effectively the whole building performance is optimized through passive and active strategies across multiple building disciplines. (e.g., passive heating, cooling, ventilation, and lighting)	Strongly Agree: 33.3% Agree: 33.3% Neutral: 33.3% Disagree: 0% Strongly Disagree: 0% **Positive Tendency: 66.6%**
SDDC. 7 Occupant Experience A respondent learned how the building optimizes occupants' quality of life while also meeting the energy performance goals of the design. (e.g., strategies for efficiency, comfort, health, and safety)	Strongly Agree: 40% Agree: 46.7% Neutral: 13.3% Disagree: 0% Strongly Disagree: 0% **Positive Tendency: 86.7%**

TABLE 3. *(Continued)*

Student's Achievements of SDDC Contest Criteria	Response
SDDC. 8 Comfort and Environmental Quality A respondent learned about the building's capability to deliver the intended comfort and indoor environmental quality levels. (e.g., ventilation, filtration, dilution, and material selection strategies)	Strongly Agree: 53.3% Agree: 46.7% Neutral: 0% Disagree: 0% Strongly Disagree: 0% **Positive Tendency: 100.0%**
SDDC. 9 Energy Performance A respondent learned about reductions of whole-building energy consumption levels, the ability to generate clean energy as needed on-site, and interactions with local grid operations. (e.g., energy consumption, clean energy generation, and the capability of the grid services)	Strongly Agree: 40% Agree: 26.7% Neutral: 33.3% Disagree: 0% Strongly Disagree: 0% **Positive Tendency: 66.7%**
SDDC. 10 Presentation A respondent learned about the team's ability to convey its design and approach to energy performance to relevant audiences accurately and effectively.	Strongly Agree: 33.3% Agree: 33.3% Neutral: 33.3% Disagree: 0% Strongly Disagree: 0% **Positive Tendency: 66.6%**

CONCLUSION

From the finding of the survey, students showed high educational satisfaction with over 90% of the highest positive tendency in the categories of embodied environmental quality and comfort and environmental quality. In contrast, the positive tendency of educational achievement in the categories of integrated performance and energy performance, and presentation was lower than 70%. The relative degree of the low percentage level regarding simulation utilization in relation to building energy and integrated performance issues was due to the lack of a ZEB simulation and evaluation techniques for undergraduate students.

In other descriptive questions, 86% of the students had never experienced ZEB competitions before, and 60% of the students expressed a desire to participate in the Solar Decathlon Design Challenge again when possible. As suggestions for improving this competition, they requested relevant elective courses (60%) to prepare for the competition systematically. They also recommended team compositions to include various grades with multidisciplinary majors (e.g., engineering, computer sciences, and others).

Under the unexpected circumstances of the COVID-19 pandemic, virtual design studios appear to restrict more active discussions and critiques of the design processes of students. However, project-based designs with the support of virtual learning tools can help students promote their individual contributions and responsibilities for a common goal. Although VDS is not an ideal platform for a design competition, it served to complete comprehensive design requirements for ZEB through integrative design thinking, problem-solving skills, and numerical simulation techniques on the VDS medium during the COVID-19 pandemic.

ACKNOWLEDGMENT

We thank CAMU students and many external consultants. This research was supported by Soyoung Kim, Jaewon Song, Hyeseon Hwang, Bowon Park, Eunjin Byun, Jaewoong Shin, Jaeyoug Jeong, Minyoung Kim, Dageon Oh, Jongchan Lee, Mingyu Kim, Yeji Park, Haerin Yang, Hyeongseon Park, Taeseok Kwon, and ZED architects & IZAC researchers.

REFERENCES

[1] Choi, G.S, & Bae, M.J. (2017) Zero Energy Building Policies and Trends in KOREA. *2017 Conference Proceedings of Society of Air-conditioning and Refrigerating Engineers of Korea*, Vol.(6) 290–293.

[2] Lee, H.S. (2018) The Convergence of Building Technology and Energy Technology, and the Policy Trend of Zero Energy Building, Convergence Research Policy Center, Vol.(102) 1–10.

[3] APEC Energy Working Group (2014) Nearly (Net) Zero Energy Building. Asia-Pacific Economic Cooperation [Retrieved May 22, 2021 from https://unepdtu.org/wp-content/uploads/sites/3/2016/04/00-apec-nearly-net-zero-energy-building-final-20141203.pdf]

[4] Tokman, L.Y. and Yamacli, R. (2007) Reality-based design studio in architectural education. Journal of Architectural and Planning Research, 24, 245–269.

[5] Chen, W. and You, M. (2010) Student response to an Internet-mediated industrial design studio course. International Journal of Technology and Design Education, 20, 151–174.

[6] Fleischmann, K. (2020) Online design education: Searching for a middle ground. Arts and Humanities in Higher Education, 19, 36–57.

[7] Milovanovic A., et al. (2020) Transferring COVID-19 Challenges into Learning Potentials: Online Workshops in Architectural Education [Retrieved April 22, 2021 from file:///C:/Users/USER/Downloads/sustainability-12-07024.pdf]

[8] Iranmanesh, A. & Onur, Z. (2021) Mandatory Virtual Design Studio for All: Exploring the Transformations of Architectural Education amidst the Global Pandemic. The International Journal of Art & Design Education, Vol. 40(1) [Retrieved May 22, 2021 from https://onlinelibrary.wiley.com/doi/full/10.1111/jade.12350]

[9] McLaughlan, R. & Chatterjee, I. (2020) What works in the architecture studio? Five strategies for optimising student learning, International Journal of Art & Design Education, Vol. 39(3).

[10] Allu-Kangkum, E.L.A (2021) Covid-19 and Sustainable Architectural Education: Challenges and Perceptions on Online Learning, Journal of Educational Research, Vol. 6(2) 7–13.

[11] The U.S. Department of Energy Solar Decathlon Design Challenge: https://www.solardecathlon.gov/