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Introducing Engineering Design to First-Year Students Through the Net Zero Energy Challenge

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ABSTRACT
First-year engineering students are often introduced to the engineering design process through project-based learning situated in a concrete design context. Design contexts like mechanical engineering are commonly used, but students and teachers may need more options. In this article, we show how sustainable building design can serve as an alternative for students of diverse backgrounds and with various interests. The proposed *Net Zero Energy Challenge* is an engineering design project in which students practice the full engineering design cycle to create a virtual house that generates renewable energy on-site, with the goal to achieve net zero energy consumption. Such a design challenge is made possible by *Aladdin*, an integrated tool that supports building design, simulation, and analysis within a single package. A pilot study of the *Net Zero Energy Challenge* at a university in Mid-Atlantic United States suggests that around half of the students were able to achieve the design goal.

KEYWORDS
Engineering design; Engineering education; Net zero energy; Sustainable building

Introduction

First-year engineering courses are a rite of passage in colleges of engineering (Ahlgren, 2001). The quality of these courses impacts students' intellectual development (Marra et al., 2000; Dym et al., 2005). Often, first-year engineering classes use project-based learning (PBL; Dym et al. 2005; Shekar, 2014) to introduce students to the engineering design process. Common projects include robotics (Ahlgren, 2001) and gearbox design (Li et al., 2019). However, students who enroll in these classes come from different academic backgrounds and often have not decided their majors yet. Hence, a mechanical engineering project may be more challenging to students who have not acquired the related prerequisites or less appealing to students who are not interested in pursuing mechanical engineering. But engineering design needs to be situated in a concrete context for it to be operationalizable, even though the goal is to teach generic concepts that can be applicable across different engineering domains.

Sustainable building design caters to the needs of introductory engineering classes. Most students are familiar with houses and have everyday experience with energy-related topics in this context, including using air conditioning (AC) and heating in different seasons, hikes in energy prices, and so on. An ambitious goal in building design is to achieve the so-called net zero performance, meaning that the building can itself generate renewable energy no less than the total amount of energy that it consumes over the course of a year. The net zero building design challenge provides ample opportunities for students to engage in the full engineering design cycle, explore the scientific principles behind everyday phenomena, and use science to guide their design decisions. The U.S. Department of Energy (DOE) has been running a sustainable building design challenge called the Solar Decathlon for two decades now, but it requires substantial financial and time commitment that prevents most students from participating. For the educational opportunity to be open to all students, we present the *Net Zero Energy Challenge*, a PBL activity for first-year engineering students. The challenge can be solved within 2–4 h, depending on the width and depth of the solution space in which students are willing to explore. The PBL activity is enabled by *Aladdin*, an integrated Web-based computer-aided design (CAD) tool that we developed to support building design, simulation, and analysis in a single package. As an key feature, *Aladdin* visualizes science concepts

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important in building physics such as solar irradiance and heat flux (Xie, Schimpf, et al., 2018; Xie, Ding, et al., 2023) as formative feedback to guide students throughout the design process.

The Net Zero Energy Challenge

First-year students are likely concerned about rising energy costs and climate change. These concerns may motivate them to learn and use engineering design to find solutions to mitigate these real-world problems.

A goal of an engineering PBL activity is to guide students through the full engineering design process, including (but not limited to) steps such as defining the design problem, exploring design options, evaluating design alternatives, and iterating many times. The *Net Zero Energy Challenge* begins with an overview of the design requirements: Students are tasked with helping a client design a house that generates as much energy as it consumes over the course of a year (i.e., achieving the net zero goal). A main performance metric is the yearly energy offset of the house under design:

$$\textit{Yearly energy offset} = \frac{\textit{Yearly energy generation}}{\textit{Yearly energy consumption}}$$

Students have an abundance of choices when it comes to house design. While a house can be as simple as a structure consisting of four walls and a roof, students can apply architectural styles from different regions and cultures, such as the Cape Cod style from the Northeastern United States, the Adobe Taos style from the Southeastern part, and the contemporary style shown in Figure 1. Students can design facades by adding and laying out windows and doors. They can also add attachments such as porches and chimneys and design the landscape using trees, flowers, and lights. They must consider constraints such as budget, minimum floor area, minimum window-to-wall ratio, and so on that may be specified by a client. All these design criteria and constraints not only serve aesthetic and practical purposes, but they also affect the energy consumption of the house and thus students' design decisions. For example, larger windows provide more natural light and are often considered more aesthetically pleasing, but they also increase the energy consumption significantly due to the increased solar radiation into the house in the summer and the increased heat losses out of the house in the winter. If students adopt a high window-to-wall ratio, they will find it more challenging to achieve a high energy offset. They will have to use more expensive low-emissivity triple-pane windows to decrease the heat loss and add more solar panels and/or install geothermal heat pumps to increase renewable energy generation. These design considerations engage students in making tradeoffs to balance different criteria under multiple constraints to arrive at an optimal solution, providing practical opportunities for students to learn these essential design skills.

Once students finish designing the shape of the house, they can evaluate its energy performance (some shape subtraction procedures may be needed for houses with complex architectures to improve the accuracy of the evaluation, but we will skip these details in this paper – interested readers can find more information on *Aladdin*'s website). *Aladdin* estimates energy consumption and generation of a house based on calculating the solar radiation on the surface of the building envelope of the house and the heat transfer between the house and the environment through the building envelope. The weather data of the location is used to model the climate conditions, a key reason why sustainable house designs in different parts of the world may be quite different. Scientific visualizations of solar radiation and heat transfer are superimposed onto the house to provide visual cues for students to inspect the energy implications of the design elements or factors individually. For instance, a longer heat flux arrow through an element (e.g., a window) is indicative of more heat exchange through it than a shorter one through another element (e.g., a wall). Figure 2 illustrates these features of *Aladdin* simulations. To offset the energy consumption, students can add solar panels on the roofs (or even the walls – though it is uncommon to do so), and they can generate a heatmap of the house to visualize the solar potential of different surfaces.

Considering that students may not be aware of the full design space, teachers can prepare them with a series of self-directed investigations that we provide through *Aladdin*. These investigations are designed to help students explore the effects of various design variables, understand the underlying principles, and make informed decisions. Each investigation focuses on only one design variable and supports the predict-observe-explain (POE) inquiry cycle: (1) **Predict**: Students predict the effect of changing the design variable on the energy usage of the house; (2) **Observe**: Students run simulations and examine the results displayed in graphs and visualizations; (3) **Explain**: Students explain their observations using science concepts and reconcile their predictions with

Figure 1. Examples of different architectural styles in *Aladdin*. (a) A Cape Cod house with three dormers, a chimney, and a garage. (b) A cluster of Adobe Taos houses. (c) A house in a contemporary style.

their observations. For example, the effect of floor insulation depends on multiple factors (such as location, season, ground temperature, air temperature, and thermostat setpoint) and can be difficult to predict. The provided investigation into this effect presents students with two houses that are identical

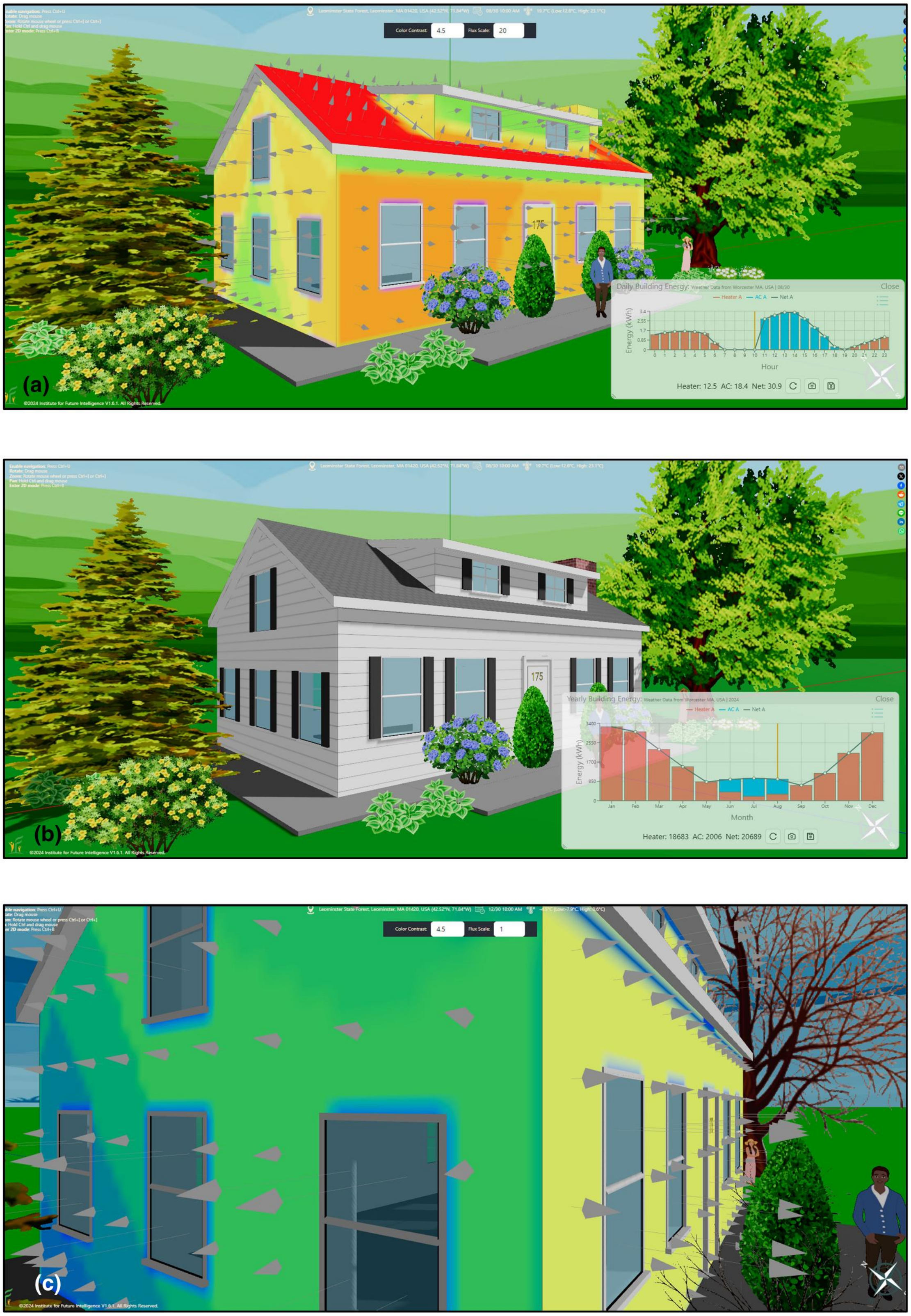

Figure 2. (a) A solar radiation heatmap for a simple Cape Cod house in central Massachusetts on August 30th, with a graph inset showing the hourly heating and cooling energy consumption. (b) The house without the heatmap but with a graph inset showing the monthly energy consumption over a year. (c) A close-up of the heat flux distribution that visualizes the daily heat exchange between the inside and the outside of the house through different parts on December 30, suggesting that the windows lose more energy than the walls in a diurnal cycle.

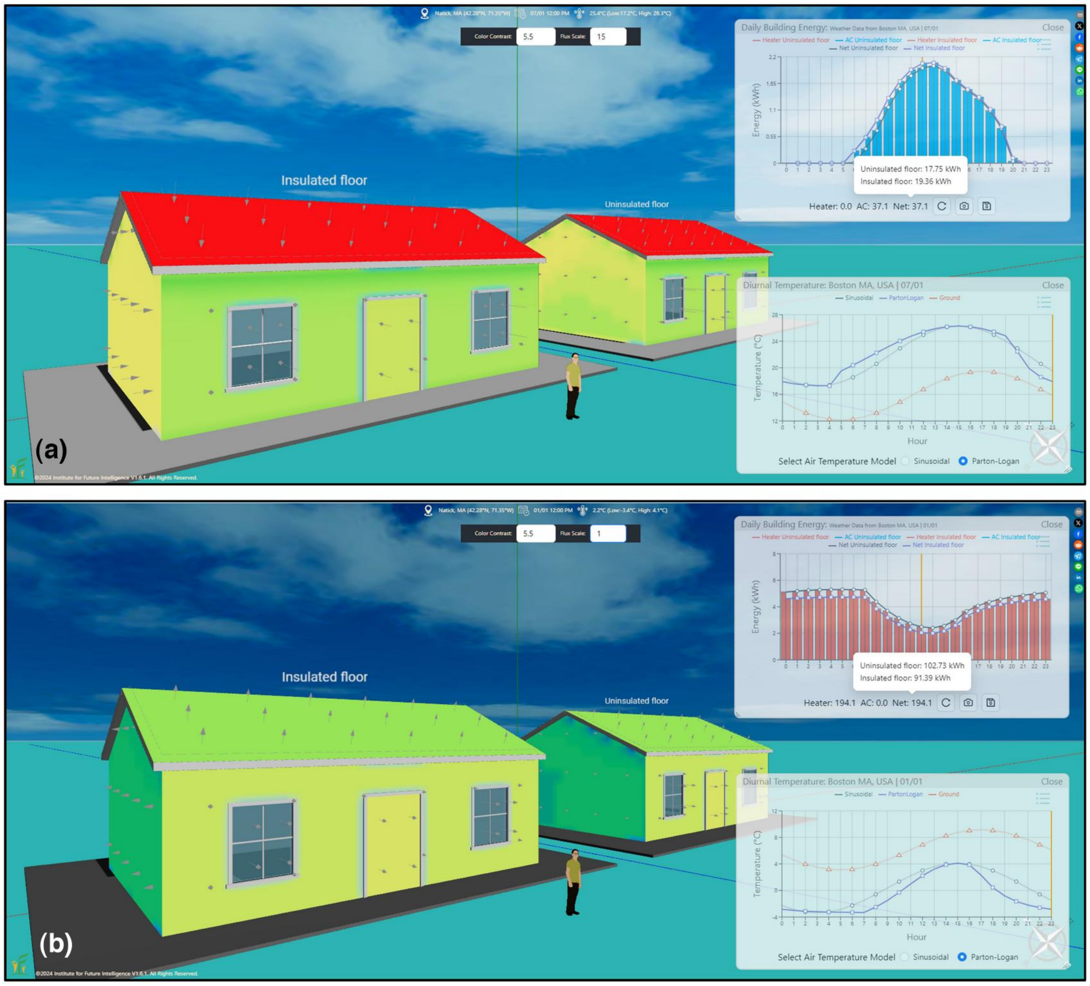

Figure 3. Investigating the effect of the floor insulation on building energy using *Aladdin*: The simulation shows that the house with an uninsulated floor uses less energy than the one with an insulated floor in the summer (a); whereas the result is opposite in the winter (b).

to each other except for the floor insulation (Figure 3). Students are guided to generate a daily temperature graph and notice that the thermostat setpoint (20 °C) is lower than the average air temperature (22 °C) but higher than the average ground temperature (16 °C) in the summer in Massachusetts (Figure 3a). Students are then prompted to reason that an uninsulated floor would be more energy efficient in the summer because it allows more thermal energy in the house to be removed through the ground, thus saving energy for AC (this is the reason why a geothermal heat pump can be used to cool down a house in the summer). But that is not the full story. If students switch the season to the winter, they will then discover that an insulated floor drives up the heating cost because it causes more thermal energy to escape from the house via the ground (Figure 3b). This example shows that a design variable can have complicated effects as it may be interconnected with other variables in the system that must be taken into account as well. Through the POE cycle, students have a chance to deepen their understanding and exercise systems thinking.

Assessing student learning in such a complex engineering design activity can be challenging. To support teacher adoption, we have developed an engineering design scoring rubric (see Appendix A). This rubric evaluates student learning in five dimensions: (1) Performance: How close the final design meets the net zero criterion; (2) Diligence: How much effort students put into their design; (3) Evidence: How students support their design decisions with data; 4) Reasoning; How rational students support their design decisions; and (5) Reflection: How much students are aware of rooms for improvement. For example, the "Evidence" dimension specifies that students provide the simulation results as data sources as part of their design "knowledge."

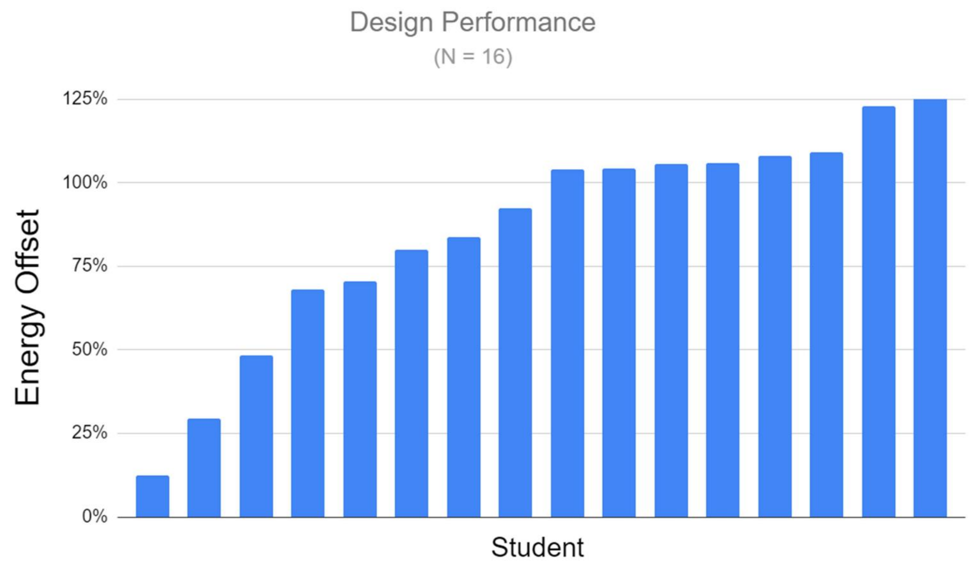

Figure 4. Students' engineering design performance, measured by the percentage of energy offset of their final house designs.

During the design activity, students may also use the scoring rubric to self-regulate, and teachers can use the Engineering Design Coaching Tool (Purzer et al., 2022) to elicit students' design reasoning and provide just-in-time feedback.

Pilot Study

Study Context and Methods

Between March and May in 2023, a pilot study of the *Net Zero Energy Challenge* was conducted with 23 undergraduate students at a private research university in Mid-Atlantic United States. Each student signed up for a 90-minute session. At the beginning of each session, the students first watched three video tutorials on how to build a simple house in *Aladdin*, how to customize the appearance of the house, and factors that affect building energy performance. The video tutorials were 12 minutes long in total, and the students used the remaining time to create their own house designs. During each session, a research assistant was present to provide technical support. At the end of each session, the students were instructed to save their final design artifacts and invited to participate in a five-minute debrief with the research assistant about their design experiences.

In addition, students' design activities were automatically logged by *Aladdin* behind the scenes. After all the design sessions ended, students' activity logs were analyzed. Each yearly building energy analysis action marks the completion of one micro-iteration. The yearly energy offset of the final design was used as an indicator of the engineering design performance of the student designer, and the changes in the energy offset over time were used to represent their design trajectories.

Results

Students spent an average of 33 minutes finishing the design activity. Of the 23 students who participated in the pilot study, seven students either did not save their final designs, or their final design files could not be retrieved due to technical issues. For the remaining 16 students who saved valid final designs, Figure 4 shows the yearly energy offset values calculated using their final designs. Eight students (50%) achieved or exceeded the given goal of 100% energy offset, with the median being 98.13% (sd = 49%).

The *Aladdin* activity logs show that 16 of 23 students performed at least one yearly building energy analysis during the study. Figure 5 shows their design trajectories reconstructed from the logs. Two students are excluded due to errors in their log data. The design trajectories of the remaining 14 students reveal the following patterns:

- Six students (#3, #11, #13, #16, #18 and #23) only performed one analysis throughout their entire design process.
- Two students (#10 and #21) not only achieved 100% offset within 10 minutes, but they also finished their entire design within 20 minutes.

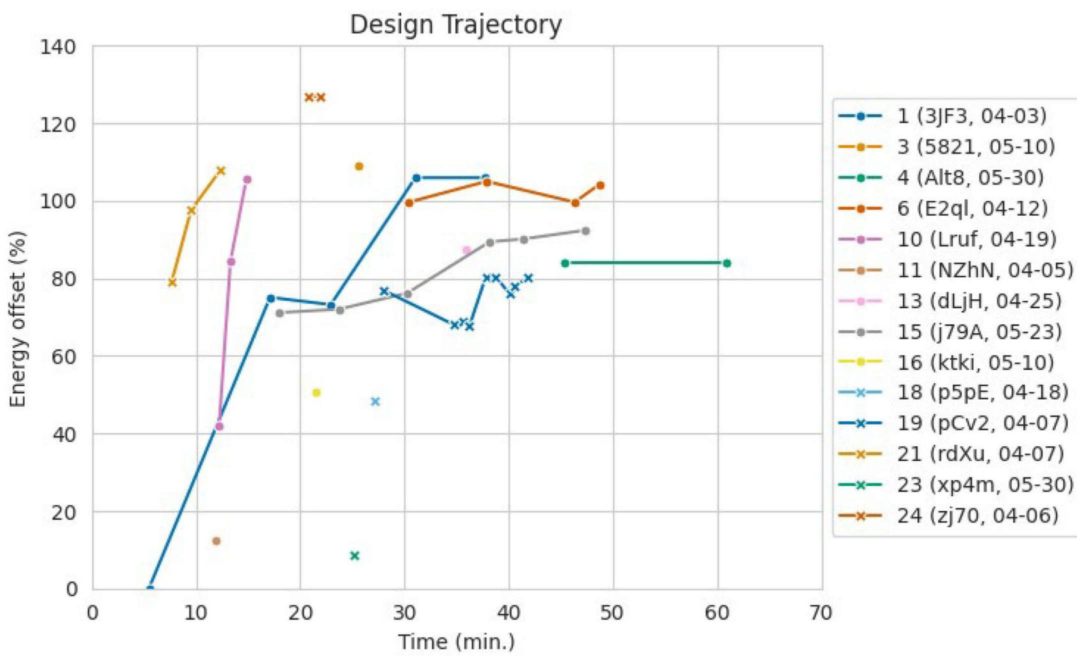

Figure 5. Students' design trajectories over time reconstructed from their data logs captured by *Aladdin* in the background. Each data point records the design performance (measured by the energy offset) of one iteration, with the time being calculated from the beginning of each design session. Clusters of data points indicate frequent iterations, and steeper lines indicate more rapid changes in design performance.

- Two students (#1 and #15) exhibited gradual improvement over time.
- Three students (#3, #6 and #24) achieved the net zero goal in their first iteration.
- Two students (#4 and #19) didn't show much improvement after at least one iteration.
- Only one student (#1) analyzed the building energy before adding solar panels, while the remaining students analyzed the building energy after adding solar panels.

To understand how *Aladdin* and the *Net Zero Energy Challenge* curriculum contributed to student learning, we analyzed the transcripts of the post-test debrief and identified representative instances of implicit learning. For example, one student not only understood the competing effects of windows ("even though putting windows made the AC [usage in the summer] worse, it made the [heating usage in the] winter much much better"), but also made a correct evidence-based trade-off decision ("you're absolutely supposed to focus on winter over the summer because the AC power was not nearly as much"). Their *Aladdin* activity log revealed that this student conducted nine yearly building energy analyses, where the average heating usage was around 10 MWh, but the average AC usage was only around 2 MWh. As an additional example, another student initially "wanted to create a pretty house, [with] a lot of windows", but she later realized that she "need to realistically make the house smaller", if she "actually want to save energy." She also tried changing different design variables like the direction of the house and the roof pitch and commented that "it was really interesting to see the energy output due to these different changes." This testimonial suggests that the simulation and visualization capabilities of *Aladdin* might have placed a role on helping students understand the effects of different design variables and make fair trade-off decisions.

Discussion

The results from this pilot study also revealed several areas in the instructional materials that need to be improved. For example, one limitation of the earlier version was that without the analysis of another iteration for comparison, it was difficult to evaluate student learning throughout the design process in terms of design performance. As a result, a later version of the instructional materials specifies that students need to document at least two iterations with their analysis results, evaluate the effectiveness of their design changes, and explain their design rationale. Another revelation is that a few students couldn't improve their designs despite their efforts. To provide additional guidance, a later version includes self-directed investigation units to facilitate self-regulated learning (Zheng et al., 2020). Finally, it was observed that only one student analyzed the building energy use before adding solar panels to generate electricity. While the *Net Zero Energy Challenge* does not explicitly require students to conduct such a "site assessment" before deciding on the positions to install solar panels, this practice may help them better understand that energy efficiency of buildings is also important in attaining the net zero goal before they start to explore renewable energy as a solution.

Conclusion

To attract and retain prospective students, first-year engineering courses should help them find connections between their personal experiences and authentic engineering practices. Sustainable building design can provide an accessible, relevant, and practical design context for the majority of first-year engineering students. Powered by the easy-to-use, Web-based engineering design tool *Aladdin*, the *Net Zero Energy Challenge* offers students an introductory engineering experience and integrated opportunities for science and math learning. Instructors can also use various teaching resources to understand student performance and support student learning.

Web Links

- DOE's Solar Decathlon: https://www.solardecathlon.gov/
- The *Aladdin* CAD software is freely available at:https://intofuture.org/aladdin.html
- The *Net Zero Energy Challenge* instructional materials are freely available at http://intofuture.org/aladdin-energy-plus-house-design.html.

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Appendix A: The net zero energy challenge scoring rubric

Criterion	Explanation	Exceeds expectations (* 1.2)	Meets expectations (* 1)	Approaching expectations (* 0.8)	Not meeting expectations (* 0.6)
Performance (20%)	N/A	Energy offset >110%	Energy offset >100%	Energy offset >75%	Energy offset >50%
Diligence (20%)	• The design obeys limitations of physical laws. • The design is practical for everyday human use. • The design is aesthetically pleasing or creative.	Student shows all three (3) types of evidence.	Student shows two (2) types of evidence.	Student shows one (1) type of evidence.	Student shows none (0) of the evidence.
Evidence (20%)	• The student tested the effect of at least one design variable using alternative designs and reported the design performance. • The student can support the final design with simulation data. • The student applied rigor to the design of simulation experiments by using control variables.	Student shows all three (3) types of evidence.	Student shows two (2) types of evidence.	Student shows one (1) type of evidence.	Student shows none (0) of the evidence.
Reasoning (20%)	• The student can explain the prioritization of design choices. • The student can explain the final design choices using scientific principles. • The student can explain the different scales of impact of design variables.	Student shows all three (3) types of evidence.	Student shows two (2) types of evidence.	Student shows one (1) type of evidence.	Student shows none (0) of the evidence.
Reflection (20%)	• The student is aware of ways to improve the design performance. • The student is aware of ways to improve the rigor of experimentation. • The student is aware of ways to improve reasoning.	Student shows all three (3) types of evidence.	Student shows two (2) types of evidence.	Student shows one (1) type of evidence.	Student shows none (0) of the evidence.