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Classroom orchestration of computer simulations for science and engineering learning: a multiple-case study approach

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ABSTRACT

This multiple case study focused on the implementation of a computer-aided design (CAD) simulation to help students engage in engineering design to learn science concepts. Our findings describe three case studies that adopted the same learning design and adapted it to three different populations, settings, and classroom contexts: at the middle-school, high-school, and pre-service teaching levels. Although the classroom orchestration of the particular learning design was customised for specific audiences and contexts, findings from this study suggest that the core components of the learning design, such as content, assessment, and pedagogy, and their alignment among them, resulted in students' learning. Specifically, results from a pre-post science assessment suggest that the three student groups arrived at similar understanding post-intervention levels, along with a significant aggregate growth in their scientific understanding. Regarding design performance, students in different groups demonstrated different levels of success in meeting design constraints. The findings also suggest that students' success rate in meeting the design constraints directly influenced their final design performance, where middle-school students had better performance than students in the other groups. That is, across the board, students increased their conceptual understanding of heat transfer, Earth, and solar science and were able to produce feasible designs. Implications of the study include how learning experiences with engineering and science simulations should be designed so that teachers can adopt and adapt materials for their specific audiences, contexts, and settings.

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1. Introduction

Recent policy guidelines such as the Next Generation of Science Standards (NGSS Lead States, 2013) and the *Framework for K-12 Science Education* call for engineering concepts and practices to be integrated into K-12 science classrooms (National Research Council, 2012). These guidelines have prompted educators and researchers to design and develop engineering-based learning experiences in the form of curriculum, hands-on learning materials, and computer simulations that can be implemented within pre-college and

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pre-service science classrooms. However, engineering design can be difficult to teach, learn, and assess (Crismond & Adams, 2012; Razzouk & Shute, 2012). Teaching and learning engineering design is challenging partly because it requires students to use their science knowledge to inform their design decision-making (Chao et al., 2017; Kolodner et al., 2003). A particular type of educational technology that can bring science and engineering practices into the classroom is computer simulations (Hennessy et al., 2007). They provide learners with data visualisations and other forms of feedback that allow them to test multiple features of their designs (Brown, 2009; Wieman et al., 2008; Xie et al., 2011). While determinants for learning with computer simulations (i.e. de Jong & van Joolingen, 1998) and their learning benefits (i.e. D'Angelo et al., 2014) have been well-documented; their adoption, adaptation, and integration into the classroom setting have not been thoroughly investigated (Higgins & Spitulnik, 2008; Lawless & Pellegrino, 2007). But effective classroom teaching with computer simulations requires an appropriate combination of instructional design and classroom orchestration.

In terms of the integration of computer simulations for science teaching, research has identified some forms of orchestration, including independent use (Hsu, 2008), small-group use (Saab et al., 2005), or whole-group instruction (Smetana & Bell, 2014). A study that identified patterns of computer simulation use in the elementary science classroom with 96 teachers was performed by Gonczi et al. (2016). Results from their study identified that 'teachers used a one-to-one student-to-computer ratio most often, either during class-wide individual computer use or during a rotating station structure' (Gonczi et al., 2016, p. 1800). On the other hand, the integration of computer simulations for engineering teaching, to our knowledge, is lagging. The few cases described by Magana and de Jong (2018) were primarily implemented in higher education settings (e.g. Dickerson & Clark, 2018; Rampazzo & Beghi, 2018). Although the aforementioned studies provide valuable contributions into describing different forms of classroom orchestration with computer simulations, to our knowledge, there is little to no research studies that describe (a) the interplay of instructional design and classroom orchestration with the use of computer simulations and their effects for science and engineering learning, and (b) how classroom orchestration might look different across different contexts (i.e. middle school, high school, and pre-service teachers). More research is needed that takes into consideration aspects of the curriculum, assessment, time, teacher effort, learning spaces, and safety constraints, among others (Dillenbourg & Jermann, 2010), particularly in the context of K-12 education (NRC, 2009).

This study describes (a) the instructional design of a lesson that integrates science learning (topics of heat transfer, Earth and solar science) with engineering design skills, and (b) how the corresponding in-class orchestration took place in three different classrooms with three different populations (middle school, high school, and pre-service teachers). The guiding research questions are: What were similarities and differences in classroom orchestrations of a lesson integrating science learning with engineering design within three different classrooms? To what extent did students' understanding of science concepts change after participating in the lesson? What was students' overall design performance, and to what extent were students able to meet the design criteria?

We first introduce the opportunities and challenges for integrating engineering design within the context of science learning at the K-12 level and the opportunities offered by computer simulations for supporting the teaching and learning processes in this context. We then ground our study in principles of classroom orchestration and instructional design theory. Then, this study presents the instructional design of a CAD simulation-enabled unit that integrates the teaching and learning of heat transfer and Earth and solar science concepts, coupled with engineering design practices. For this, we describe in detail how we carefully aligned the content, assessment, and pedagogy of our instructional design. Then, following a within-case analysis approach and with guidance from Nussbaum and Diaz's framework (2013), we identified the three elements of classroom orchestration: context, aim, and specification, to describe how the same unit was adopted, adapted, and orchestrated in a middle school, high school, and pre-service teacher setting. Then, we present a cross-case comparison to identify similarities and differences across cases. Finally, we present learning outcomes from each implementation in the form of measured science learning and design performance.

2. Teaching and learning engineering design in science contexts

Integrating engineering into pre-college classrooms is often coupled with different forms of supports for learning, including supports built into the curriculum (Chiu et al., 2017; Kolodner et al., 2003), support built into assessment instruments such as design journals (Moore et al., 2016), and support provided by teachers (Crismond, 2011).

Engineering design challenges coupled with these kinds of scaffolding can also be provided through technology (Kim & Hannafin, 2011). In particular, computer-based learning environments with embedded simulations offer several advantages to supporting K-12 science learning. Computer-based simulations can provide: (1) a unified environment for engaging in interdisciplinary learning across science, technology, engineering, and mathematics disciplines as called for by the NGSS (Dasgupta et al., 2019); (2) the ability to quickly generate and revise design artifacts in ways that would not be feasible with physical materials (Schimpf et al., 2018); (3) visualisations of how scientific phenomena may affect design artifacts which may not be easily perceivable in everyday life (Chiu & Linn, 2014; Magana et al., 2019); (4) provide feedback about design performance along with different criteria in the form of visualisations and summary graphs (Chiu et al., 2017; Dasgupta et al., 2019; Xie et al., 2018) and tailored suggestions for revising their design artifact (Schimpf et al., 2019). Furthermore, research on students learning with CAD simulations show gains in understanding of scientific concepts (Chao et al., 2017; Chiu et al., 2017; Magana et al., 2019), growth in design thinking abilities such as making trade-offs and evaluating alternative concepts (Goldstein et al., 2019), development of spatial abilities (Chang, 2014; Sung & Ou, 2002), and increased problem-solving skills (Fang & Tajvidi, 2018). In the current work, we leverage computer-based CAD simulation environments, in conjunction with other forms of scaffolding, as an integrated environment for learning science and engineering design knowledge, skills, and abilities.

Assessing learning outcomes in engineering design can be difficult as these often take the form of skills, practices, and ways of thinking (Crismond & Adams, 2012; Razzouk & Shute, 2012), which are not easily measured with traditional assessments like pre/post surveys. One common alternative strategy for assessing engineering design thinking is to analyzing students design performance, more specifically how well their final design solution addresses design criteria for the challenge (Schimpf et al., 2018; Goldstein et al., 2016; Mentzer, 2014; Shah et al., 2012). Design performance outcomes give insight into students understanding of the problem, its requirements, and their ability to apply good design practices to arrive at a solution and thus more directly assess student's ability to engage in engineering design thinking and practices.

Regarding the scaffolding or instructional design approach, one critical aspect of integrating engineering-based learning experiences into the science classroom is understanding how these units or lessons are adopted and adapted for actual classroom teaching (Williams et al., 2004). Teachers may use curricular materials as-is, adapt them to fit their specific classroom context and environment, or use them as the basis for the design of new activities (e.g. Davis & Varma, 2008; Remillard, 1999). Thus, some instructional supports within the curricular materials may be used or emphasized, while others may not be used or de-emphasized. Our study explores how the same CAD simulation with the same instructional design approach was then implemented across three different learning contexts with related science learning and design outcomes.

3. Theoretical framework and implications for the study

The literature on classroom orchestration and instructional design served as the theoretical framework for our study. Classroom orchestration is different than instructional design. Instructional design focuses on intrinsic activities that carefully pre-define the intended learning outcomes, the evidence of the learning, and the pedagogies and scaffolding that will support different forms of learning (Graff, 2011; Wiggins & McTighe, 1997). For approaching the lesson's instructional design in this study, we followed the guidelines from Understanding by Design (Wiggins & McTighe, 1997, 2005). Understanding by Design proposes a *backward design* (or backward planning) of curricular units starting with the end goal first (i.e. the learning objectives), followed by defining mechanisms for identifying students' achievement of the academic goals (i.e. assessment). The third step then focuses on how to deliver the content, coupling it with specific pedagogies, scaffolding methods, or learning strategies (i.e. the teaching method). Understanding by Design, therefore, allowed us to think about curricular design by following three main stages: (a) identifying the desired learning outcomes (the content of the lesson), (b) determining the acceptable evidence of learning (the method of assessing learning), and (c) planning the experiences and instructional approach (or pedagogy).

In contrast, classroom orchestration occurs when teachers balance or cope with extrinsic constraints such as time management, curriculum relevance, space limitations, teacher effort, and so forth (Dillenbourg, 2013). Specifically, orchestration involves the facilitation of 'the dual flow of information in a classroom, across digital and physical information containers' (Dillenbourg, 2013, p. 491). While teachers and instructors plan and design learning interventions following pedagogical approaches (Dillenbourg, 2013), these often need to be tailored in real-time to manage the learners' needs and classroom dynamics (Dillenbourg & Jermann, 2010; Roschelle et al., 2013). In other words, classroom orchestration is usually characterised by the teacher playing a driving role in the control and awareness of classroom interaction, and has the flexibility and freedom to change and adapt activities as necessary (Dillenbourg, 2013), or capturing the classroom orchestrations across three different learning contexts with same instructional design approach and related learning and design outcomes. We identified and documented three elements we thought were appropriate in demonstrating these classroom orchestrations. These three elements were (a) context – description of setting and participants, (b) aim – teaching and learning goals, and (c) specification – detailed description of how content, assessment, pedagogy, and technology played out in the actual classrooms.

Instructional design theory and classroom orchestration theory have two implications for our study. First, our study used Understanding by Design to carefully align learning outcomes, evidence of the learning, and pedagogical approach, as described in Section IV. Second, our study used Dillenbourg's orchestration framework for framing the within- and cross-case comparison of the three case studies in terms of context, aim, and specification, as described in Section VI.

4. Instructional design

This section presents the details of our instructional design that was adopted, adapted, and implemented that elicited from students the application of their science knowledge and how they engaged in design practices. The instructional design was embodied in a design challenge that followed the guidelines from Understanding by Design (Wiggins & McTighe, 1997, 2005).

4.1. Learning outcomes

The two major intended learning outcomes of this learning design were that first, students would learn science concepts as they engaged in engineering design, and second, that students would demonstrate design skills via the creation of engineering solutions that met specific criteria. Specifically, students were expected to learn Earth and solar science concepts such as Earth's tilt and the seasons, the impact of the rotation and orbit of the Earth on the path of the Sun, how the path of the Sun affects solar energy solutions, energy transfer (light, heat, electricity), including heat transfer in the form of conduction, convection, and radiation, and renewable energy solutions to climate change. Depending on the focus of the design challenge, it was expected that the students would apply some of these concepts as they engaged in the use of multiple engineering design strategies to construct and optimise their designed homes to be energy efficient and meet the design criteria.

4.2. Evidence of the learning

To characterise learning within each classroom implementation, we measured students' science conceptual understanding as well as final design performance. A science learning assessment provided evidence of students' attainment of the specific concepts in solar science and heat transfer through contextualised scenarios and prompts. To evaluate design performance, we collected students' final designs to identify if they were successful at solving the design challenges per the given project criteria. The students' final solutions represented the cumulative results of their design processes and what they were able to achieve through their interaction with the CAD simulation.

4.3. Pedagogical approach

Learning by Design ™ (Kolodner, 2002b) was used as the pedagogical approach to connect scientific inquiry practices and engineering design practices. Learning by Design ™ (LBD) suggests using 'a project-based inquiry approach to science learning with roots in case-based reasoning and problem-based learning, pointing out the theoretical contributions of both' (Kolodner et al., 2003, p. 495). By implementing the lesson following principles of LBD, our goal was for students to achieve content knowledge in a target domain and improve their engineering design skills. By doing so, students were expected to engage in an iterative process of designing, constructing, and testing physical or virtual models, where such models supported them in understanding science content (Kolodner, 2002a). Engaging in the challenge also elicited students to use their design skills (Kolodner, 2002a).

LBD provided a set of components that guided different ways to integrate science content with engineering skills as part of the lessons described below. For example, a strategy consistent across the three case studies was the use of open-ended design activities for promoting collaborative learning and the integration of rich feedback received through the CAD simulation and the instructor (Kolodner et al., 1998). The simulation software used for this study was a CAD tool called Energy3D (Xie et al., 2018), a CAD simulation specifically designed for learning environments. Energy3D has the potential to support design learning by providing different forms of visual and analytic feedback supported by two engines (a) the solar simulation engine, which computes the energy received by any surface at any location of the Earth from the Sun at any time of the year, and (b) the building simulation engine that models the energy production, flow, usage, and control of a building (Xie et al., 2018). See Figure 1 for a screenshot of the Energy3D graphical user interface.

5. Methods

5.1. Methodology

To understand the dynamics of the classroom orchestration within each of the settings, we used a multiple-case study design (Creswell & Plano Clark, 2018). Given that the goal of our study was to identify similarities and differences of classroom orchestration along with their effects in science and engineering learning, a cross-case analysis approach was deemed appropriate. According to Baxter and Jack (2008), a cross-case analysis is used when the researcher wants to identify differences within and between cases. Specifically, we selected three cases, one at the middle school level, one at the high school level, and one with pre-service teachers, as these are critical contexts for engineering integration in science at the K-12 level (NRC, 2009). Each of the cases was considered the unit of analysis (Baxter & Jack, 2008). A cross-case analysis approach enabled us to explore differences within and across cases, where our goal was to examine orchestration and learning outcomes across cases (Yin, 2009). The use of multiple cases or units of analysis was

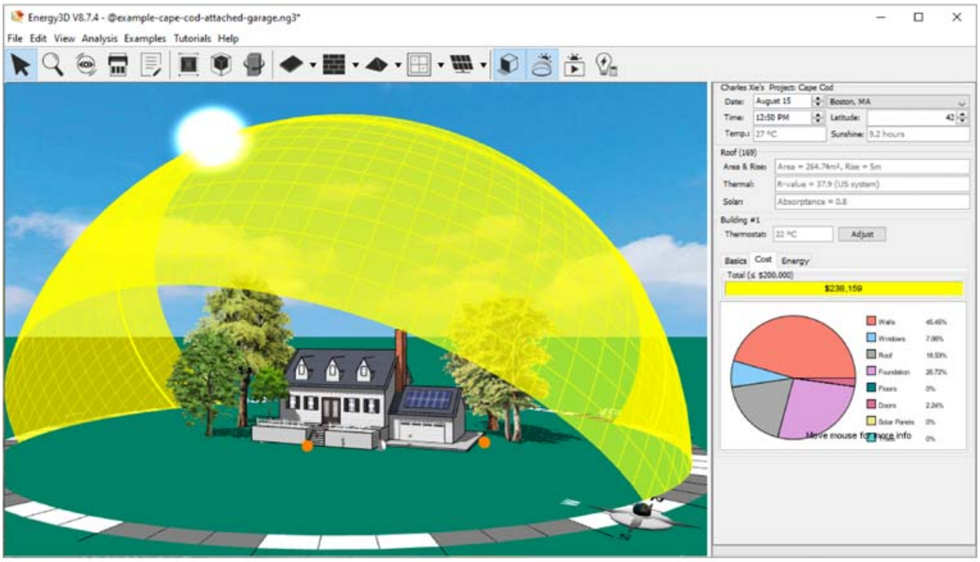

Figure 1. Screenshot of the Energy3D graphical user interface.

therefore used as a strategy for identifying contextual variations (Patton, 2002). Each case was first analyzed thoroughly as an independent unit of analysis. Then, we compared cases to establish the range of generality of the cases, as well as the conditions under which those findings occurred (Miles & Huberman, 1994). The following sections describe the details of the methods, including context and participants, as well as data collection and analysis methods.

5.2. Participants and context

We used purposive sampling methods to choose a representative population consisting of middle school science students, high school science students, and pre-service teacher science students, providing a wide range of K-12 contexts where engineering practices have recently been adopted. Both the middle and high school populations were located in the same school district in a mid-Atlantic state. Both populations were chosen because of its strong engineering pathway, offering engineering electives at middle and high school levels. The state had recently revised curricular frameworks and standards to include engineering into K-12 science standards. The pre-service teacher population was selected from a Midwestern higher education institution. This course was selected because it was recently redesigned to include outcomes focused on the integration of science learning with engineering practices. Based on these sampling procedures, the contexts of this study were three different science classes, one at the middle-school level (n=71), one at the high-school level (n=30), and one at the undergraduate level with a population of pre-service teachers from an elementary education program (n=51). The middle school students were enrolled in four earth and science classes at the same school, and the classes mirrored the demographics of the school, with 35.3% Black, 16.2% Hispanic/Latino, 36.2% White students, 5.3% Asian/Pacific

Islander/Hawaii, and 7.0% Multi-Racial or other races with 50.3% of the students receiving free or reduced lunch. The high school participants were enrolled in two environmental science classes taught by the same teacher. The classes mirrored the demographics of the school, with 29.0% Black, 12.3% Hispanic, 46.1% White students, 6.1% Asian/Pacific Islander/Hawaii, and 6.5% Multi-Racial or other races, with 39% of students receiving free or reduced lunch. The demographics of the pre-service teacher population mirrored the demographics of the university's population, with 8.5% Asian, 2.9% Black or African American, 5.2% Hispanic or Latino/a/x, 64.0% White, 13.7% non-resident alien, 0.1% American Indian or Alaska Native, 0.1% Native Hawaiian or other Pacific Islanders, and 5.5% with ethnicity unknown. Data collected for this study occurred in the Spring of 2019 and Fall of 2019.

5.3. Data sources

Data collection consisted of document analysis of the lesson plans to capture the details of the instructional design, classroom observations to identify the details of the classroom orchestration, and member checking with each of the teachers and instructors from each course to validate the accuracy of our observations. The case documentation was performed by a researcher who coordinated the lesson implementation and who also was present at the time the delivery of the lesson took place.

Data sources also included pretest and posttest assessments of specific concepts in solar/Earth science (e.g. angle of incidence and seasonal variation) and heat transfer (e.g. thermal radiation and surface area of transfer). Assessment items consisted of multiple-choice questions. For specific assessment items, please refer to Appendix D. Assessment items were originally selected from green building applied science textbooks (e.g. Hens, 2011) and aligned with the project learning context. The assessment was piloted through prior studies (Dasgupta et al., 2019; Xie, et al., 2018; Chao et al., 2017). These prior analyses enabled the team to identify questions that demonstrated minimal pre/post differences or similarly exhibited skewed responses (mostly correct, mostly incorrect) and improve questions for the present implementation. That question analysis and final selection of items were performed jointly by all researchers as part of a working session. The assessments were given at the beginning and end of the unit across all cases. Pre/post assessments were used as evidence regarding the effectiveness of how each unit was orchestrated. Students' final design performance from the CAD simulation environment was also collected as a measure of design achievement. Validity and reliability considerations for the data collection methods are discussed in Section e.

5.4. Data analysis

To describe the classroom orchestration that happened in each case, we followed Nussbaum and Diaz proposed framework for classroom logistics for integrating digital and non-digital resources. Nussbaum and Diaz (2013) suggested that in order to identify the effect of classroom logistics on learning, it is important to detail the way teachers structure their classes and the actions they perform when they play that out into the classroom. In their framework, Nussbaum and Diaz (2013) identified three elements of classroom orchestration: context, aim, and specification. While context and aim determine the orchestration conditions, the specification defines the orchestration itself. Each case was thoroughly analyzed individually under this framework, and then, we compared the cases by looking at each specific dimension of the framework.

Pretest and posttest assessments were scored whether students responded correctly or incorrectly, with one point per correct response. Descriptive statistics were used to identify measures of central tendency and spread. Inferential statistics (paired t-tests) were used to identify any learning gains.

The design solutions were scored with a rubric assessing the following project criteria: size, cost, and net energy produced at the end of the challenge. These design criteria are summarized in Table 1.

As observed in Table 1, each classroom implementation defined their own design criteria and constraints. To assess design performance, we first identified how well students met the design constraints (%) according to each implementation's criteria. From each final design, we extracted the data for size, cost, and net energy from students' final designs. Then, we normalised the size, cost, and net energy based on the rubric presented in Table 2. Students whose designs were outliers or did not meet the size or cost constraints were assigned a value of zero. Students were also assigned a value of zero if they had positive net energy, as a sign of not having an energy-efficient house.

5.5. Validity, reliability, and trustworthiness considerations

To address validity, reliability, and trustworthiness considerations, we implemented the following strategies. First, the lesson design was jointly designed by all the authors of this manuscript, with combined expertise in learning sciences, science education, engineering education, and learning design and technology. In addition, external feedback was provided by an advisory committee with expertise in discipline-based education research, educational psychology, and learning systems. This lesson was also piloted and revised as part of previous studies (Dasgupta et al., 2019). Second, each classroom orchestration performed by teachers and instructors was documented by each researcher who was also involved in the instructional design of the unit. To validate the accuracy of the observations, member checking was performed with each of the teachers and instructors from each context. This included the processing of validating notes and asking additional clarification questions. The same researchers were in charge of coordinating the lesson implementation within each classroom setting and were also present at the time the delivery of each lesson took place. Third, all learning materials and assessments were jointly designed by all authors. The internal consistency of the assessment as measured by Cronbach's alpha coefficient was 0.32, which is considered low. This can be due to a low number of questions, low inter-relatedness between items, or heterogeneous constructs (Taber, 2018; Tavakol & Dennick, 2011). For this study, it was not expected the internal consistency (i.e. item equivalence) of the assessment be high because of the

Table 1. Design criteria and constraints for three classroom cases.

Case	Size (m^2)	Cost ($)	Energy Consumption (kWh)
Middle-School Students	100-200	150,000	≤0
High-School Students	100-200	150,000	≤0
Pre-Service Teachers	150-200	120,000	≤0

Table 2. Rubric for calculating students' final design performances.

Criterion	Normalised Size	Normalised Cost	Normalised Net Energy	Final Design Performance
Formula	Size/ (highest constraint for size)	Cost/ (highest limit for cost constraints)	Net energy/ (Highest net energy produced by the same group of students)	Normalised Size/3 +Normalised Cost/3 +Normalised Net Energy/3

different science concepts tested. However, additional tests of face validity and construct validity were used to gauge how good the assessment was at measuring the concepts of Earth science, renewable energy, and heat transfer. Specifically, assessment questions were further reviewed by experts from an advisory board with research programs in engineering design, science education, and learning sciences. Also, learning materials and assessments were pilot tested and subsequently refined from previously implemented assessments in another study (Magana et al., 2019). Finally, for scoring the final design performance, two researchers used a rubric in Table 1 that was piloted as part of another study (Seah et al., 2020). Two raters in the Seah et al. (2020) study applied inter-rater reliability procedures to jointly score the entire sample of students' design solutions until both reached an agreement. The same two raters jointly scored the full sample of final design solutions for this study.

6. Results - classroom orchestration

Following a case study approach, we first applied within-case analysis to describe each of the cases individually to provide a deeper look at how the classroom orchestration occurred from design to implementation (Schwandt, 2014). Our theoretical framework guided this exploration by describing how the instructional design was embodied in three different classroom orchestrations. The classroom orchestrations were described in terms of context, aim, and specification, as prescribed by Dillenbourg (2013). Then, we present a cross-case comparison to identify similarities and differences across cases (Schwandt, 2014). Finally, we present the learning effects from each of the implementations in the form of measured science learning, as well as design performance.

6.1. Within-case analysis of individual cases

We first performed an in-depth exploration of the middle-school student classroom (Case 1), the high-school student classroom (Case 2), and the pre-service teacher classroom (Case 3).

6.1.1. Classroom Orchestration of Case 1: middle-school student classroom

Context. Case 1 consisted of the middle school participants who were enrolled in four Earth science classes at the same school with the same teacher in a mid-Atlantic state. The state had recently revised curricular frameworks and standards to include engineering into K-12 science standards. The Earth Science class focused on Earth's composition, structure, processes, and environment in space, including weather and climate, and utilising Earth's resources. As an introduction to these topics, the students engaged in a scaffolded design project to create a net energy zero home. The duration of the project included two 45-minute class periods and two 75-minute block periods. Students (n=71) worked in small groups, typically pairs with some groups of three.

Aim. Case 1 aimed to help students understand basic Sun-Earth relationships such as seasons and Earth's tilt, how the Sun's position in the sky affects the amount of available solar energy, and apply that understanding to design energy-efficient homes. The project was explicitly sought out by the teacher as they wanted to integrate an engineering design project in their class. The project provided guidance about engineering design practices such as problem definition, conducting research, generating and testing designs, and evaluating and refining designs. The aim was for students to learn about Earth science topics by learning and applying concepts through the design project.

Specification. The Net-Zero Energy Home Design Challenge (i.e. a challenge about building a house that would use less energy to heat and cool than would be generated from solar panels) was based upon knowledge integration (Chiu & Linn, 2011; Linn & Eylon, 2006) and informed engineering design (e.g. Burghardt & Hacker, 2004; Crismond & Adams, 2012) perspectives. Knowledge integration (KI) values the connections that students build among ideas across time. KI instructional patterns encourage students to elicit prior knowledge, add normative ideas through investigations with simulations and the physical world, distinguish among ideas by evaluating productive and unproductive ideas, and reflecting and sorting out ideas and connections. Informed engineering design stresses an intentional approach to design, helping students to focus on developing relevant knowledge and skills instead of mindless construction. The planned activities for the unit for Case 1 are presented in Figure 2.

The project instantiated the guiding frameworks through an online interactive notebook in Google Docs. The notebook guided students through four different mini-challenges. Challenge 1 involved building a house that costs under $150,000 with an area of 100-200 square meters and a height of at least 6 meters. Challenge 2 involved reducing the annual net energy of the home by at least 500kWh without using any solar panels by using passive solar strategies. Challenge 3 involved trying to maximize the energy from a single solar panel, and Challenge 4 involved putting everything together by building a net-zero energy house. In each mini-challenge, there were explicit steps to help students engage in different design practices. For example, at the beginning of each mini-challenge, specifications, and constraints of the challenge were listed with places for students to elicit ideas or ask questions about the criteria. Resources such as videos or relevant websites were linked for students to conduct research about the specific learning goals of the mini-challenge. The notebook served as a place for students to record and explain their design choices in Energy3D. Within Challenge #3, the notebook also guided students to share and

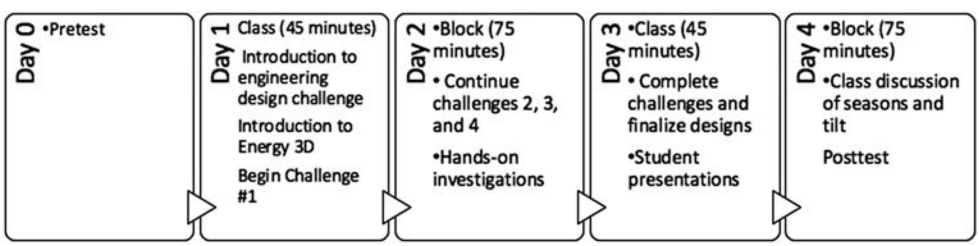

Figure 2. Planned activities for the duration of the unit for Case 1.

compare their designs with another group. The notebook also guided students through a hands-on investigation with a solar panel, LED, and a flashlight to investigate how the angle of the solar panel affects the amount of energy it captures. Students also used the notebook to prepare a class presentation of their final design.

Students took the pretest in a class directly preceding the start of the project. On the first day, students were introduced to the overall design challenge of building a net energy zero home, discussed engineering design practices, and an instructor modelled the use of Energy3D. With the remaining time, students began the challenges in Energy3D. Day two was a block period of 75 minutes where students continued designing in Energy3D and making notes in their notebooks. Some students conducted hands-on investigations with the solar panels. On day three, during a class of 45 minutes, students finished their designs and presented them to the class. On day 4, a block period of 75 minutes, the teacher engaged students in a reflection and discussion about concepts of seasons and Earth's tilt, and gave students the posttest. As an extra activity, the teacher felt it was important for the students to be able to build physical models of their designs. After the posttest, students physically built their designed houses from cutouts of the exported designs in the cardstock.

As each student group was working at their own pace, different groups were at different phases and challenges at different times. Thus, some of the student groups skipped some challenges (mainly challenge 3) and went straight to the final challenge of building a net-energy zero home by optimising the number and placement of solar panels, windows, trees, as well as optimising the design of their homes.

6.1.2. Classroom Orchestration of Case 2: high-School student classroom

Context. Case 2 consisted of the high school participants who were enrolled in two environmental science classes taught by the same teacher. This case was implemented in the Spring of 2018, and the course focused on students being able to both understand scientific concepts that relate to the environment and also to examine solutions for resolving or preventing environmental problems. To support these objectives, the students participated in a scaffolded design project in their regular classroom setting over five consecutive class blocks, with each block lasting approximately 90 minutes. There were 30 students in the class, and they participated in 17 small groups (usually pairs) on the same activities (i.e. there was no control group).

Aim. The scaffolded design project aimed to support students to develop an integrated understanding of how concepts such as energy transfer and the Earth's rotation could be used to create efficient renewable energy solutions. While the students may have been familiar with some of the concepts prior to this project, the aim was for students to be able to draw upon their current understanding to create design solutions. Explicit guidance was provided to students about the design cycle stages, such as understanding the specifications, developing knowledge about relevant concepts, ideating and building designs, testing designs, and evaluating and refining designs. Through this process, it was hoped that students might refine or extend their understanding of the environmental science concepts and the challenge they were given.

Specification. The students participated by completing a series of four scaffolded design challenges using Energy3D, and after each, they used the Web-based Inquiry Science Environment (Slotta & Linn, 2009) to record their designs, share them with

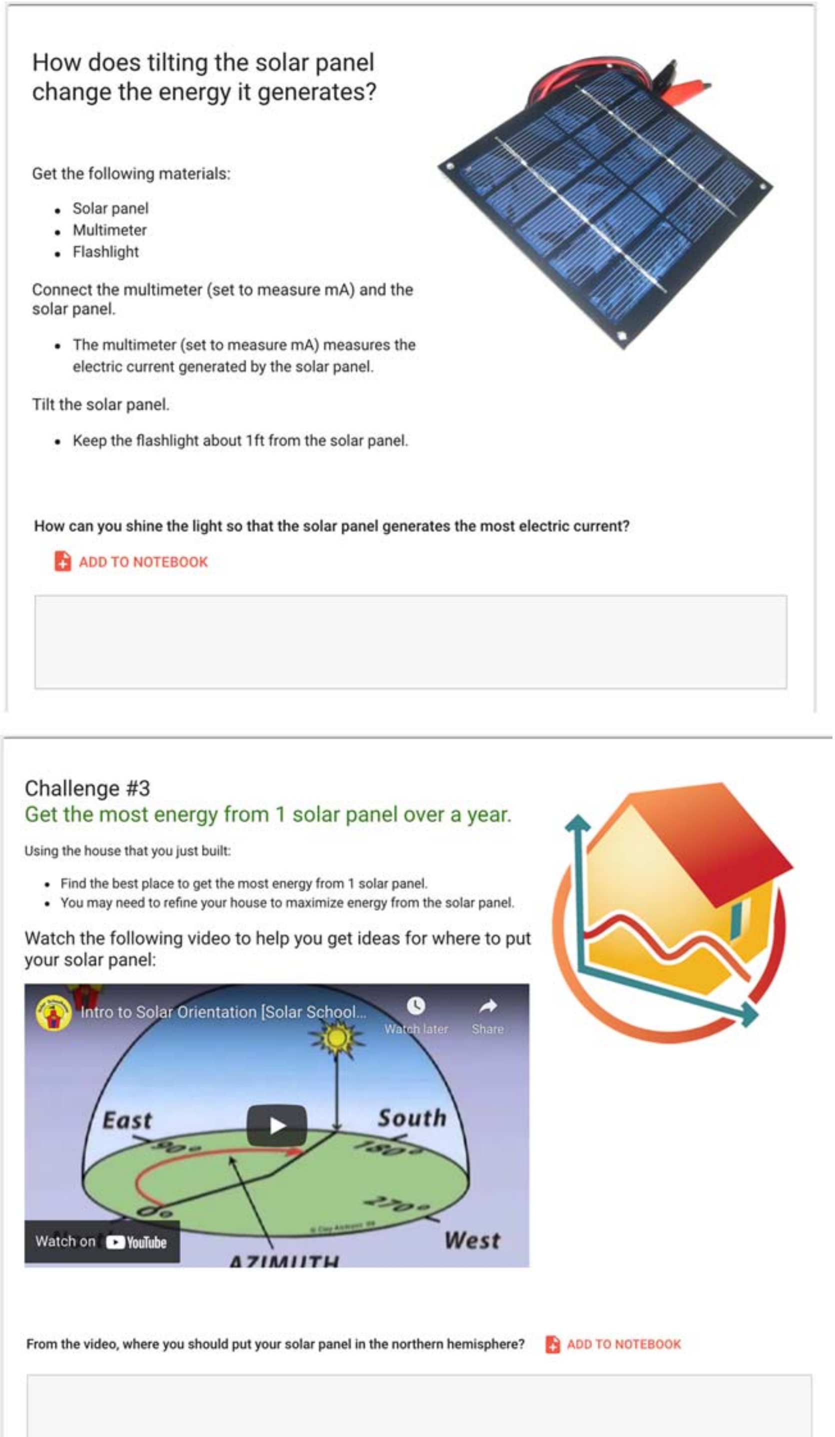

Figure 3. Screenshots of the WISE project website.

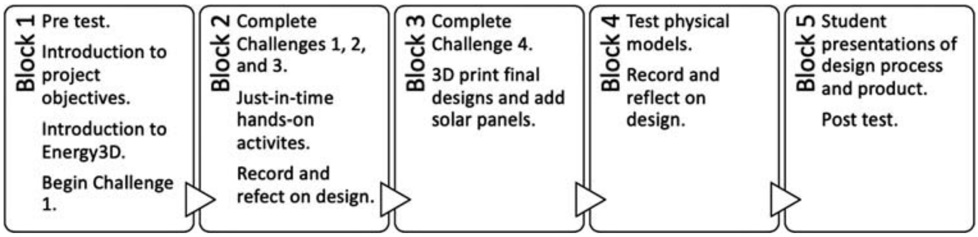

Figure 4. Planned activities for the duration of the unit for Case 2.

their classmates, and answer questions about the rationale for their designs. WISE includes a variety of tools that explicitly support inquiry learning and engineering design projects (Chiu et al., 2013). WISE also includes short tutorial materials available to the students to view as needed. These tutorial materials were about topics such as how solar panels work and how the rotation and orbit of the Earth impact the apparent path of the Sun across the sky. In addition, the students participated in short hands-on activities such as investigating the impact of changing the angle of incidence between a light source and a solar panel (see Figure 3). The classroom teachers and researchers supported students by answering questions or assisting with how to use Energy3D.

The students participated in the project for five consecutive class blocks (see Figure 4). During Block 1, students completed the pretest before being introduced to the overall aim of the project and then to the Energy3D specifically. During Block 2, students used Energy3D to design solutions to each of the first three scaffolded design challenges, recording and reflecting on their designs. During Block 3, students designed solutions for the final design challenge, Challenge 4, and their final designs from Energy3D were printed, so during Block 4, they were able to create and test a physical model that included real solar panels (see Figure 5). The final class, Block 5, was spent with students presenting their design product and process to school administrators and reflecting on their learning. The students also completed the posttest.

The scaffolded design challenges were created to give students opportunities to be successful throughout the project, as well as help students to become familiar with Energy3D in stages. For example, Challenge 1 asked students to build a house in Energy3D within a fixed budget but without any constraints about the energy efficiency of the house. This helped students become familiar with how to add, resize, and remove items in Energy3D, such as walls and windows, and how to use Energy3D to find the cost and size of their designs. Challenge 2 asked students to run the energy analyses with Energy3D and revise their designs in order to improve the energy efficiency of their design without using solar panels. To do this, the students might adjust the size or position of windows, roof overhangs, or nearby trees, or could adjust the location of the house to warmer or colder climates. Challenge 3 asked students to include only one solar panel and adjust its orientation so as to improve the energy efficiency of the house. The final challenge, Challenge 4, then asked students to design a net-zero energy house that met all of these four constraints:

- Energy-efficient: Consume no net energy over a year (try to make the Annual Net Energy as negative as possible).

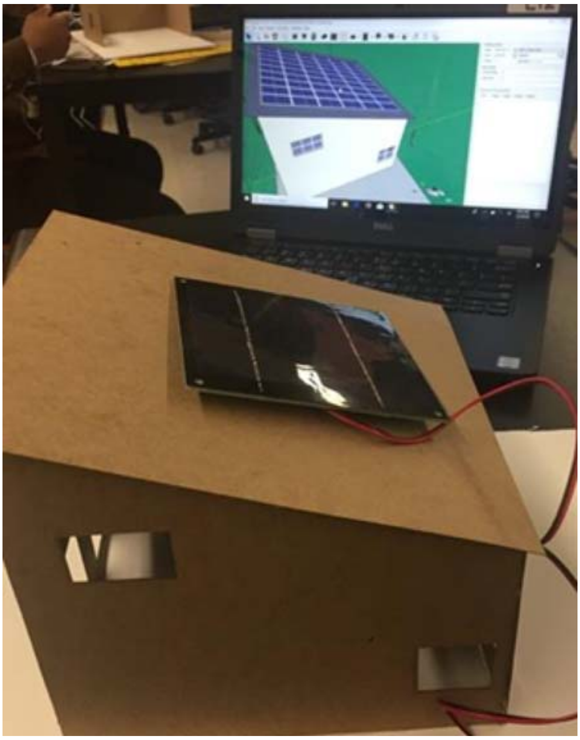

Figure 5. A student design in Energy3D (top right) and the physical model of the design (foreground).

- Cost: The house should not cost more than $150,000.
- Size: The house should comfortably fit a four-person family: Building area 100-200m^2, height to top of roof 6-10 meters.
- Curb appeal: Each side of the house must have at least one window on each wall. Solar panels cannot hang over roof edges.

The constraints were chosen so that while many different design solutions were possible, it was also necessary for students to consider trade-offs, make design revisions, and consider solar science concepts to successfully find solutions. For example, with an unlimited budget, it is a relatively straightforward task to design a house that satisfies the other constraints. However, the budget constraint limits the number of solar panels a student can use in their design, which motivates the need to know where to put the panels to generate the most energy, and therefore the need to know the solar science concepts that underpin these phenomena. Students were assessed using the pre and posttest scores, and on the design solutions after each of the scaffolded design challenges and their reflections on each of their designs.

6.1.3. Classroom Orchestration of Case 3: pre-service teacher classroom

Context. Case 3 was implemented with a population of pre-service teachers who came from a large midwestern university. The pre-service teachers were enrolled in Physics for Elementary Education course during the Fall 2019 semester. This class was chosen for this study as it targeted helping pre-service teachers develop an understanding of physical science concepts. The course outcomes focus on developing practices and ideas outlined in the Project 2061 Benchmarks (AAAS, 1995) and NRC Science Education Standards (NRC, 2012) or content and nature of science focused on middle school learning goals. Specific course objectives were to develop knowledge of (a) physical science, particularly physics concepts, at a deeper level than elementary school, and (b) practices of science and engineering design.

This case was carried out in a Physics for Elementary Education course during the Fall 2019 semester. The course outcomes focus on developing practices and ideas outlined in the Project 2061 Benchmarks (AAAS, 1995) and NRC Science Education Standards (NRC, 2012) or content and nature of science focused on middle school learning goals. Specific course objectives were to develop knowledge of (a) physical science, particularly physics concepts, at a deeper level than elementary school, and (b) practices of science and engineering design. To fulfill these objectives, the unit was carried out in a four-week period. The unit was called: *Integrating engineering design in the physics classroom with Energy3D*. There was a total of 51 students who participated in this study, with 20 students in the control group (i.e. 11:30 am lab session) and 31 students in the experimental group (i.e. 2:30 pm lab session).

This four-week unit took place on week 9, week 10, week 11, and week 12 during the semester. In each week, there was a 50-minute lecture and 2 hours and 50-minute lab session. For this particular unit, lecture time in week nine and week ten were not allocated for this unit. The total number of lectures and lab sessions involved for this unit were two lectures and four lab sessions. Throughout this unit, students were required to work 100% either in the lecture or the lab session. However, students were given two extra days to complete their lab reports if they didn't get to finish them in class.

Aim. The course outcomes were expanded into learning objectives that focused on finer-grained target ideas and that were combined with disciplinary practices to make concepts more understandable and explicit. Thus, the unit was designed around the concepts of heat transfer (i.e. radiation, conduction, and convection), with the goals of helping students to develop (1) a deeper understanding of these concepts, as well as (2) argumentation and design skills, through lectures, physical experiments, and a design challenge using CAD. The disciplinary objective of the unit was: To identify and experiment with the processes of heat transfer, including conduction, convection, and radiation. The skill objective was: To engage in disciplinary practices of science and engineering such as design skills, experimentation skills, and argumentation skills.

Specification. The pedagogical approach used in this unit was a modified engineering design cycle incorporated into a 3E's inquiry learning cycle (Rebello, 2019). The 3E's represented Explore, Explain, and Elaborate. The engineering design cycle was inspired by the approach of Learning by Design ™. The general structure of this unit followed this specific pattern: (a) Explore – students were given time in the lab to explore science concepts through physical experiments, (b) Explain – students were given time in the lecture to discuss and develop an explanation of science concepts with the instructors and with peers, and (c) Elaborate – students were given time in the lab to apply science concepts to design through an engineering design challenge.

Every student in this unit followed this general structure, except for one detail – the scaffold of argumentation. Students from one lab session (i.e. 2:30 pm) were given specific instructions on how to generate effective arguments as well as an argumentation framework (i.e. Claim, Evidence, Reasoning) to guide them through all their in-class activities and assignments such as lab reports. In contrast, students from the other lab session (i.e. 11:30 am) were not. Aside from this difference, students, in general, were required to work both in teams and individually. Specifically, students were told to work in teams when they had a discussion in lectures, when they performed experiments in the lab (i.e. work in pairs), when they worked on their design challenge, including documenting it. On the other hand, students were told to work individually to respond to discussion questions in the lecture by submitting an individual response using i > Clicker, as well as to complete their lab reports.

As mentioned before, this unit included a 50-minute lecture and a 2-hour and 50 minutes lab each week. Specifically, this study started in the lab session on week 1. In this lab, students were given a pretest to assess their existing knowledge on relevant science concepts. Upon completion of the pretest, students were introduced to a design challenge that they needed to work on throughout this unit. The end goal of the design challenge was for students to build an energy-efficient home under certain requirements and constraints. These requirements included building an energy-efficient house whose area should be around 150 – 200m^2 within the budget of $120,000. With the remaining time, students were asked to work on a suboptimal design where they had to revise an existing home by making it energy efficient. The purpose of this activity was to let students familiarise themselves with the tool as well as to get them started on thinking about their design strategies.

In week 2, students spent the entire lab session working on physical experiments related to radiation. As they worked on those experiments, they completed a corresponding lab report. In week 3 when students came back, they spent time in the lecture discussing and reviewing the radiation concepts they worked on the week before. When they went to the lab session in week 3, they worked on physical experiments related to conduction and convection. Again, they completed the corresponding lab report as they went. Figure 6 presents an overview of the lesson implementation.

In week 4, students spent time in the lecture discussing and reviewing the conduction and convection concepts from the week before with the instructor. The goal of doing this was to ensure students' understanding of the topics and to clarify any misconceptions if needed. Finally, in the lab session, students were asked to complete the design challenge where they had to build an energy-efficient home from scratch. Once they were finished

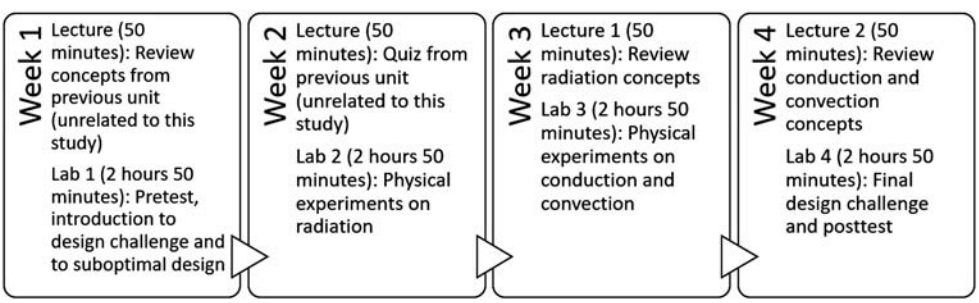

Figure 6. Planned activities for the duration of the unit for Case 3.

with the design challenge, the students concluded the unit by completing a posttest. The figure below depicts the procedures for this unit.

As part of this unit, students were provided with materials to guide their learning. These included CAD software (i.e. Energy3D), four Word lab worksheets, two Excel sheets for data collection during the physical experiments, two PowerPoint templates for students to document their design, and two lecture PowerPoint slides. As a result of their learning, students were required to generate and submit relevant artifacts, which included four lab experiment reports, two data collection Excel sheets, two Energy3D .ng3 files, and two PowerPoint design reports.

Either in class or through their artifact submission, students were provided with both formative and summative assessments. In both the lecture and the lab, students were provided with just-in-time feedback through either question and answer (Q&A) or when the instructors saw a need for feedback or correction. In addition, students were assessed for their i > Clicker responses in lecture (i.e. 3 points each lecture), group discussions (i.e. 5 points each lecture), and lab reports (i.e. 40 points each lab). These artifacts were assessed using a generic rubric that looked at completeness, clarity, and correctness. Students were also provided with written feedback on these submissions if necessary.

6.2. Cross-case analysis of classroom orchestrations

We compare and contrast the three case studies for each of the three dimensions: context, aim, and specification. Our goal is to highlight similarities and differences in the way the same lesson was adopted or adapted for each of the different circumstances, populations, and contexts.

Context. From the three dimensions, context is the one that presents the largest variations. Not only did the target populations of middle school, high school, and pre-service teachers vary, but so did the specific course and intended outcomes where the lesson was implemented. Similarly, while cases 1 and 2 implemented the lesson primarily within the in-class setting, case 3, at the college level, presented a combination of in-class and laboratory delivery. A summary of the dimensions of the contexts for each of the three cases is presented in Appendix A.

Aim. The second dimension compared the aims of the units. While case 1 and case 3 focused on practices of science and engineering, the main goal of case 2 was to acquire disciplinary concepts. Although there were slight differences in the disciplinary objectives adapted to the standards of each of the grade levels, the skill objectives consistently had comparable elements focusing on the development of disciplinary practices in science and engineering. A summary of the dimensions of the aims for each of the three cases is presented in Appendix B.

Specification. The third dimension, specification, presents similarities in terms of how the units were designed but differences in how the unit was implemented for a particular target population. All three cases designed the unit with the framework of Learning by Design™, and some form of inquiry-based learning, such as knowledge integration. However, each case added more specific pedagogical approaches or scaffolding methods to facilitate the integration of science learning and the engineering design processes. A common element across the three cases was the use of some form of teamwork. To promote engagement, each of the three cases also involved the generation of artifacts such as journals, worksheets, or other forms of note-taking and reflective practice. These generative processes were also supplemented with in-class discussion for each of the three cases, and each of the cases included at least one form of summative assessment.

Differences identified in the specification method relate to specific uses of pedagogies and technologies. While for case 1 and case 3, students recorded their observations using traditional methods like journals and worksheets, case 2 used WISEengineering to both structure and scaffold the interaction. On the other hand, cases 1 and 3 included some form of interaction with physical devices. Assessment methods were also more comprehensive for cases 2 and 3. A summary of the dimensions of the specification for each of the three cases is presented in Appendix C.

7. Results about science and engineering learning

7.1 Science learning

The results of the students for each of the three cases regarding their performance in the pre-post science assessment are displayed in Table 3. The assessment had six total items, with each item scored as one or zero, leading to possible scores ranging from zero to six. Pretest and posttest means are normalised, so they reflect percent correct. Students were dropped from analysis if they had missing data. All groups had scores below 50% at the pretest and made gains toward 50% in their posttest scores. More specifically, pre-service teachers had a pretest mean score of 41% (SD=1.38) and a posttest mean score of 45.7% (SD=1.20). A paired t-test (t=1.07) revealed no significant difference from pre to post (p=.29). On the other hand, high school students had a pretest mean of 37% (SD=.80) and posttest mean score 47.2% (SD=1.27), with a paired t-test revealing significant growth in their science understanding (p=.027). Note that results from the high school students should be interpreted with caution given the low sample size. Finally, middle school students had a pretest mean of 37% (SD=1.13) and a posttest mean score of 44.2% (SD=1.49) with a paired t-test revealing significant growth in their science understanding at below .05 (p=.047). These findings should also be interpreted with caution, given the large portion of missing data. While pre-service teachers did not exhibit learning gains that were statistically significant, it is worth noting that their pretest mean scores were higher than the high school and middle school students at a descriptive level. However, a subsequent one-way ANOVA between the pretest scores for the three groups revealed no significant differences F=.53 (p=.59). This suggests all three groups started with roughly the same science knowledge. A similar one-way ANOVA between posttest scores for the likewise revealed no significant differences F=.12 (p=.88), suggesting student groups arrived at similar levels of understanding post-intervention. Lastly, while acknowledging differences among the cases' orchestration, an

Table 3. Change in students' science understanding.

Group	N	Pretest Mean	Std. Dev.	Posttest Mean	Std. Dev.	Paired t-test t	p-value
Middle-School Students	37	37%	1.13	44.2%	1.49	2.05	.047
High-School Students	23	37%	.80	47.2%	1.27	2.37	.027
Pre-service Teachers	46	41%	1.38	45.7%	1.20	1.07	.29
All Groups	106	38.7%	1.18	45.5%	1.31	2.77	.007

aggregate analysis of all students revealed they had a pretest mean of 38.7% (SD=1.18) and a posttest mean of 45.5% (SD=1.31) revealing significant growth in the aggregate groups scientific understanding (p=.007).

7.2. Design performance

Students' ability to meet the design constraints was assessed for each case. This was done by calculating the percentage of students who were able to meet each design constraint in terms of size, cost, and energy consumption (see Table 1). For example, 26 out of 33 middle-school students were able to meet the size constraint (i.e. 100-200m^2, which resulted in a score of 79% success rate. Table 4 presents the percentage of students meeting the design constraints for each case.

Middle school students were more successful in meeting the size (79%) and cost (73%) requirements as compared to energy consumption (15%). On the other hand, high-school students were more successful in meeting the size (80%) and energy consumption requirements (73%), as compared to the cost (7%). Pre-service teachers, similarly, were more successful in meeting the size (74%) and energy consumption requirements (61%) compared to the cost (9%). Comparison across three cases suggest that high-school students were the most successful in meeting both the size and energy consumption requirements; middle-school students were most outstanding in meeting the cost requirement, and the pre-service teachers' design were the ones who were able to better balance all requirements and constraints.

To get a better idea of how students' ability in meeting design criteria related to their final design performance, performance in the final design was calculated using the design criteria presented in Table 2. For this, students' performance in each case was compared only with other students' performance within the same case. We did not compare one case with the other as each case had different design constraints and limitations. Table 5 details the mean scores for normalised size, cost, net energy, and final design performances for all three cases.

Our findings indicate that middle-school students had better mean scores for final design performances (46%) as compared to the high-school and pre-service teachers. Middle-school

Table 4. Percentage of students meeting the design constraints for each case.

Case	# of Groups	Size (%)	Cost (%)	Net Energy (%)
Middle-School Students	33	79%	73%	15%
High-School Students	15	80%	7%	73%
Pre-Service Teachers	23	74%	9%	61%

Table 5. Students' Mean size, cost, net energy and final design performances.

Case	# of Groups	Normalised Size Mean (%)	Normalised Cost Mean (%)	Normalised Net Energy Mean (%)	Final Design Performance Mean (%)
Middle-School Students	33	54%	70%	13%	46%
High-School Students	15	50%	6%	30%	29%
Pre-Service Teachers	23	77%	8%	20%	35%

students were also more successful at meeting the budget constraints than the students in the other two cases. However, they struggled the most when making their house energy efficient. On the other hand, high-school students were the most successful in making their house energy efficient, but they had difficulties meeting the budget constraints. However, as observed in Table 4, only one of the high school students made a house within the given cost limit with their normalised mean calculated as 6%. In contrast, pre-service teachers were more successful at meeting the size constraints. However, they had difficulty making their house cost-efficient as their budget constraints were harder to meet as compared to middle-school students. In terms of normalised size mean, pre-service teachers were more successful at meeting the size constraints. For making houses cost-efficient, middle-school students were exceptional. In the achievement of building an energy-efficient house with zero or negative net energy, high-school students were remarkable. Overall final design performances mean show that middle-school students had better performance while designing an energy-efficient house. In summary, our findings in Table 4 and Table 5 suggest that students' success rate in meeting the design constraints had a direct positive influence on their final design performance.

8. Discussion and implications

Prior work has suggested that a proper combination of supports and the use of technology in the classroom can be an effective and viable pedagogy for teaching science with technology (Khan, 2011). However, how to properly design learning interventions, and more importantly, how to actually adapt and deliver them for classroom implementation, is a complex task (Dillenbourg, 2013). The results from this study present three cases of classroom orchestration for three different target audiences and contexts, using the same learning design that aimed at integrating science knowledge and engineering practices enabled by the use of computer simulations. While the literature on the use of computer simulations in the classroom has primarily focused on their effectiveness for learning (D'Angelo et al., 2014; Jimoyiannis & Komis, 2001; Smetana & Bell, 2012), not as much emphasis has been placed on classroom orchestration. In this regard, this study started with a flexible learning design that initially aligned the intended learning outcomes with evidence of the learning and was coordinated following a feasible pedagogical approach (Wiggins & McTighe, 1997). Specifically, the learning goal was to promote science content with engineering practices by engaging students in design challenges enabled by CAD simulations.

Although the classroom orchestration of the particular learning design was adapted for specific audiences and contexts, findings from this study suggest that the core components of the learning design and their alignment resulted in student learning. For all contexts, students increased their knowledge of targeted science concepts and were able to produce feasible designs. For instance, middle school students were able to perform as well as undergraduate students in terms of design performance and pre/posttest gain. These results speak to the potential and importance of providing these kinds of experiences to younger students. However, students also benefited in different ways, perhaps due to emphasis placed on different elements as part of the classroom orchestration and the specific scaffolding they received (knowledge integration, argumentation). Specifically, differences from pretest to posttest may be due to how the instruction around the science concepts was orchestrated across the three cases. For both the middle and high school cases, science concepts were embedded and very contextualised on the design project by using four sub-challenges. Scaffolding the design of the big challenge in sub-challenges might have helped middle school and high school students gain disciplinary knowledge (Sadler et al., 2000). For example, the hands-on investigations for the high school class involved thinking about solar radiation and angles of solar panels when students were trying to maximize energy to the solar panels. In contrast, the pre-service teachers had more traditional investigations in the form of laboratory experiments where they learned about energy transfer that they then had to apply (and transfer the knowledge) to the context of designing an energy-efficient home. As the assessments were grounded in the context of the design project, it is not surprising that the middle and high school students performed better than the pre-service teachers. However, results might be different with a more generalised and less contextualised assessment.

In terms of engineering design performance, the classroom orchestration may also have had an impact on what students identified the most relevant criteria to meet in their design solutions (e.g. pre-service teachers were posed with constraints that were harder to meet). Specifically considering the idea of design trade-offs, different groups focused on attaining different constraints. For instance, it can be observed that middle school students focused a lot on the size of the building and did not pay a lot of attention to energy efficiency. In contrast, high school and pre-service teachers presented design solutions that performed better in final energy consumption. These results also resonate with potential differences between 'engineering design-based science' and science (Bethke Wendell & Rogers, 2013). Engineering science can be conceptualised as the science that is needed to complete an engineering project, which can be different than how a scientist or science educator may conceptualise the content. For example, middle and high school students focused on the relationships between the Sun-Earth system to understand where to place solar panels and windows, representing 'engineering design-based science' or the science needed to complete the project. They did not, however, talk about the underlying processes of radiation, convection, and conduction that govern energy transfer within buildings (e.g. the underlying science). Results suggest the need for further investigation and articulation for how engineering science may differ from traditional science investigations within engineering projects and the implications for how to design and orchestrate these kinds of activities within classrooms.

Other implications include how the design of curricular materials can support teachers to adopt and/or adapt specific parts depending on their audience, context, and setting and the importance of using a classroom orchestration lens to investigate how the materials are enacted. Given that teachers can choose to use curricular materials as-is, adapted, or remixed to fit particular learning settings (e.g. Remillard, 2005), results highlight the potential benefit of providing flexible curricular materials that can be customised by different instructors. For instance, while middle school and high school students were able to have continuous exposure to the learning experience on a daily basis, the orchestration for the pre-service teacher population had to fit a 50-minute weekly lecture with a two-hour weekly lab. Thus, instructors had different constraints on how they could enact the project. Using a classroom orchestration framework enabled a comparison of how these learning materials were used across settings.

9. Conclusions

Educational researchers have argued that the generalizability of the design of learning interventions guided by theory requires taking into consideration aspects of the curriculum, assessment, time, teacher effort, learning spaces, and safety constraints (Dillenbourg & Jermann, 2010). This emphasis on generalizability calls for a shift to balance between more idealistic learning designs and how those actually play out in the classroom and the corresponding learning impact (Roschelle et al., 2013). Classroom orchestration focuses precisely on the adoption, scale, and impacts of learning interventions. In this study, we have specifically addressed the need for more empirical research on the integration of domain-specific computer technologies for engineering practice in the context of science classrooms (Koretsky & Magana, 2019), such as Energy3D. We described three different case studies that adopted the same learning design and adapted it to particular populations, settings, and contexts. Although this study has limitations regarding strong learning effects or the lack of detailed classroom observations, we believe that the results from classroom assessments suggest that by following proper integration of scaffolding and guidance, students from all the cases were able to gain science understanding and deliver feasible design solutions.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethical Approval

This study received ethical approval from the Institutional Review Boards of the three participating institutions.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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References

[AAAS] American Association for the Advancement of Science. (1995). *Project 2061: Science literacy for a changing future, a decade of reform*. ERIC Clearinghouse.

[NRC] National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. National Academy Press.

[NRC]. (2009). *Engineering in K-12 education: Understanding the status and improving the prospects*. National Academies Press.

Baxter, P., & Jack, S. (2008). Qualitative case study methodology: Study design and implementation for novice researchers. *The Qualitative Report*, *13*(4), 544–559. https://doi.org/10.46743/2160-3715/2008.1573

Bethke Wendell, K., & Rogers, C. (2013). Engineering design-based science, science content performance, and science attitudes in elementary school. *Journal of Engineering Education*, *102*(4), 513–540. https://doi.org/10.1002/jee.20026

Brown, P. (2009). CAD: do computers aid the design process after all? *Intersect: The Stanford Journal of Science, Technology and Society*, *2*(1), 52–66. https://ojs.stanford.edu/ojs/index.php/intersect/article/view/117

Burghardt, M. D., & Hacker, M. (2004). Informed design: A contemporary approach to design pedagogy as the core process in technology. *Technology teacher*, *64*(1), 6–8. https://eric.ed.gov/?id=EJ706287

Chang, Y. (2014). 3D-CAD effects on creative design performance of different spatial abilities students. *Journal of Computer Assisted Learning*, *30*(5), 397–407. https://doi.org/10.1111/jcal.12051

Chao, J., Xie, C., Nourian, S., Chen, G., Bailey, S., Goldstein, M. H., Purzer, S., Adams, R. S., & Tutwiler, M. S. (2017). Bridging the design-science gap with tools: Science learning and design behaviors in a simulated environment for engineering design. *Journal of Research in Science Teaching*, *54*(8), 1049–1096. https://doi.org/10.1002/tea.21398

Chiu, J., Gonczi, A., Fu, X., & Burghardt, M. (2017). Supporting Informed Engineering Design across Formal and Informal Contexts with WISEngineering. *International Journal of Engineering Education*, *33*(1), 371–381. https://www.ijee.ie/covers/covandabs33-1B.pdf

Chiu, J. L., & Linn, M. C. (2011). Knowledge integration and wise engineering. *Journal of Pre-College Engineering Education Research (J-PEER)*, *1*(1), 2. https://doi.org/10.7771/2157-9288.1026

Chiu, J. L., Malcolm, P. T., Hecht, D., DeJaegher, C. J., Pan, E. A., Bradley, M., & Burghardt, M. D. (2013). WISEngineering: Supporting pre-college engineering design and mathematical understanding. *Computers & Education*, *67*, 142–155. https://doi.org/10.1016/j.compedu.2013.03.009

Chiu, J., & Linn, M. C. (2014). Supporting knowledge integration in chemistry with a visualization-enhanced inquiry unit. *Journal of Science Education and Technology*, *23*(1), 37–58. https://doi.org/10.1007/s10956-013-9449-5

Creswell, J. W., & Plano Clark, V. (2018). *Designing and conducting mixed methods research*. SAGE Publications, Inc.

Crismond, D. P. (2011). Scaffolding strategies for integrating engineering design and scientific inquiry in project-based learning environments. In M. Barak & M. Hacker (Eds.), *Fostering human development through engineering and technology education* (pp. 233–255). Brill Sense.

Crismond, D. P., & Adams, R. S. (2012). The informed design teaching and learning matrix. *Journal of Engineering Education*, *101*(4), 738–797. https://doi.org/10.1002/j.2168-9830.2012.tb01127.x

D'Angelo, C., Rutstein, D., Harris, C., Bernard, R., Borokhovski, E., & Haertel, G. (2014). *Simulations for STEM learning: Systematic review and meta-analysis.* SRI International.

Dasgupta, C., Magana, A. J., & Vieira, C. (2019). Investigating the affordances of a CAD enabled learning environment for promoting integrated STEM learning. *Computers and Education*, *129*, 122–142. https://doi.org/10.1016/j.compedu.2018.10.014

Davis, E. A., & Varma, K. (2008). Supporting Teachers in Productive Adaptation. In Y. Kali, M. Linn, & J. E. Roseman (Eds.), *Designing Coherent Science Education: Implications for Curriculum, Instruction, and Policy* (pp. 94–122). Teachers College Press.

de Jong, T., & van Joolingen, W. R. (1998). Scientific discovery learning with computer simulations of conceptual domains. *Review of Educational Research*, *68*(2), 179–201. https://doi.org/10.3102/00346543068002179

Dickerson, S. J., & Clark, R. M. (2018). A classroom-based simulation-centric approach to microelectronics education. *Computer Applications in Engineering Education*, *26*(4), 768–781. https://doi.org/10.1002/cae.21918

Dillenbourg, P. (2013). Design for classroom orchestration. *Computers & Education*, *69*, 485–492. https://doi.org/10.1016/j.compedu.2013.04.013

Dillenbourg, P., & Jermann, P. (2010). Technology for classroom orchestration. In M. S. Khine, & I. M. Saleh (Eds.), *New science of learning: Cognition, computers and collaboration in education* (pp. 525–552). Springer.

Fang, N., & Tajvidi, M. (2018). The effects of computer simulation and animation (CSA) on students' cognitive processes: A comparative case study in an undergraduate engineering course. *Journal of Computer Assisted Learning*, *34*(1), 71–83. https://doi.org/10.1111/jcal.12215

Goldstein, M. H., Purzer, Ş, Adams, R. S., Chao, J., & Xie, C. (2019). The relationship between design reflectivity and conceptions of informed design among high school students. *European Journal of Engineering Education*, *44*(1-2), 123–136. https://doi.org/10.1080/03043797.2018.1498458

Goldstein, M. H., Vieria, C., Adams, R. S., Purzer, Ş, & Zielinski, M. K. (2016). Developing a measure of quality for engineering design artifacts. Conference Proceedings: *Frontiers in Education (FIE) Annual Conference*, Erie, PA.

Gonczi, A. L., Chiu, J. L., Maeng, J. L., & Bell, R. L. (2016). Instructional support and implementation structure during elementary teachers' science education simulation use. *International Journal of Science Education*, *38*(11), 1800–1824. https://doi.org/10.1080/09500693.2016.1217363

Graff, N. (2011). An effective and agonizing way to learn": backwards design and new teachers' preparation for planning curriculum. *Teacher Education Quarterly*, *38*(3), 151–168. https://www.jstor.org/stable/23479622

Hennessy, S., Wishart, J., Whitelock, D., Deaney, R., Brawn, R., Velle, L. l., McFarlane, A., Ruthven, K., & Winterbottom, M. (2007). Pedagogical approaches for technology-integrated science teaching. *Computers & Education*, *48*(1), 137–152. https://doi.org/10.1016/j.compedu.2006.02.004

Hens, H. (2011). *Applied Building Physics*. Ernst & Sohn.

Higgins, T. E., & Spitulnik, M. W. (2008). Supporting teachers' use of technology in science instruction through professional development: A literature review. *Journal of Science Education and Technology*, *17*(5), 511–521. https://doi.org/10.1007/s10956-008-9118-2

Hsu, Y. S. (2008). Learning about seasons in a technologically enhanced environment: The impact of teacher-guided and student-centered instructional approaches on the process of students' conceptual change. *Science Education*, *92*(2), 320–344. https://doi.org/10.1002/sce.20242

Jimoyiannis, A., & Komis, V. (2001). Computer simulations in physics teaching and learning: a case study on students' understanding of trajectory motion. *Computers & Education*, *36*(2), 183–204. https://doi.org/10.1016/S0360-1315(00)00059-2

Khan, S. (2011). New pedagogies on teaching science with computer simulations. *Journal of Science Education and Technology*, *20*(3), 215–232. https://doi.org/10.1007/s10956-010-9247-2

Kim, M. C., & Hannafin, M. J. (2011). Scaffolding problem solving in technology-enhanced learning environments (TELEs): Bridging research and theory with practice. *Computers & Education*, *56*(2), 403–417. https://doi.org/10.1016/j.compedu.2010.08.024

Kolodner, J. L. (2002a). Facilitating the learning of design practices: Lessons learned from an inquiry into science education. *Journal of Industrial Teacher Education*, *39*(3), 9–40. https://eric.ed.gov/?id=EJ782298

Kolodner, J. L. (2002b). Learning by design™: Iterations of design challenges for better learning of science skills. *Cognitive Studies*, *9*(3), 338–350. https://doi.org/10.11225/jcss.9.338

Kolodner, J. L., Camp, P. J., Crismond, D., Fasse, B., Gray, J., Holbrook, J., Puntambekar, S., & Ryan, M. (2003). Problem-based learning meets case-based reasoning in the middle-school

science classroom: Putting learning by design (tm) into practice. *The journal of the learning sciences*, *12*(4), 495–547. https://doi.org/10.1207/S15327809JLS1204_2
Kolodner, J. L., Crismond, D., Gray, J., Holbrook, J., & Puntambekar, S. (1998). *Learning by design from theory to practice* [Paper presented]. The Proceedings of the international conference of the learning sciences.
Koretsky, M. D., & Magana, A. J. (2019). Using technology to enhance learning and engagement in engineering. *Advances in Engineering Education.* Invited Manuscript for Special Issue on Innovation through Propagation: A Roadmap for Engineering Education. 7(1) p. 1-53.
Lawless, K. A., & Pellegrino, J. W. (2007). Professional development in integrating technology into teaching and learning: Knowns, unknowns, and ways to pursue better questions and answers. *Review of educational research*, *77*(4), 575–614. https://doi.org/10.3102/0034654307309921
Linn, M. C., & Eylon, B.-S. (2006). Science education: integrating views of learning and instruction. In P. A. Alexander, & P. H. Winne (Eds.), *Handbook of educational psychology* (pp. 511–544). Lawrence Erlbaum Associates Publishers.
Magana, A. J., & de Jong, T. (2018). Modeling and simulation practices in engineering education. *Computer Applications in Engineering Education*, *26*(4), 731–738. https://doi.org/10.1002/cae.21980
Magana, A. J., Elluri, S., Dasgupta, C., Seah, Y. Y., Madamanchi, A., & Boutin, M. (2019). The Role of Simulation-Enabled Design Learning Experiences on Middle School Students' Self-generated Inherence Heuristics. *Journal of Science Education and Technology*, *28*(4), 382–398. https://doi.org/10.1007/s10956-019-09775-x
Mentzer, N. (2014). High school student information access and engineering design performance. *Journal of Pre-College Engineering Education Research (J-PEER)*, *4*(1), 4. https://doi.org/10.7771/2157-9288.1074
Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: An expanded sourcebook*. Sage.
Moore, R., Alemdar, M., Lingle, J. A., Newton, S. H., Rosen, J. H., & Usselman, M. (2016). *The engineering design log: A digital design journal facilitating learning and assessment (RTP)* [Paper presented]. The 123rd ASEE Annual Conference & Exposition., New Orleans, LA.
National Research Council. (2012). *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*. The National Academies Press.
NGSS Lead States. (2013). *Next Generation Science Standards: For states, by states*. The National Academies Press.
Nussbaum, M., & Diaz, A. (2013). Classroom logistics: Integrating digital and non-digital resources. *Computers & Education*, *69*, 493–495. https://doi.org/10.1016/j.compedu.2013.04.012
Patton, M. Q. (2002). *Qualitative Research & Evaluation Methods* (2nd ed.). Sague Publications.
Rampazzo, M., & Beghi, A. (2018). Designing and teaching of an effective engineering continuing education course: Modeling and simulation of HVAC systems. *Computer Applications in Engineering Education*, *26*(4), 739–748. https://doi.org/10.1002/cae.21916
Razzouk, R., & Shute, V. (2012). What Is Design Thinking and Why Is It Important? *Review of Educational Research*, *82*(3), 330–348. https://doi.org/10.3102/0034654312457429
Rebello, C. M. (2019). *Scaffolding Evidence-Based Reasoning in a Technology Supported Engineering Design Activity* [Paper presented]. The 13th Conference of the European Science Education Research Association (ESERA).
Remillard, J. T. (1999). Curriculum Materials in Mathematics Education Reform: A Framework for Examining Teachers' Curriculum Development. *Curriculum Inquiry*, *29*(3), 315–342. https://doi.org/10.1111/0362-6784.00130
Remillard, J. T. (2005). Examining key concepts in research on teachers' use of mathematics curricula. *Review of educational research*, *75*(2), 211–246. https://doi.org/10.3102/00346543075002211
Roschelle, J., Dimitriadis, Y., & Hoppe, U. (2013). Classroom orchestration: synthesis. *Computers & Education*, *69*, 523–526. https://doi.org/10.1016/j.compedu.2013.04.010
Saab, N., van Joolingen, W. R., & van Hout-Wolters, B. H. (2005). Communication in collaborative discovery learning. *British Journal of Educational Psychology*, *75*(4), 603–621. https://doi.org/10.1348/000709905X42905

Sadler, P. M., Coyle, H. P., & Schwartz, M. (2000). Engineering competitions in the middle school classroom: Key elements in developing effective design challenges. *The Journal of the Learning Sciences*, *9*(3), 299–327. https://doi.org/10.1207/S15327809JLS0903_3

Schimpf, C., Huang, X., Xie, C., Sha, Z., & Massicotte, J. (2019). Developing Instructional Design Agents to Support Novice and K-12 Design Education. *126th ASEE Annual Conference & Exposition*. Presented at the American Society for Engineering Education Annual Conference, Tampa, FL.

Schimpf, C., Sleezer, R. J., & Xie, C. (2018). Visualizing Design Team Analytics for Representing and Understanding Design Teams' Process. *125th ASEE Annual Conference & Exposition*. Presented at the American Society for Engineering Education Annual Conference, Salt Lake City, UT.

Schwandt, T. A. (2014). *The Sage dictionary of qualitative inquiry* (4th ed.). Sage publications.

Seah, Y. Y., Karabiyik, T., & Magana, A. J. (2020). The interplay between design strategies use and design performance. Proceedings of the 2020 International Conference of the Learning Sciences (ICLS), Nashville, TN. June 19-23, 2020.

Smetana, L. K., & Bell, R. L. (2012). Computer simulations to support science instruction and learning: A critical review of the literature. *International Journal of Science Education*, *34*(9), 1337–1370. https://doi.org/10.1080/09500693.2011.605182

Shah, J. J., Millsap, R. E., Woodward, J., & Smith, S. M. (2012). Applied Tests of Design Skills—Part 1: Divergent Thinking. *Journal of Mechanical Design*, *134*(2), 021005. https://doi.org/10.1115/1.4005594

Slotta, J. D., & Linn, M. C. (2009). *WISE Science: Web-based Inquiry in the Classroom. Technology, Education–Connections*. ERIC.

Smetana, L. K., & Bell, R. L. (2014). Which setting to choose: Comparison of whole-class vs. small-group computer simulation use. *Journal of Science Education and Technology*, *23*(4), 481–495. https://doi.org/10.1007/s10956-013-9479-z

Sung, W.-T., & Ou, S.-C. (2002). Web-based learning in the computer-aided design curriculum. *Journal of Computer Assisted Learning*, *18*(2), 175–187. https://doi.org/10.1046/j.0266-4909.2002.00225.x

Taber, K. S. (2018). The Use of Cronbach's Alpha When Developing and Reporting Research Instruments in Science Education. *Research in Science Education*, *48*(6), 1273–1296. https://doi.org/10.1007/s11165-016-9602-2

Tavakol, M., & Dennick, R. (2011). Making sense of Cronbach's alpha. *International journal of medical education*, *2*, 53–55. https://doi.org/10.5116/ijme.4dfb.8dfd

Wieman, C. E., Adams, W. K., & Perkins, K. K. (2008). PhET: Simulations that enhance learning. *Science*, *322*(5902), 682–683. https://doi.org/10.1126/science.1161948

Wiggins, G., & McTighe, J. (1997). *Understanding by Design*. Association for Supervision and Curriculum Development.

Wiggins, G., & McTighe, J. (2005). *Understanding by design* (2nd ed.). Pearson Education.

Williams, T. D., Grimble, B. J., & Irwin, M. (2004). Teachers' link to electronic resources in the library media center: A local study of awareness, knowledge, and influence. *School Library Media Research*, *7*. https://eric.ed.gov/?id=EJ965623

Xie, C., Schimpf, C., Chao, J., Nourian, S., & Massicotte, J. (2018). Learning and teaching engineering design through modeling and simulation on a CAD platform. *Computer Applications in Engineering Education*, *26*(4), 824–840. https://doi.org/10.1002/cae.21920

Xie, C., Tinker, R., Tinker, B., Pallant, A., Damelin, D., & Berenfeld, B. (2011). Computational experiments for science education. *Science*, *332*(6037), 1516–1517. https://doi.org/10.1126/science.1197314

Yin, R. K. (2009). *Case study research: Design and methods (Vol. 5)*. Sage Publications, Inc.

Appendices

Appendix A: Comparison of contexts among the three cases

Dimension	Case 1	Case 2	Case 3
Grade and course	Earth Science for middle school students	Environmental Science for high school students.	Physics for elementary education course for pre-service teachers.
Unit name	Design your own zero-energy house challenge with Energy3D	Net-Zero Energy (or Energy-Plus) House Challenge	Integrating engineering design in the physics classroom with Energy3D.
Course outcomes	• Understand Earth composition, structure, processes, including weather and climate and utilising Earth's resources • Engage in investigations and engineering design	• Understand scientific concepts that relate to the environment • Examine solutions for resolving or preventing environmental problems	• To develop the knowledge of physical science, particularly physics concepts at a deeper level than elementary school. • To develop knowledge of practices of science and engineering design.
Duration	Four classes, two 45-minute classes and two 75-minute blocks.	Five class blocks, each approx. 90 mins.	A total of 4 academic weeks. Each week consisting of 1 lecture for 50 minutes, and 1 lab for 2 hours and 50 minutes with a total of 2 lectures and 4 labs.
Time in the semester	Middle of fall semester for a year-long course	Early Spring for a year-long course.	Fall of 2019 in weeks 9, 10, 11 and 12.
Prerequisite knowledge	No specific prerequisite knowledge	No specific prerequisite knowledge	No specific prerequisite knowledge.
Out-of-class work	None	None	Students were given 2 extra days to complete their lab report and submit on Blackboard (if they did not get to finish it in the lab).

Appendix B: comparison of aims among the three cases

Dimension	Case 1	Case 2	Case 3
Unit objectives	• Engage students in engineering design to help students learn earth science concepts	• Understand scientific concepts that relate to the environment • Examine solutions for resolving or preventing environmental problems	• To develop the knowledge of physical science, particularly physics concepts at a deeper level than elementary school. • To develop knowledge of practices of science and engineering design.
Disciplinary objectives	Students will develop understanding about Earth's tilt and the seasons, the impact of the rotation and orbit of the Earth on the path of the Sun, how the path of the Sun affects solar energy solutions	Students will develop and use knowledge about energy transfer (light, heat, electricity), the impact of the rotation and orbit of the Earth on the apparent path of the Sun, and renewable energy solutions to climate change.	Students will identify and experiment with the processes of heat transfer including conduction, convection, and radiation.
Skill objectives	Students engage in engineering design practices, namely doing research, generating and testing solutions, and evaluating and refining solutions using Earth science understanding.	Students will engage in engineering design practices including: understanding the specifications, developing knowledge about relevant concepts, ideating and building designs, testing designs, and evaluating and refining designs.	Students will engage in disciplinary practices of science and engineering such as design skills, experimentation, skills and argumentation skills.

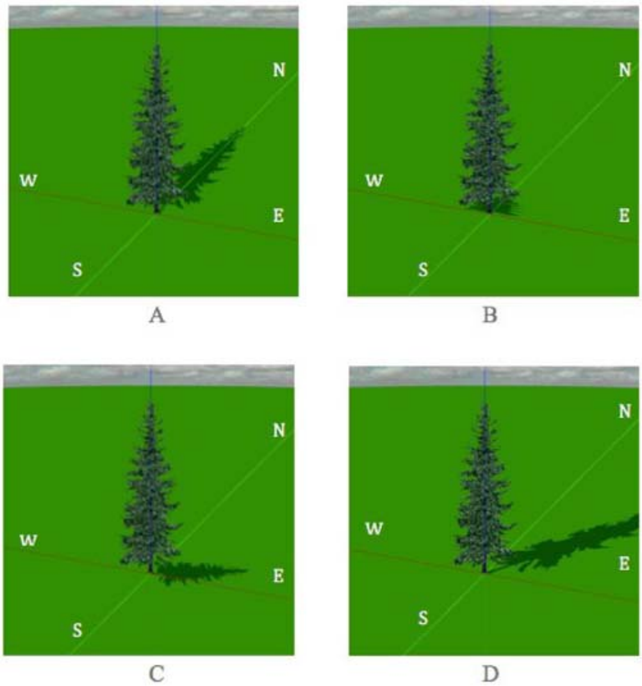
Appendix C: comparison of specifications among the three cases

Dimension	Case 1	Case 2	Case 3
Instructional design	• Learning by Design™ • Knowledge Integration meta-principles	• Learning by Design™ • Knowledge Integration delivered by WISEngineering	• Learning by Design™ implemented in the lab portion of the course. • Inquiry-based learning
Pedagogical approach	• Knowledge Integration Instructional pattern • Informed Engineering Design	• Scaffolded design cycles	• Use of an argumentation framework to support the 3 E's process (Explore, Explain, Elaborate).
Sociology of learning	• Students worked in pairs, discussing their designs with each other and teachers.	• Students worked in pairs, discussing their designs with each other and with the teachers.	• Teamwork for in-class discussions, laboratory experiments (in pairs), design challenge (in pairs) and documentation of final design (in pairs). • Individual work to respond in-class questions via an i > Clicker, and documentation of the experiment via individual lab reports.
Materials and technology	• Energy 3D software • Interactive student notebook in Google Docs	• Energy3D software • Project website WISEngineering.	• Energy3D software provided in a USB • Lab worksheets (4 in total) • Excel sheets for students to document the data they collect in lab (2 in total) • Argumentation framework embedded in lab worksheets (for experimental group) • PowerPoint template for students to document their designs (2 in total) • Lecture slides
Student-generated artifacts	• Energy 3D design solutions • Student notebooks	• Energy3D design solutions after each of the scaffolded design challenges. • Physical models of final Energy3D design. • Student reflections on each of their designs.	• 4 lab experiment reports • 2 data collection excel files • 2 energy3D .ng3 files (suboptimal design and final design) • 2 PowerPoint files (suboptimal design and final design)
Formative assessment	• In-class questions with other students and teachers	• In-class question with other students and teacher	• In-lecture discussion • In-lab feedback (spontaneous Q&A)
Summative assessment	• Pretest and posttest assessments	• Pre and posttest assessments • Energy3D design solutions after each of the scaffolded design challenges. • Student reflections on each of their designs.	• Pretest and posttest assessments • I > Clicker responses • Group discussions • Lab reports • Quiz

Appendix D: science learning instrument

Appendix A contains the questions completed by all groups as a pre and posttest of their science understanding.

Solar Science Challenge Questions
Thank you very much for participating in this study! Your responses are very important to us. Please take your time and try your best! *Required

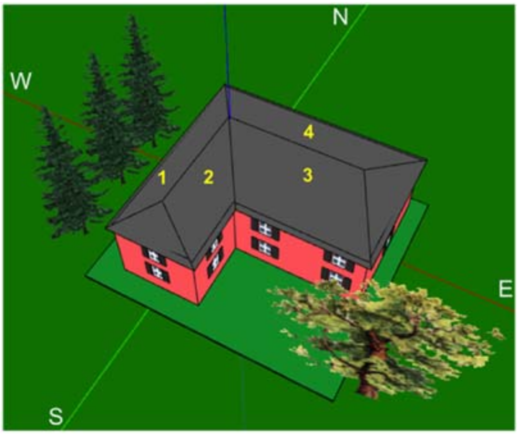


The images below show the same tree and its shadow at different times and dates in Virginia.

1. **Which image is likely to show the tree and its shadow at noon in the Summer?** *
   Select one answer.
   A.
   B.
   C.
   D.

2. **Which image is likely to show the tree and its shadow in the afternoon in the Winter?** *
   Select one answer.
   A.
   B.
   C.
   D.

The house below is located in Charlottesville, VA. The homeowner plans to install solar panels on the rooftop. Four possible locations for the solar panels are shown in the image.

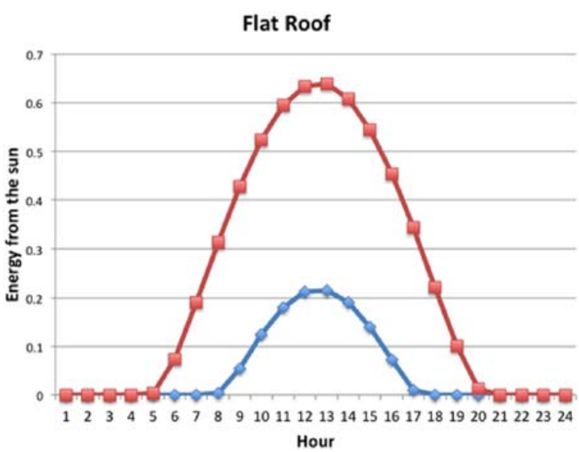


3. **Which location on the roof would you choose to install solar panels in order to maximize the energy converted from solar energy to electrical energy?** *

Select one answer.

A. Location 1
B. Location 2
C. Location 3
D. Location 4

The graph below shows the amount of energy from the Sun hitting a flat roof in Charlottesville, Virginia, over 24 hours. The different lines (red or blue) indicate different seasons.

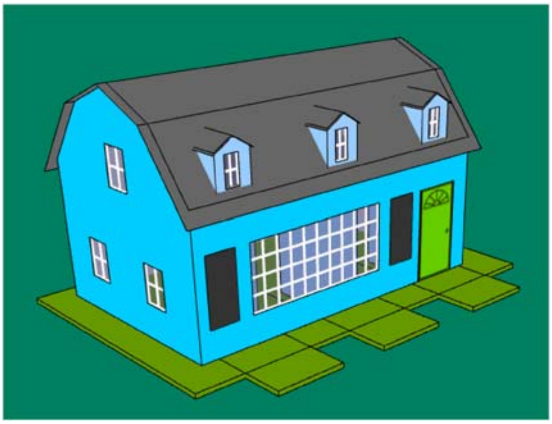


4. **Which season is indicated by the BLUE line?** *

Select one answer.

A. Summer
B. Winter

You are designing a house for a client in Charlottesville, Virginia. The client would like to have a large window on one side of the house. There are no trees or other buildings around this house.

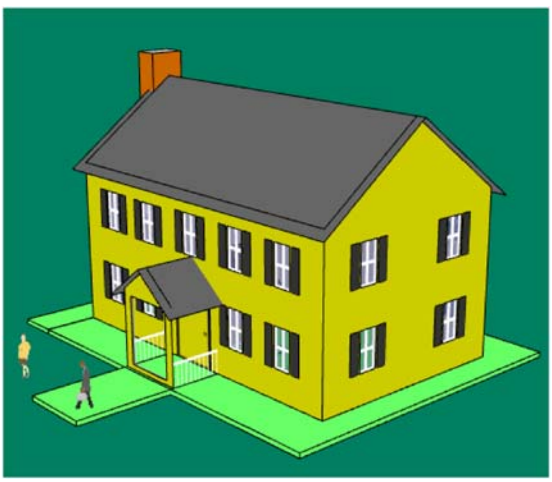


5. **To maximize the energy efficiency of the house in the WINTER, on which side of the house would you choose to install the large window?** *

Select one answer.

A. East side
B. West side
C. North side
D. South side

A two-story house is about 30 feet high and located in Virginia. The house owner wants to plant trees to improve energy efficiency of the house.



6. **Which of the following trees would you choose, assuming the total costs of these options are the same?** *

Select one answer.

A. Ten trees, 5 feet tall and 4 feet wide, Evergreen (doesn't shed leaves annually)
B. Ten trees, 5 feet tall and 4 feet wide, Deciduous (sheds leaves annually)
C. Two trees, 25 feet tall and 20 feet wide, Evergreen (doesn't shed leaves annually)
D. Two trees, 25 feet tall and 20 feet wide, Deciduous (sheds leaves annually)