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Molly H. Goldstein, Sharifah A. Omar, Senay Purzer, Robin S. Adams
Purdue University

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Comparing Two Approaches to Engineering Design in the 7th Grade Science Classroom

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Abstract

In schools, design projects can be implemented at a variety of ways and with varying degrees of resources from teachers and schools. However, little work has been done on the differences between student learning outcomes and the type of design projects. This study compares two design projects implemented in 7th grade classrooms (*n*=677) at two different schools to explain affordances of each approach based on differences in project authenticity, scale, and depth of context in supporting student learning outcomes. The main data sources were an engineering science test and a design reasoning elicitation problem, administered at each school before and after the design project. To understand the relationship between students' science learning gains and school implementation, we conducted a sign test to compare between-group differences and a Mann Whitney Test to compare within-group differences. Then, we performed a content analysis to examine students' design reasoning and a two-way contingency table analysis to understand if a student's school implementation was related to the changes in design trade-off reasoning. Students at both schools exhibited statistically significant but small gains on their engineering science test scores. While students at the school with a more interdisciplinary, more authentic design project had higher scores on the engineering science test, students at the school with a smaller scale implementation discussed more trade-off factors in their design reasoning elicitation problem. These findings suggest that differences in project implementation appear to be associated with different learning outcomes, and there are potential benefits to both authenticity and simplicity in design projects.

Introduction

The last several decades have seen an increasing interest and emergent body of research on integration of engineering and technological design in K-12 education systems worldwide. In the United States, the *Next Generation Science Standards* (NGSS) and its formative document, *A Framework for K-12 Science Education* (NRC, 2012), provide the impetus for the inclusion of science and engineering practices in science education. Engineering design can make mathematics and science concepts relevant by reinforcing the application of these concepts in solving tangible and relatable problems (Miaoulis, 2014; Roth, 1996). Engaging in engineering design also motivates students and offers opportunities to foster and promote critical thinking while also requiring the application of science and mathematics concepts (Ganesh & Schnittka, 2014).

A Framework for K-12 Science Education (NRC, 2012) stresses the need for students to engage in both science and engineering practices at every grade level so that students "understand the work of engineers, as well as the links between engineering and science" (p. 42). NGSS articulates the integrated teaching of disciplinary practices, disciplinary core ideas, and cross-cutting concepts and hence argues for a three-dimensional learning. Despite the fact that educators have taken diverse approaches to integrating engineering and science through design, little research has investigated the affordances of different approaches to design in the classrooms. Different design project implementations reasonably could lead to diverse learning outcomes, and the current study seeks to understand the differences in student learning offered by design projects of differing levels of authenticity and scale.

Conceptual Framework

Relationship between Design and Science Learning

Design is a process of learning (Dym, Agogino, Eris, Frey, & Leifer, 2005; Fosmire & Radcliffe, 2014; Neeley, Sheppard, & Leifer; Neeley, 2006). As students participate in design, we expect that they will also learn science (Apedoe et al., 2008; Hmelo, Holton, & Kolodner, 2000; Kolodner, 2002; Kolodner et al., 2003; Schnittka & Bell, 2011). As shown in Figure 1, our conceptual framework (Purzer, Goldstein, Adams, Xie, & Nourian, 2015) characterizes the interaction between scientific inquiry and design inquiry, situated in a shared spaced of learning while designing. The intersection of science and design knowledge marks the nature of the interaction that brings together knowledge and practices in science knowledge and practices in design, resulting in knowledge-based design decisions. Crismond and Adams (2012) describe aspects of this knowledge construction as “using knowledge of physical laws, how things work, methods of construction, everyday knowledge, application of known cases, and knowledge gained from design revisions and experiments” (Crismond & Adams, p. 8). This framing illustrates the ways students concurrently learn science inquiry and design. Purzer et al. (2015) have examined evidence of such integrated learning during idea framing, idea fluency, and balancing benefits and trade-offs by analyzing high school students’ design processes and reflective notes. Their study suggests that in particular, when students attempt to balance benefits and trade-offs in a design, they are apt to make deeper science connections (Purzer et al., 2015).

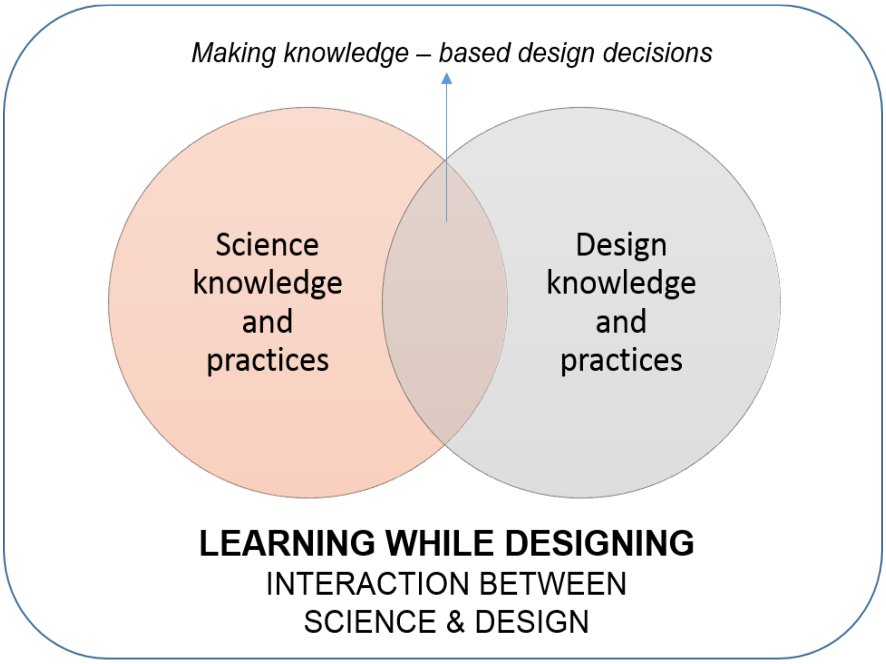

Figure 1. Science and design knowledge informing design decisions (adapted from Purzer et al. (2015))

The integration of engineering and science is thought to lead to a deeper learning and development of transferable knowledge (NRC, 2013). Further, design learning also offers opportunities for schools and educators to support the literacies and skills needed for the 21st century (Burdick & Willis, 2011). The four main learning and innovation skills as explained in the *Framework for 21st Century Learning* are: critical thinking, communication, collaboration, and creativity (Ananiadou & Claro, 2009). The integration of design into K-12 classrooms would allow students to develop these four skills through working and solving design problems. Supporting the benefits of design-based learning, *Design as a Catalyst for Learning* (Davis, 1997) provides a comprehensive summary of design learning in the K-12 classroom and evidence that design learning is supported by teachers as students’ interpersonal and communication skill are enhanced in addition to flexibility in thinking skills. Others (Kolodner et al., 2003) also report that design learning environments offer affordances such as learning of communication, decision making, and collaboration skills.

Design Rationales & Design Trade-off Decisions

A design rationale is explicit reasoning and argumentation for a particular design artifact (MacLean, Young, Bellotti, & Moran, 1991), and can be a useful tool in the design process “from reasoning and reviewing to managing, documenting, and communication (MacLean, Young, Bellotti, & Moran, 1991, p. 204)." We can also think of design as a process of understanding, ideating, and negotiating. To develop student designers' decision-making ability, Crismond and Adams (2012) suggest strategies to elicit student explanations for their design choices including efforts to have students describe pros and cons for all design options. This practice of describing pros and cons, or making design trade-offs, is also described in the *Framework* as part of the *disciplinary core idea:* optimizing the design solution.

> Optimization often requires making trade-offs among competing criteria. For example, as one criterion (such as lighter weight) is enhanced, another (such as unit cost) might be sacrificed (i.e., cost may be increased due to the higher cost of lightweight materials). In effect, one criterion is devalued or traded off for another that is deemed more important. When multiple possible design options are under consideration, with each optimized for different criteria, engineers may use a trade-off matrix to compare the overall advantages and disadvantages of the different proposed solutions. The decision as to which criteria are critical and which ones can be traded off is a judgment based on the situation and the perceived needs of the end-user of the product or system. Because many factors—including environmental or health impacts, available technologies, and the expectations of users—change over time and vary from place to place, a design solution that is considered optimal at one time and place may appear far from optimal at other times and places. Thus different designs, each of them optimized for different conditions, are often needed. (National Research Council, 2012, p. 209)

Understanding how students' design reasoning with respect to trade-offs develops in an integrated engineering and science setting would then allow a glimpse into how students develop science knowledge and engineering design competence.

Various Forms of Design in the Classroom

Engineering design can be implemented in a variety of ways with varying degrees of resources from teachers and schools. Little work has been done comparing different methods of teaching design, with most published work focusing only on the bigger picture and overview of different engineering programs developed at K-12 level (Brophy, Klein, Portsmore, & Rogers, 2008; Kelley, Brenner, & Pieper, 2010). In college settings, Svihla, Petrosino, and Diller (2012) compared kit-based and re-design projects to understand how to support students' learning in design. They identified limitations of kit-based projects as compared to re-design projects. In assessing the impact of design-based learning units in comparison to high-quality inquiry science units, Silk, Schunn, and Cary (2009) found that students from both instructional methods showed improvement from pre- to post-test but those who participated in a design project showed greater improvement. Other research in engineering design compares traditional methods of science education to those infused with design learning, such as Learning By Design (LBD) (Kolodner, 2012), Model Eliciting Activities (MEA) (Zubrowski, 2002), and Knowledge and Skill Builders (Burghardt & Hacker, 2002). However, these studies do not empirically compare variations in implementation of design in the middle school science classroom. To address this research gap, this study explores the affordances offered by two approaches to engineering design at two schools with very different engineering design implementation strategies through the following research questions:

1. How do student learning gains compare between design projects with differing implementation approaches?
2. How do students' design rationales develop in these different design approaches?

Method

Participants and Context of the Study

This study took place at two suburban middle schools in the United States, with pseudonyms Bay Middle School and Brookside Middle School. Both schools are located within the same affluent, resource-rich, suburban town and pull from the same population of students (e.g., similar demographics, socioeconomic status, etc.). All students participated in classroom design challenges, but data are analyzed only for students for whom parents authorized consent per IRB guidelines and who completed both pre- and post-tests. A total of 362 seventh grade (ages 13-14) students at Bay Middle School worked individually for a total of 10 hours over two weeks under the guidance of three science teachers and one instructional coach. The role of an instructional coach is similar to a lead teacher who facilitates the overall planning and implementation of a project. An instructional coach has typically been a former teacher, but with the role has more project management responsibilities in a school setting, and might provide this support across multiple subjects across a few grade levels. At Brookside Middle School, 315 seventh grade (ages 13-14) students worked in groups of four to five students and spent a total of 45 hours on the project over a month under the guidance of three science teachers, three mathematics teachers, and one instructional coach. Both Bay and Brookside Schools use block scheduling, replacing a more traditional 40-50-minute daily subject class with longer 90-minute classes of each subject that meet fewer times each day and week. Teachers at both schools had common planning times, allowing full collaboration among teachers. Table 1 details participant and school information while Figure 2 details the design project timeline at both schools.

Table 1. Comparison of the context and projects at Bay and Brookside middle schools.

	Bay Middle School	**Brookside Middle School**
Students (*N*)	362	315
Teachers	3 science	3 science, 3 mathematics
Instructional coach present?	Yes	Yes
Time spent	10 hours over 2 weeks	45 hours over 5 weeks
Classrooms participating	Science	Science and Mathematics
Class length	Block (90-minute)	Block (90-minute)
Teacher collaboration	Common planning period	Common planning period
Student group size	1 (worked individually)	4-5 students/group
External client	No	Yes, a local home builder who introduced the project and served as judge

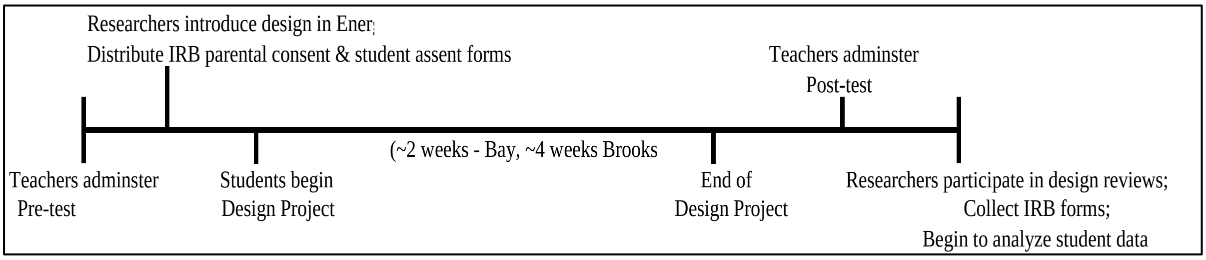

Figure 2. Timeline of project milestones and involvement

School Design Projects

Both schools implemented a similar engineering design project, which focused on designing energy-efficient homes using computer-aided design (CAD) software called Energy3D (http://energy.concord.org/energy3d/). Energy3D is a simulation-based engineering tool that enables students to design, analyze, and construct green, energy-efficient buildings necessary for sustainable development (Nourian & Xie, 2016). The software is created as an educational research tool to support engineering and science learning. It offers a friendly 3D graphical user interface for drawing buildings and evaluating their performance using cost breakdown analysis and energy (solar and heat) simulations (see Figure 3). After students complete their final design sketches in Energy3D, the software allows users to print out the final design on simple cardstock paper to assemble a physical prototype.

Students at both schools were introduced to Energy3D through a 20-minute workshop delivered by the Purdue research team. Groups of approximately 30 students at a time came to a computer laboratory as a researcher introduced the Energy3D software and demonstrated how to design in Energy3D including incorporating design features, how to run analyses, and graph interpretation. Additionally, instructional videos were available on the Energy3D website for students who were absent or students wanting additional instruction time. Because of the large number of students at both schools, three separate researchers ran three separate instructional workshops over the course of one day per school.

The energy efficient home design project at both schools involved utilizing Energy3D to design single-family homes that attempted to balance energy consumption, construction cost, livability, and aesthetics. However, the two schools differed in the scale and the context of their implementations. The following sections describe these differences.

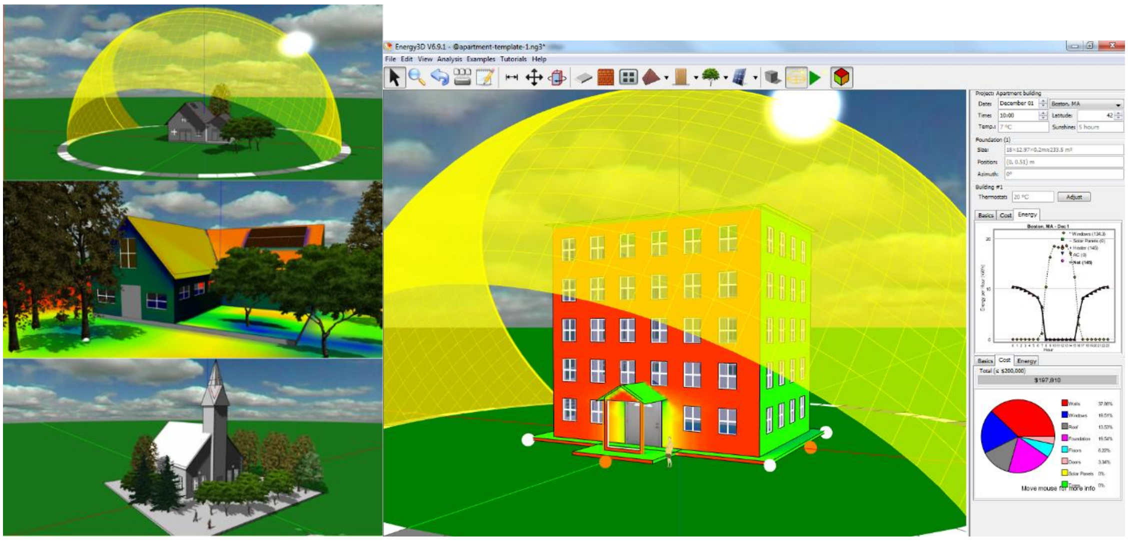

Figure 3. (Left) Energy3D solar simulator, heat maps, and example building. (Right) Energy3D performance calculations (e.g., energy, cost).

Bay Design Project

After an introduction and a brief practice time with the software, students from Bay Middle School worked individually on the project in their science class (see Figure 4). Students were given a challenge to design an energy-efficient, single family home with a set of criteria and constraints such as minimizing energy needed to keep the house comfortable on a sunny day or cold night, minimizing the cost of the building, being large enough to accommodate a family of four, and having an attractive exterior. Because students worked individually, all students assumed the role of a designer and were asked to create three unique homes to meet the specified criteria and constraints. They were also tasked with evaluating the three homes' designs based on these specifications. At the end of the two weeks' project, students presented their "best" solution to the class, explaining what made their solutions perform well. The three science teachers collaborated, and selected the 15 best design solutions from the entire grade-level based on both overall design and student effort. These 15 students presented their design solutions to their entire grade-level in an auditorium-style 3-minute presentation through one slide, detailing the highlights of their home such as final construction cost, annual energy consumption, and a physical prototype. Researchers in attendance provided design feedback to the group of 15 students and selected the top three designs within that group.

Figure 4. Students working with Energy3D in the Science classroom at Bay Middle School

Brookside Design Project

Brookside utilized a comparatively more authentic and complex implementation (Goldstein, Loy, & Purzer, 2017). First, the project was integrated throughout both mathematics and science classes, with mathematics and science teachers and the instructional coach working together throughout their common planning period to collaborate on cohesive implementation as well as student milestones and mini-lessons. Second, a local homebuilder kicked off the project with a whole-grade level assembly (see Figure 5). He introduced the design challenge by showing lot layouts within a new building community. Students then took buses out to the construction site to get a better feel for the building lot and for the community. The homebuilder asked that the students design homes that would fit in the community that were attractive, buildable, and energy-efficient. Students worked in teams of four to five, with each student working within an explicit role of: architect, landscape architect, interior designer, and mechanical engineer (see Goldstein, Loy, & Purzer (2017) for more details).

Figure 5. Homebuilder kick-off presentation at Brookside Middle School

In the science classroom, student work included individual and team research through several experiments to address design decisions, such as insulation and roofing options. In the mathematics classroom, students worked mostly independently to design their home in Energy3D. Students worked on state-specific math standards such as scale, size of home, and slope of roof in addition to data analysis associated with energy consumption and cost.

At the conclusion of the project, student teams at Brookside Middle School were given 10 minutes to present their final designs to a panel of judges composed of homebuilders, architects, realtors, city officials, and other community members to decide on the top designs in the classroom. Six panel reviews (one for each land lot) ran simultaneously so that all of the teams were able to pitch their ideas. The homebuilder and architect at the firm met with the winning team to discuss their design, make improvements, and develop blueprints. This blueprint was then fully developed as a real house option in the neighborhood.

Data Sources

We collected data using two instruments administered as a pre- and post-test to understand and compare the affordances offered by two approaches to design. The instruments were: (1) a multiple-choice engineering science in sustainable design test and (2) a design reasoning elicitation problem. Students at both schools completed the pre- and post-tests through an electronic survey platform before starting and then at the conclusion of their design project.

Engineering Science Test in Sustainable Design

The Engineering Science Test in Sustainable Design in the current study includes nine multiple-choice items designed to assess student learning of integrated engineering-science after completion of a design challenge. The nine-items were selected from the original 19-item assessment, Green Building Science Test. In this earlier version to ensure content validity the assessment items were drawn from green building science textbooks (e.g., Hens, 2012; Montoya, 2010). To ensure instructional sensitivity, the items were further selected based on the learning opportunities offered in the design challenge in the Energy3D design environment. The test items were reviewed by a panel of experts including green building science experts, engineering design professors, learning scientists, and high school science teachers to ensure their content validity and developmental appropriateness. Further details on the development of this instrument is described in detail in Chao et al. (2017).

The nine items were selected to be: (1) aligned with the design challenge applicable to both of the middle schools in the study and (2) pragmatically shorter to allow students to complete the assessment during class time. The alignment with the design challenge at hand ensured instructional sensitivity to the learning environment. We ensured developmental appropriateness by working with middle school teachers to review the entire instrument. This assessment was meant to be cognitively difficult, as it asks students to integrate science and engineering. The highest possible test score was nine (9) points, as each test question was scored in a binary manner as correct or incorrect. The item difficulty index ranged between 16.8 and 79.4. Our test item difficulties reflect that this test was not intended to assess mastery of material but rather assess various levels of understanding. For example, norm-referenced tests are designed to be more difficult than mastery tests with a large spread of testers' scores, typically between .4 and .6 (Professional Testing Inc, 2006). The Engineering Science Test in Sustainable Design is a cognitively complex test as it requires coordinated use of knowledge in science and design. The target concepts measured by the test are:

- Sun path and insolation (i.e., sun path, hours of sun exposure, angle of incidence, seasonal variation, geographic variation, solar heat gain coefficient)
- Heat transfer (i.e., thermal radiation, flow from warm to cool, surface area, temperature gradients, thermal conductivity)
- Representations (i.e., solar heat maps, graphs, interpretations)

Design Reasoning Elicitation Problem

An open-ended question asked students to explain their reasoning in selecting a design solution from three possible alternatives (see Figure 6). The problem states that the engineer in this situation needs to balance trade-offs between energy and cost while making sure enough light enters the building. The question was developed such that there is not an obvious choice, nor one correct answer. Hence the question elicits students to make connections between the benefits and the trade-offs from differing factors between the buildings. The analysis of student responses assessed the extent to which students considered multiple trade-off factors when making a design decision (see Table 2).

Table 2. The trade-off factors associated with building data

Trade-offs factors	Data provided as part of the task
Technical	● Total annual energy consumption
	● Approximate volume of building
Human	● Total area of windows surface and walls
	● Number of trees
Economic	● Total construction costs
	● Approximate volume of building

An engineer is asked to determine the best option among three buildings. She needs to balance trade-offs between energy and cost while making sure enough light enters the building through windows.

	Building 1	**Building 2**	**Building 3**
Annual Net Energy Consumption (kWh)	-1,000	0	50
Total Material Cost ($)	59,626	55,000	49,000
Volume (m^3)	160	150	150
Number ofTrees	3	4	3
Total Wall Surface (m^2)	185	180	180
Total Window Surface (m^2)	16	8	10

Using the information provided above, which building would you suggest the engineer selects?

a) Building 1
b) Building 2
c) Building 3

Please explain your choice:

____

____

Figure 6. The open-ended *Design Reasoning Elicitation Problem* students answer in pre- and post- test

Data Analysis

A multi-method approach (Morse, 2003) was used with quantitative analysis of the *Engineering Science Test in Sustainable Design* and both quantitative and qualitative analysis of the design reasoning elicitation problems. The results from both analyses are reviewed together to explain the affordances offered by two approaches to engineering design.

Quantitative Data Analysis to address RQ1: How do student learning gains compare between design projects with differing implementation methods?

To compare the learning gains between the two schools with different implementation of design projects, we conducted a series of statistical analyses to compare groups. For within-group comparisons, we analyzed changes between pre-test to post-test scores at each school independently. Then, for group comparisons, we analyzed the test scores between the two schools.

Before performing these analyses, we first checked for normality in the distribution of the data by performing Shapiro Wilk (S-W) tests for normality, skewness, and kurtosis (see Table 3). Results suggested that the normality assumption was not met, requiring the use of nonparametric statistical tests for all of our statistical analyses.

Table 3. Tests of normality for Bay and Brookside pre- and post-test data

		df	Shapiro-Wilk	skewness	kurtosis	*p*
Pre-Test	Bay	315	.93	.78	.82	<0.01
	Brookside	315	.93	.72	.34	<0.01
Post- Test	Bay	315	.94	.62	.05	<0.01
	Brookside	315	.97	.20	-.64	<0.01

Within-Group Comparison

We used a sign test for within-group comparisons to compare the pre- to post-test median scores to investigate student learning gains at each school. The sign test is comparable to the Wilcoxon signed rank test and the paired samples *t*-test and is used when the distribution of differences is neither normal nor symmetrical, respectively (Dixon & Mood, 1946; Olshen, 1967).

Between-Group Comparison

To compare student learning based on project implementation, we first used a Mann-Whitney *U* test to show that pre-test scores were not statistically different between the two schools, then used a similar test to analyze the differences in median scores of the post-tests between Bay and Brookside Middle Schools. Mann-Whitney is a non-parametric test equivalent to the independent samples *t*-test, appropriate for non-normal data distribution (Krauth, 1983). We hypothesized that students from Brookside would score higher on average than students from Bay on the science knowledge post-test due to the scale of the project and high degree of integration at Brookside. In calculating the effect size, we first calculated the effect size η^2 for the non-parametric test (Fritz, Morris, & Richler, 2012) and converted it to Cohen's *d* effect size for better interpretation (Cohen, 1988).

Qualitative Data Analysis to address RQ2: How does students' design reasoning develop in these different design approaches?

We performed a content analysis to categorize students' answers systematically to the open-ended question asking them to explain their decision and reasoning for selecting a design solution among three alternatives.
Using the foundation of our conceptual framework of students making science connections as they attempt to balance benefits and trade-offs in a design, we looked at the explicit trade-offs they mentioned in their rationale. In this systematic characterization, students' reasoning for choosing the best building was categorized into one of three trade-off factor categories, as "a synthesis of technical, human and economic factors" (Asimow, 1962) (see Table 4). An additional category, "Vague Quality Reference," was created to categorize responses that simply listed the data presented in the question (i.e., construction cost, energy consumption, window-to-wall ratio, number of trees) without a clear connection between these factors. We identified responses with trade-off connections when students used contrasting conjunctions such as "although," "but," and "whereas," as these words reflect students' attempts to connect the positive aspects to negative aspects of the building design, consistent with skill theory (Fisher, 1980, 2006; Fischer & Bidell, 1998), referred to by Crismond and Adams (2012) in their description of trade-offs behaviors in informed designers. Consequently, in our analysis, the first three categories are not mutually exclusive, meaning students could make zero, one, two, or three trade-off connections. We first implemented a binary coding system [1 0] in analyzing the responses, with 1 indicating that the particular trade-off factor exists and was explicitly mentioned by the student. Then, we summed the total number of trade-off factors (0-3) in each student response. However, the fourth category "Vague Quality Reference" is mutually exclusive from either of the first three categories.

Table 4. Coding scheme for students' responses to the Design Reasoning Elicitation Problem

Code Category	Explanation
Technical	Rationale explicitly references the energy efficiency or annual energy consumption of their choice. Students might reference the overall energy consumption
Human	Encompasses responses that reflect the livability & aesthetics of the house including one or more of the following: ratio of window to wall, size of house, and number of trees.
Economic	Rationale explicitly mentions the construction costs of their selection. Does not include responses that discuss negative energy resulting in energy cost savings, as those responses are coded as "technical."
Vague Quality Reference	This category encompasses student responses that simply list more than one trade-off factor (technical, human, & economic) from the question prompt without clearly stating a connection between the factors or data supporting these factors. This category is mutually exclusive from the first three categories.

Two researchers independently analyzed and coded student responses according to the coding scheme. Cohen's κ was calculated to determine inter-rater reliability between the two researchers. The resulting Cohen's κ value was .94, indicating substantial agreement (Landis & Koch, 1977) prior to resolving inconsistencies. Table 5 includes examples of students' responses within the coding framework (see Table 5).

Table 5. Sample student responses to the Design Reasoning Elicitation Problem

#	Sample responses	Coding category				Number of trade-off connections
		Technical	Human	Economic	Vague Quality	
1	"It is right in the middle."	0	0	0	0	0
2	"it has the lowest energy consumption "	1	0	0	0	1
3	"It costs the less, and even though the net energy may be the highest, it still can be energy sufficient."	1	0	1	0	2
4	"Although building one is slightly more costly, the difference of increase in cost is outweighed by how much more energy efficient it is compared to the other buildings. It also was the largest of them and has a decent amount of trees too."	1	1	1	0	3
5	"uses less energy, gains money, and is bigger"	0	0	0	1	1

*Note: Coding categories Technical through Economic are not mutually exclusive from each other, but are exclusive from Vague Quality.

Quantitative Data Analysis to address RQ2: How do students' design reasoning develop in these different design approaches?

To understand to what degree students at Bay cited trade-offs in their design reasoning as compared to Brookside students, we first compared the non-matched average of pre- and post-test response scores at each school in a histogram to inspect the types of response levels visually before and after the design activity at both schools. Then, to understand whether a statistical relationship exists between school design approach and level of design reasoning, we conducted a two-way contingency analysis. In particular, we were interested in the differences between citing two to three trade-offs, as discussion of more than one trade-off shows how students consider the relationship between competing and complementary design features.

Results

Science Learning Gains after Design Activity

Students at both schools exhibited statistically significant but small improvement on their *Engineering Science Test in Sustainable Design* post-test as compared to pre-test. An exact sign test used to compare the differences in the median scores in the pre- and post-test for Bay and Brookside indicated a significant difference, meaning that students at both schools exhibited significant gains from pre- to post-test after completing the design project (see Table 6).

Table 6. Sign test results for Bay and Brookside Middle School

	Bay Middle School (N = 362)		Brookside Middle School (N = 315)	
	Pre-Test	Post-Test	Pre-Test	Post-Test
Mean	2.64	3.38	2.57	3.93
Median	2.00	3.00	2.00	4.00
Std. Deviation	1.59	1.85	1.69	2.18
Z	6.042		9.381	
p	0.000		0.000	
Effect size (Cohen's *d*)	0.47		0.77	

The difference in median scores on the pre-tests of Bay and Brookside was not statistically significant, as shown in the Mann-Whitney *U* test result (Z = -.753, p = .452), implying that the two schools had comparable pre-test scores in the beginning of the project. However, at the end of the project their post-test *Engineering Science Test in Sustainable Design* scores differ, with students at Bay scoring lower than students at Brookside (see Figure 7). The difference in median post-test scores between the two schools was statistically significant Z = -3.48, p = 0.001), meaning that students at Brookside did indeed score significantly higher on the post-test than students at Bay. A small Cohen's effect size value ($\underline{d}$ = .27) however, suggests low practical importance (Cohen, 1988).

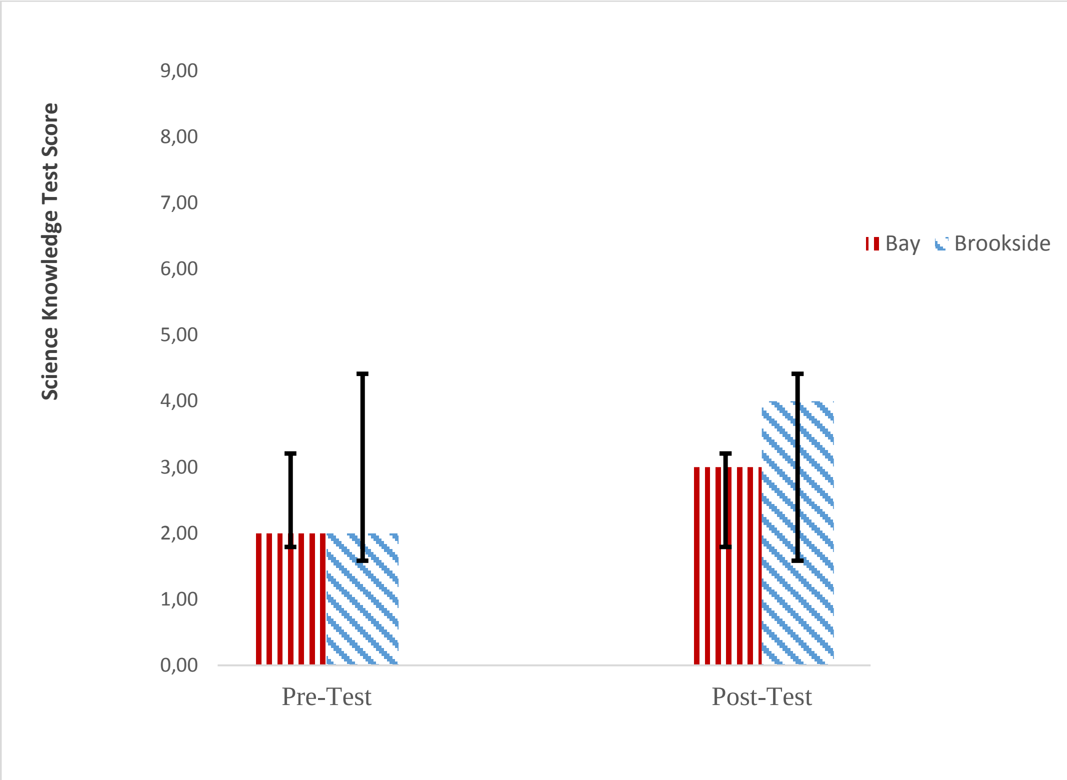

Figure 7. Pre- and post-test score trends for the *Engineering Science in Sustainable Building Design Test*

The results show that completion of a design project yielded statistically significant but small increases for students at both schools. Students at Brookside (where the project was implemented on a much larger scale) saw a greater increase in science knowledge compared to students at Bay. While the difference between post-test scores at both schools was significant, the difference in score gain is not proportional to the difference in hours of in-class time and effort of implementation. Controlling only for in-class time spent, students at Brookside saw a median score increase of two points over 45 hours, for an increase of ~0.04 points per hour, while students at Bay saw a median score increase of 1 point over 10 hours, for an increase of 0.10 points per hour (see Figure 3). These findings suggest that integrated engineering-science knowledge gains can be enhanced by increasing the scale of a design project's implementation, but that even a relatively small-scale implementation can produce at least small but significant results. Simply participating in a design project appears to be enough to yield a significant increase in related science knowledge.

Development of Design Reasoning after Design Activity

In analyzing student responses to the open-ended design reasoning elicitation problem, 55.5% of students at Bay and 59.3% of students at Brookside initially considered at least one trade-off factor when describing their building selection on the pre-test. However, the post-test responses indicate an increase, with 79.3% of students at Bay and 60.1% of students at Brookside considered at least one trade-off factor in their design reasoning. Further, the number of students who considered three trade-off factors also increased from pre- to post-test at both schools (see Figure 8). This suggests that participating in either scale of design project impacted students' tendency to take into account multiple features of a design and their attempts to balance benefits and trade-offs when making design decisions, an important behavior of informed designers.

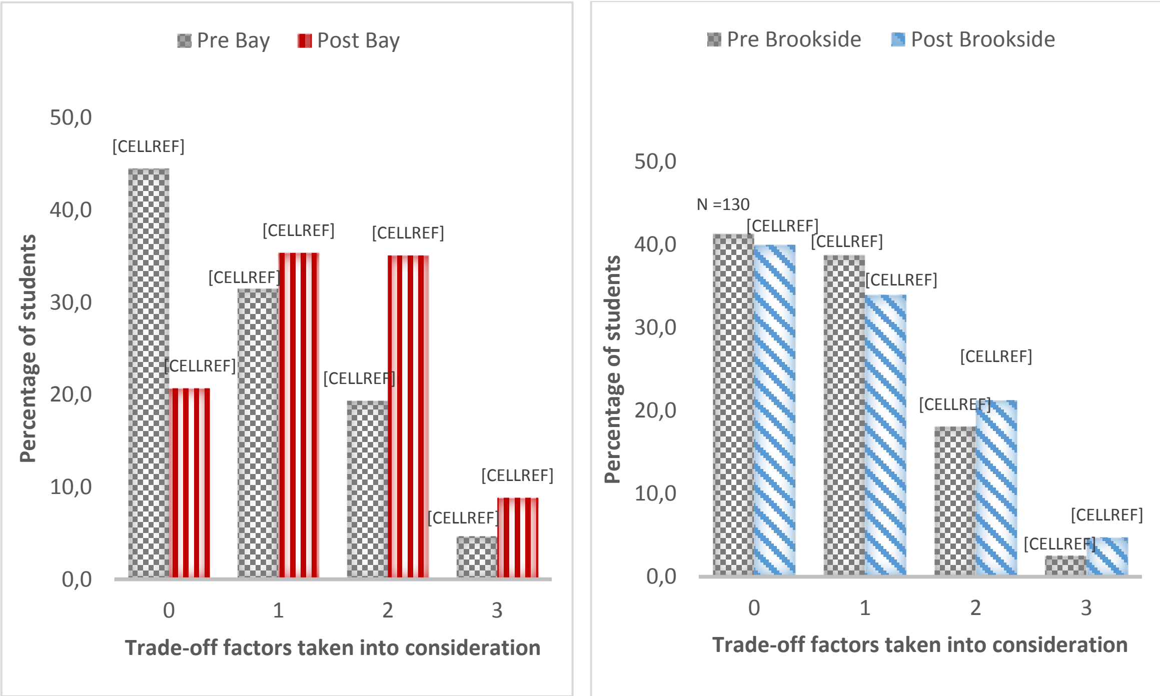

Figure 8. Number of trade-off factors students at Bay and Brookside consider from pre- to post-test.

The post-test results of trade-off factors taken into consideration at each school are shown in Figure 10. After the design project, students at both Bay and Brookside discussed one factor (i.e., cost, energy efficiency, or livability/aesthetics) in similar proportions. However, a greater percentage of students at Bay (35.1%) discussed two trade-offs as compared to Brookside (21.3%).

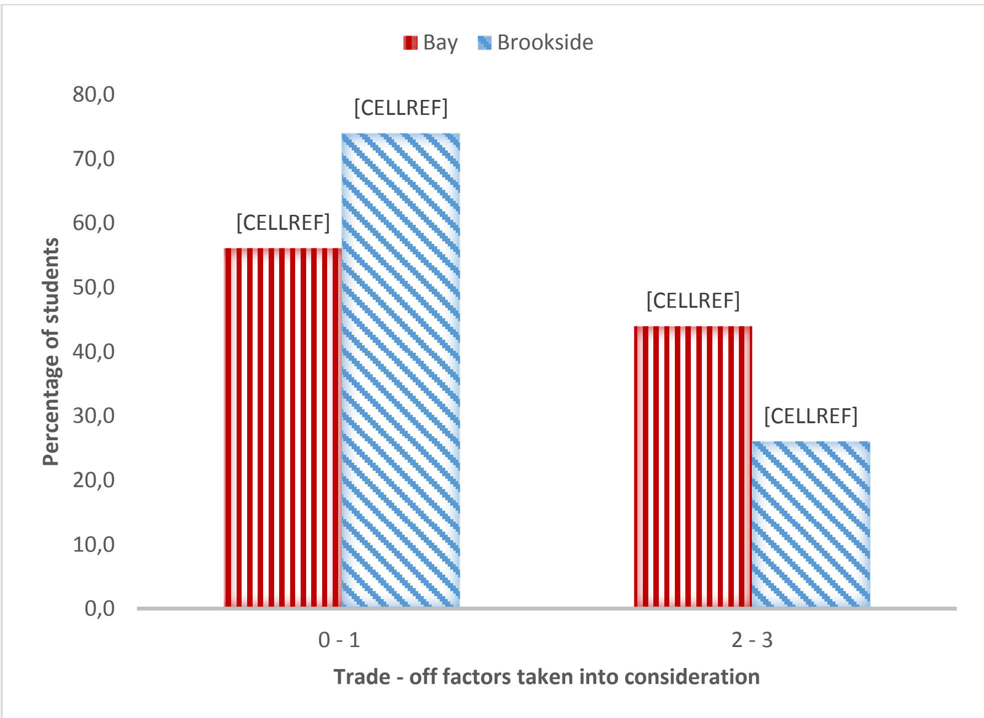

Figure 9. Frequency of Bay and Brookside students who consider (0 and 1) and (2 and 3) tradeoffs factor in the post-test.

A two-way contingency table analysis was conducted to evaluate whether a student's school implementation was related to level of trade-off considered. School and level of tradeoff were found to be significantly related, with Pearson χ^2 (1, N = 677) = 23.52, $p < .001$, Cramer's $V = .19$. The effect size, $\Phi = .19$, indicates that this relationship is moderate. Traditionally, Φ values of .10 and .30 represent small and medium effect sizes respectively (Cohen, 1988). Students at Bay were more likely to cite 2-3 tradeoffs in their response than students at Brookside at the end of the design challenge, despite the involved level of implementation at Brookside.

Illustration of Design Reasoning after Design Activity

Table 7 illustrates the cases of four students' design reasoning improvement after the design project and provides information on their performance in the *Engineering Science Test in Sustainable Design*. Pre- and post-test responses of two students from Bay Middle School, with pseudonyms Amelia and Eric, and two students from Brookside Middle School, with pseudonyms Anna and Jack, are presented to show individual changes within students (see Table 7).

Table 7. Pre- and post-test scores and design reasoning from four students at Bay and Brookside

		Pre Test Responses	Post Test Responses
Bay Middle School	Amelia	"It has the smallest total material cost." *(Score 1 out of 3)*	"Even though the windows might a little small, the cost is pretty cheap. Also, the Annual Net Energy Consumption is at 0, which is good. There are 4 trees to block the windows and stop some heat from escaping, too. *(Score 3 out of 3)*
	Eric	"its middle of the other two and its even." *(Score 0 out of 3)*	"It is very energy efficient and its larger with more windows. Aside from the cost it is the best out of the three houses." *(Score 3 out of 3)*
Brookside Middle School	Anna	"I don't know" *(Score 0 out of 3)*	"Building 1 is the best choice because it has the most windows, the most wall surface, the largest volume, and the lowest annual net energy consumption, while still maintaining a low cost by being only 10,000 dollars more than the cheapest option." *(Score 3 out of 3)*
	Jack	"Because it cost less with materials" *(Score 1 out of 3)*	"Building three because it cost less and has a better energy consumption than the other homes. Also home number three has less trees but saves more energy. *(Score 3 out of 3)*

Initially, Amelia considered only one benefit of the house, i.e., the low construction cost. However, after she completed the design project, Amelia's response to the design reasoning elicitation question changed as she took into consideration all three trade-off factors of human, economic, and technical in describing her selection. In addition, her performance on the Engineering Science in Sustainable Design Test improved from a score of three to four, showing a small improvement in her integrated engineering and science knowledge. Eric's pre- and post-test design reasoning responses exhibit a similar pattern of improvement. Eric initially scored zero in design reasoning in his pre-test as he gave a very vague design decision reasoning. However, in his post-test response, Eric managed to consider all factors, noting the positive and negative relationship between these factors. Furthermore, he showed marked improvement, from one to four, on the Engineering Science in Sustainable Design Test.

Anna's responses are similar to Eric's in that she improved from not being able to articulate her design choice to being able to defend her choice with strong rationale that demonstrated she is balancing both the pros and cons of the designs. Along with an improvement in design reasoning, she exhibited a noticeable improvement in performance on the Engineering Science in Sustainable Design Test, from a score of one to five. Meanwhile, Jack's pre-test response mentioned only the economic factor of "low material cost" as he justified his choice of house. Yet, in his post-test, Jack managed to consider both the benefits and trade-offs in the house design. He mentioned that the fewer number of trees was a con for the design but that the cost and energy consumption were big benefits. Jack also demonstrated an improvement from two to six on the Engineering Science in Sustainable Design Test.

Discussion

Differing Project Scales Offered Different Learning Affordances to Students

This study makes explicit two different approaches to design curricula. Through comparing two different approaches to design in the middle school classroom, this study demonstrates that design projects of different levels of authenticity and integration offer different learning affordances to the students. Calls for the integration of engineering design in K-12 science education, necessitate that teachers implement new teaching methods that promote integration.

Studies have cited that many K-12 teachers feel ill-prepared and lacked confidence to teach engineering due to their unfamiliarity in design, engineering, and technology (Hong, Purzer, & Cardella, 2011; Hsu, Purzer, & Cardella, 2011; Yaşar, Baker, Robinson-Kurpius, Krause, & Roberts, 2006). In fact, integrating engineering into traditional curricula can be challenging even if teachers are enthusiastic (Schmidt & Fulton, 2008; Moore, Mathis, Guzey, Glancy, & Siverling, 2014). While these studies have focused on the teacher aspect of implementation, the current study would be welcome information to these teachers as explains different affordances gained with different implementation methods.

Students at Brookside, who took part in a design project at a more integrated scale in a more time-intensive approach with a real stakeholder, saw significantly more science learning gains than the students at Bay, although with a small effect size. This finding suggests that there are benefits to teachers' extra efforts to develop authentic and interdisciplinary projects. While some schools may have support and resources to implement such an authentic design project, other schools may find it to be a daunting task. Educators should weigh the level of time commitment, resources, and knowledge required to develop a design curriculum that is authentic and that sufficiently build students' desired science knowledge. In addition, future research should examine learning beyond applied science concepts and evaluate student development of competencies in other critical areas such as the 21st Century Skills including but not limited to communication, critical thinking, information literacy (Ananiadou & Claro, 2009).

Students at Bay were more likely to discuss multiple tradeoffs in their attempts to justify design selection than students at Brookside. This consideration of multiple tradeoffs involved in selecting a design indicates that students are beginning to understand the concept of making trade-offs when designing. This finding is promising as prior research state that beginning designers tend to focus on either the positive or negative features of an idea, and later develop more complex design thinking involving trade-offs and making connections between the positive and negative features of the idea (Crismond & Adams, 2012). As students progress toward becoming informed designers, they begin to consider more features, analyzing various strengths and weaknesses of the idea while making connections between them. With this progression, the decision-making process would thus become more comprehensive, and students from Bay Middle School in considering more trade-off factors are on the path toward informed design behaviors. Moreover, these results suggest that students at Bay might consider design more holistically than optimizing one feature.

The illustration of overall student performance through the four cases presented in Table 7 gives a glimpse into students' developing understanding of integrated science and engineering after participation in a design project. In all four cases, regardless of implementation scale and authenticity of the design project, students began to show a greater understanding of integrated engineering and science as demonstrated through the improvement on the Engineering Science in Sustainable Design Test. Moreover, their design reasoning became more elaborate as they discussed design decisions in a more comprehensive manner, considering positive and negative features of a design and weighing these features against each other.

This finding, that Bay students have developed a more sophisticated ability to make design tradeoffs, while the seems to contrast with the finding that Brookside students demonstrated statistically better science learning outcomes, suggests that there are different benefits to different types of implementation. As counterintuitive as it might seem that students involved in a smaller-scale design project might end up with a more comprehensive design rationale, there are a few possible explanations for this result. To begin, because the design project at Bay was an individual project, all students acted as the designer requiring individual analysis and decisions. Students at Brookside, however, worked collaboratively in different roles such as architect, landscape architect, interior designer, and mechanical engineer. By having these explicit roles, students at Brookside possibly had a different experience and exposure to engineering design as compared to students at Bay. However, design team roles in the Brookside design project also provided the opportunity for increased collaboration and teamwork among students. Additionally, the pre- and post-test assessments focused solely on engineering and science. We would expect that students at Brookside also saw large mathematics learning gains due to the integrated nature of the design project in the mathematics and science classrooms.

Conclusions and Future Work

In this study, we illustrate that proficiency in science extends beyond core content knowledge to science practices and cross-cutting concepts (NRC, 2012) as the educational experience aims for students to be able to do more than "know" and "understand" to being able to "analyze," "compare," "explain," and "argue" (Pellegrino, 2013) for a deeper understanding. From simply participating in an engineering design project, students at both schools were able to practice these competencies. Our findings suggest that, while science learning can be improved by implementing more in-depth design projects, most of the benefit to learning is received simply by participating in a design project at all. This would be welcome information for schools that are concerned they do not have the time or expertise to implement an effective engineering design-based science curriculum. Students saw improvement overall in science learning gains and development of design reasoning with respect to assessing trade-offs regardless of scale of project. However, as this study involved a number of factors differentiating the two design project implementations, additional work is necessary to determine the factors that contribute the most to student science learning and enable the development of more effective design curricula. Future work should investigate the relationship between student design rationale and final design artifacts in order to more fully understand the thinking and behaviors of middle school designers. Future research should also examine outcomes beyond science learning, when comparing different implementation of design projects.

Limitations

The findings of this study can be generalized only to student population similar to the sample used in this study. The resource-rich environment in both schools enabled students to have a high degree of computer literacy. These student characteristics and research design features should be considered when using the findings of this study to inform curriculum design or formulate new research hypotheses. Additionally, due to the large number of variables including time, number of teachers, presence of external stakeholder or not, and scale of the project, this study does not attempt to identify a single factor that contributes to the differences in students' learning between the two different design project implementations.

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Author Information

Molly H. Goldstein
School of Engineering Education
Purdue University
USA
Contact e-mail: *goldstm@purdue.edu*

Robin S. Adams
School of Engineering Education
Purdue University
USA

Şenay Purzer
School of Engineering Education
Purdue University
USA

Sharifah A. Omar
School of Ag & Biological Engineering
Purdue University
USA