SUSTAINABILITY EDUCATION OF ENGINEERING STUDENTS USING
AUGMENTED REALITY AND SIMULATION GAMES

A Dissertation in
Architectural Engineering

by

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ABSTRACT:

The world we live in is rapidly changing, both in terms of technology in society as well as the world itself. Engineering students are expected to grasp more concepts in a faster manner than ever before in order to adapt to this rapidly changing world. For future engineers to stay relevant in society, they must be taught important concepts in such a way that they can gain all necessary information in their relatively short college years. The field of sustainability is a key engineering topic gaining attention in recent years due to our changing world conditions. Current teaching methods intended to introduce Architectural Engineering students to in-depth sustainable building design concepts do not typically begin until the later part of students’ academic careers.

This research sought to improve sustainability education of engineering students through the development and implementation of an augmented reality-based simulation game called ecoCampus. ecoCampus allowed first-year engineering students to create different “what if” design concepts, visualize those designs in the context of an existing space, and receive performance feedback about those concepts related to sustainability and other key building metrics. The findings from the implementation of ecoCampus were compared to two other, paper-based experimental treatment activities to understand the benefits of this type of tool.

ecoCampus was shown to help students resist the tendency toward design fixation within the context of a self-directed, time-constrained learning environment better than with the use of paper-based design methods. Additionally, through the design brainstorming process, students demonstrated a tendency to critically assess their design concepts to improve their developed designs more than students who completed the paper-based methods were able to do. In addition to the educational contributions, this research documented the process for creating this type of new educational tool, which included the specific steps followed to create ecoCampus as well as the pitfalls that were observed during development. The findings from this research have helped to create an understanding about how these types of technologies can be used in future educational research efforts and also an understanding of a process that can be followed for developing future applications like ecoCampus.
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CHAPTER 1 INTRODUCTION

“Education is not the filling of a pail, but the lighting of a fire.”
- William Butler Yeats

1.1 Background

Students generally have only a finite amount of time at a given educational institution to gain the necessary knowledge and skills required to live the professional lives they desire. This poses a challenge to students and educators in the engineering discipline because the curriculum continues to grow with an ever changing world, while the amount of time students spend at school remains constant. The Accreditation Board for Engineers and Technology (ABET), American Society of Civil Engineers (ASCE) and other panels and blue ribbon commissions have said that engineering students need to be better trained in, among other things: engineering fundamentals, “real-world” engineering design, material in frontier areas of engineering, critical and creative thinking skills, and problem-solving methods, all while maintaining few enough credit hours in the engineering curriculum so that students can complete it in four years (American Society of Civil Engineers 2008; Felder et al. 2000; Rugarcia et al. 2000). This is a lofty goal that requires educators to teach more efficiently so that students are able to achieve increasing levels of understanding about key engineering principles.

Currently, there are problems with the process of teaching engineering students. There tends to be a mismatch between the learning styles of engineering students and the teaching styles of professors (Felder and Silverman 1988). Teachers tend to rely on lecture-based instructional methods, which is reliant on an instructor’s ability to verbally convey a substantial amount of information. While there are potential benefits to this type of instruction, there are several potential pitfalls with this approach as well (Wankat and Oreovicz 1993). Engineering students tend to require, among other things, visual learning opportunities and feedback on their performance (Wankat and Oreovicz 1993). Lecture-based teaching methods may not typically meet these learning needs (Finke 1990; Finke et al. 1996; Rieber 1994). Despite this mismatch,
the lecture-based teaching method continues to be the standard instructional method employed in education (Felder et al. 2000). As a result, the challenges associated with the education of engineering students today are largely the same problems that occurred in years past because the teaching process has not greatly evolved with the times (Mills and Treagust 2003; Rugarcia et al. 2000). To combat this problem, teaching methods must become more innovative. Instructors must begin to employ new methods and technologies to engage and educate students so that engineers, in a broader sense, remain beneficial and relevant to society in the future (American Society of Civil Engineers 2008; National Academy of Engineering 2004).

1.2 Problem statement

The current challenges associated with the engineering educational process require not only a shift in the teaching methods employed at universities, but also in the topics that are covered. While there are many topics that may be significant for engineering students of today, arguably none are more important than the topic of sustainability. Buildings account for nearly 40% of all energy consumption in the United States and the criticality of designing sustainable buildings for our future is only likely to increase (U.S. Department of Energy 2011; U.S. Energy Information Administration 2010). The following sections examine the problems related to engineering education on a broad level, but also the specific challenges associated with the current educational methods for teaching sustainable design concepts at The Pennsylvania State University.

1.2.1 Engineering education at large

By and large, engineering students tend to be visual learners (Felder and Silverman 1988; Wankat and Oreovicz 1993). Because teaching methods have generally not strayed from a lecture-based teaching method that does not emphasize visual learning, there is a mismatch between teaching styles and learning styles of students in the engineering discipline (Finke et al. 1996; Mills and Treagust 2003; Rieber 1994; Rugarcia et al. 2000). This is clearly a challenge in
the way that engineering education is addressed today. With all great challenges, however, come great opportunities.

One possible method for addressing the challenges associated with the education of engineering students is to utilize teaching methods that employ new technologies to teach course content in a more interactive and engaging manner. Recent advances in mobile computing technologies may offer a significant benefit to students in the engineering discipline as a complement to the traditional lecture-based methods. This research has specifically targeted augmented reality and simulation game technologies to offer an efficient and visual learning environment that can be fun and engaging (Aldrich 2005; Bartle 2003; Nikolic et al. 2010). This type of active student engagement in the learning process can have very positive effects on the skills that students take away from the activity (Galarneau 2004).

1.2.2 Engineering education at The Pennsylvania State University

As described in Sections 1.1 and 1.2.1, there are significant challenges associated with education of engineering students at colleges today. This research explores the potential for new educational methods to take a first step toward improving the broad engineering education process by focusing on educating engineering students at Penn State. Specifically, this work explores the topic of sustainable building design in the engineering discipline. This topic has been gaining significant attention in recent years in building design, construction, and operation (Bernstein 2010). It is of particular importance because buildings consume almost 40% of all energy in the United States and is only likely to increase in the future (U.S. Department of Energy 2011). Engineering students must become better prepared to understand the sustainability implications of building design concepts to attempt to slow or even reverse this trend of high energy consumption of built environments.

In the Architectural Engineering (AE) Department at Penn State, the topic of sustainability is widely researched among different students and faculty members in different design options, discussed in certain extracurricular groups and organizations, and studied through certain class
projects and assignments. These opportunities offer students a chance to learn about sustainability in-depth, typically, as it relates to a specific building system. Many of these hands-on opportunities for students to learn about sustainability in the built environment occur in their later years of study, which may be due in part to the fact that students are not admitted into the AE program until after their first year and are still learning the fundamental AE principles until their later years of study. In striving to achieve the educational goals set forth by the NAE (National Academy of Engineering 2004) and ABET (Felder et al. 2000), there is a need to teach sustainability in a building engineering context early in the educational process to adequately prepare students for their future academic years and eventual careers.

1.2.3 Engineering education in first-year case study course at The Pennsylvania State University

In striving to better educate students about building sustainability earlier in their academic careers, this research targeted the first-year seminar course for students interested in AE at Penn State (AE124S). In semesters prior to this work, an interactive, hands-on design activity had not been incorporated into the sustainability portion of the course. Instead, tours of the School of Architecture and Landscape Architecture’s (SALA) Stuckeman Family building on Penn State’s University Park campus were offered. The SALA building obtained the Leadership in Energy and Environmental Design® (LEED) rating’s gold level of certification, which is tied for the highest rating of any building on campus. The tours offered were coupled with an in-class lecture related to sustainability and the LEED point system. While there is certainly still value in these traditional methods, there are also some drawbacks associated with these methods alone.

With traditional instructional methods, students are provided information which they then need to remember. This does not inherently require extensive student attention. Students who are disinterested or distracted are not necessarily forced to actively listen during the tour or in class. Disengaged students may retain only a small amount of the information discussed (Dewey 1913). Furthermore, they may even begin to talk, use electronic devices, or engage in another form of distracting behavior. In this case, not only are these students not retaining any of the information
mentioned, but they may also inhibit other students in the class from retaining the relevant information as well.

In addition to holding students’ attention, other challenges related to information consistency are present in the guided tour. To accommodate the many different student class schedules, several tours are given during different timeslots. The challenge with offering many different timeslots is that the same tour guide typically cannot cover all tour times. Therefore, several tour guides may be required to cover all of the different tour times. This introduces the possibility of inconsistency between tours. While tour guides are given the same basic material to review prior to giving their tours, each guide will have a slightly different background understanding of the building and sustainability concepts. This different perspective on each tour could allow certain points in the tour content to be presented differently from what was expected or omitted entirely.

Aside from the fact that students can disengage with the tour material and get different information from different tour guides, the tour itself only includes the most basic level of learning. From the revised Bloom’s taxonomy (Krathwohl 2002), the traditional tour typically only involves information related to the basic knowledge or remembering level of learning. Higher level thinking skills such as analysis, evaluation, and creation are not mandated by this passive teaching method.

From a situated learning theory perspective, the guided tours and in-class lecture may not create the best environment for students to learn. Ultimately, the reason for discussing sustainability in AE education is to prepare students to go on in their future careers so they may eventually apply this knowledge of sustainability to future building projects. Situated learning theorists suggest that the best way for someone to learn content that will eventually be applied to a certain situation is to actually learn while in that situation (Lave and Wenger 1991). In the context of AE, this means that the best way to teach new engineering students how to design more sustainable buildings is to put them in a situation where they may actually attempt to design a particular building system.
1.3 Overview of research

This work has explored how the education of building design and engineering students can be improved through the implementation of augmented reality (AR) and a simulation game design activity. In this research these technologies have helped to improve student learning in a few specific ways, which is supported by prior research that suggested benefits of these technologies in visualization and obtaining feedback about design possibilities not afforded through traditional lecture and tour-based teaching methods (Azuma 1997; Furmanski et al. 2002). This research has examined the benefits of using these technologies in a self-directed learning context through the development and implementation of a new educational tool, called ecoCampus.

ecoCampus is a mobile computer-based application that tasks students with redesigning a particular building component for an existing building on Penn State’s campus. For the initial development of this new tool, students were tasked with redesigning the SALA Building’s exterior curtain wall. The developed prototype allowed students to explore several “what if” design scenarios, visualize those designs in the context of the existing building, and receive tailored feedback about their design. With the incorporation of feedback in the ecoCampus interface, users are challenged to critically assess the different forms of feedback they receive to determine how to modify a particular design to improve performance. To complete this design activity, students were required to utilize higher level thinking skills, beyond simple knowledge-based understanding. To create a successful wall design concept, they needed to understand the sustainability information that they were taught: apply the concepts to a new sustainable design; analyze and evaluate the design concept to determine if it would meet necessary performance goals; and create their finalized design.

To help to isolate the variable of implementing a computerized technology-based design activity from the act of completing a design activity alone, several different paper-based versions of the sustainable design activity were implemented in the first-year AE seminar course at Penn State while ecoCampus was being developed. The data collected through the different treatment activities was compared to assess specific aspects of the learning that varied based on the format of the activity. This process of developing computerized and non-computerized versions of the
sustainable building design activity as well as the analysis of results has helped to answer specific research questions.

1.4 Research questions

This research has provided an understanding of two questions related to sustainable building design education through the use of augmented reality and simulation games:

1. What is the pedagogical value of using an augmented reality-based simulation game to improve sustainable building design education for engineering students and students in related disciplines?

2. What are the key steps for creating a functional augmented reality-based simulation game for educating engineering students about building design?

To address these broad research questions, more specific sub-questions were addressed in this work. To address the broad topic of pedagogical value related to the use of augmented reality and simulation games, several sub-questions were answered including:

1.a) Can this mode of interaction engage students in a self-directed, time-constrained learning environment?

1.b) Can this mode of interaction encourage students to resist the tendency toward design fixation in a self-directed, time-constrained learning environment?

1.c) Can this mode of interaction get students to utilize higher level thinking skills to critically analyze designs to create better design solutions to problems?

1.d) What are the aspects of the learning process that do not benefit from the use of an augmented reality-based simulation game interface?
In addition to providing an understanding of the pedagogical value associated with an augmented reality-based simulation game, a better understanding of the process associated with developing and implementing these technologies in the engineering classroom has also been generated. In addressing the second broad research question related to the process for developing an augmented reality-based simulation game and leveraging this technology in the engineering classroom, the following sub-questions were addressed:

2.a) What is the general process necessary to develop a program like ecoCampus?

2.b) What specific tasks were necessary to develop ecoCampus?

2.c) What potential pitfalls were observed while creating ecoCampus that hindered the development process?

1.5 Research scope

This project focused on developing and implementing an augmented reality-based simulation game to understand the benefits and challenges associated with creating and using this technology for educating students about building sustainability. The prototype created, called ecoCampus, has been developed as a proof-of-concept-level prototype. While it is a functional tool, it still has certain limitations and is not intended to be a commercially viable system. It has served to illustrate several key educational benefits that an augmented reality-based simulation game can offer building design students related to sustainability.

The process by which ecoCampus was developed is intended to help future researchers, but it has not been validated through the creation of several different educational tools. The process documented is not considered to be the best possible process for development, but rather a process that, if followed, can successfully lead to a functional educational tool. The value of this work is in its contribution to the current body of knowledge related to the pedagogical value of
augmented reality and simulation games in engineering and the development of tools using these technologies. This contribution can offer benefit to future research that intends to expand the use of these technologies to further enhance the design education environment.
CHAPTER 2 LITERATURE REVIEW

To frame the work conducted in this research, this chapter explores prior related works. These prior works have shown the benefits that augmented reality and simulation games can offer for a variety of contexts. Additionally relevant educational studies and theories are covered to illustrate how this work ties into existing research. Finally, the works are summarized to identify the knowledge gaps that currently exist where this research project will provide new knowledge to the current understanding of how augmented reality and simulation games can benefit engineering design and sustainable education.

2.1 Learning styles

In order to understand how ecoCampus can benefit students, it is important to understand the learning styles of the students who are the targeted users for the application. There are several possible categories for learning styles of students. Research has identified and described the different learning styles among students, in general (Felder and Silverman 1988). The findings of this research are summarized in Table 2-1. Engineering students tend to have a strong preference toward (among other learning aspects) active, visual learning experiences where they can obtain feedback about their experience (Felder and Silverman 1988; Wankat and Oreovicz 1993).

In addition to the different learning styles that can be present among students, the actual process of learning has been broken down into components (Krathwohl 2002). This research examined Bloom’s Taxonomy (Bloom 1969) and updated several aspects of the learning processes originally described. These specific processes can be seen in Table 2-2, along with a few typical verbs to describe each cognitive process. These learning processes have been identified and modified by several different researchers (Bloom 1969; Krathwohl 2002; Wankat and Oreovicz 1993). While they may differ slightly in terminology or the ordering of one or two of the categories, they all generally agree that the depth of learning increases as students use the higher numbered cognitive processes. While all of these cognitive processes can be taught to students, frequently only the first three are tested (Wankat and Oreovicz 1993). This presents an
educational opportunity to structure learning activities to encourage students to develop and utilize the higher level thinking skills that will be required of them in their future academic and professional careers.

Table 2-1: Summary of preferred student learning styles and the corresponding preferred teaching style with a brief description of that style adapted from (Felder and Silverman 1988).

<table>
<thead>
<tr>
<th>Preferred Learning Style</th>
<th>Preferred Teaching Style</th>
<th>Description of Learning Style</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensory Perception</td>
<td>Concrete Content</td>
<td>Students prefer to gather data through the senses and learn through specific facts and data.</td>
</tr>
<tr>
<td>Intuitive Perception</td>
<td>Abstract Content</td>
<td>Students prefer to learn through speculation, imagination, and hunches and be taught basic principles and theories.</td>
</tr>
<tr>
<td>Visual Input</td>
<td>Visual Presentation</td>
<td>Students prefer to learn through pictures and figures and they retain more course content from visual stimuli.</td>
</tr>
<tr>
<td>Auditory Input</td>
<td>Verbal Presentation</td>
<td>Students prefer to learn through words and sound and they retain more of course content from discussions and explanations.</td>
</tr>
<tr>
<td>Inductive Organization</td>
<td>Inductive Organization</td>
<td>Students prefer to learn from simple examples to form their understanding of the broader general concepts.</td>
</tr>
<tr>
<td>Deductive Organization</td>
<td>Deductive Organization</td>
<td>Students prefer to learn broad general concepts and then back up these concepts with more specific applications.</td>
</tr>
<tr>
<td>Active Processing</td>
<td>Active Student Participation</td>
<td>Students prefer to experiment with learning content and assess outcomes to learn educational concepts.</td>
</tr>
<tr>
<td>Reflective Processing</td>
<td>Passive Student Participation</td>
<td>Students prefer to manipulate and experiment with information introspectively.</td>
</tr>
<tr>
<td>Sequential Understanding</td>
<td>Sequential Perspective</td>
<td>Students learn processes in a step by step process gradually building up their understanding of material.</td>
</tr>
<tr>
<td>Global Understanding</td>
<td>Global Perspective</td>
<td>Students may not pick up a great deal of knowledge from learning individual steps until they suddenly “get” the bigger picture.</td>
</tr>
</tbody>
</table>
Table 2-2: Description of the cognitive processes adapted from (Krathwohl 2002).

<table>
<thead>
<tr>
<th>Cognitive Process</th>
<th>Verbs to describe cognitive process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Remember</td>
<td>Copy, Define, Identify, Indicate, Label, Name, Recall, Recognize, Reproduce, State</td>
</tr>
<tr>
<td>2. Understand</td>
<td>Categorize, Chart, Classify, Explain, Generalize, Infer, Predict, Relate, Summarize</td>
</tr>
<tr>
<td>3. Apply</td>
<td>Choose, Compute, Demonstrate, Develop, Employ, Produce, Restructure, Solve, Use</td>
</tr>
<tr>
<td>4. Analyze</td>
<td>Appraise, Break down, Combine, Deduce, Detect, Distinguish, Question, Separate</td>
</tr>
<tr>
<td>5. Evaluate</td>
<td>Argue, Assess, Conclude, Critique, Explain, Judge, Justify, Recommend, Validate</td>
</tr>
<tr>
<td>6. Create</td>
<td>Change, Compose, Construct, Derive, Design, Expand, Generate, Plan, Produce, Synthesize</td>
</tr>
</tbody>
</table>

### 2.2 Educational theories

With all of the different learning styles and different levels of learning that exist, there is not one single best way to educate all students on all topics. Different educational theories exist to understand the benefits of various learning environments and educational strategies, which may offer benefit to different types of students with different learning styles. In this section, the educational theories and prior works that relate to the core educational functions of ecoCampus are covered.

#### 2.2.1 Active learning environments

Active learning has been generally defined as an instructional method that engages students in the learning process (Prince 2004). It has also been defined as a format of learning requiring students to actually do things and think about what they are doing (Bonwell 1991). In a college classroom there can be many different students with different backgrounds and these different students can have different learning styles and, therefore, require different instructional environments for achieving maximum benefit outside of strictly lecture-based environments (Anderson and Adams 1992). Active learning strategies can be effective in engaging the students who do not learn as well from lecture-based learning environments. Prior work has showed that
the introduction of computer-based, interactive, and engaging activities allow undergraduate students across a range of different backgrounds to significantly improve their understanding of physics principles (Chi 2009; Hake 1998; Laws et al. 1999). Other work has shown that students can not only show improved test scores, but also more engagement with course content through active learning environments (Oliver-Hoyo and Allen 2005). While active learning environments often strive to help students develop higher level thinking skills, there may also be benefit to active learning environments for developing basic thinking skills as well.

There is a great deal of support for active learning environments and many different texts that discuss methods for implementing active teaching strategies into the classroom (Meyers and Jones 1993; Wankat and Oreovicz 1993), but there are also others who question active learning as an educational method (Prince 2004). Active learning often strives to enable learners to develop higher level thinking skills, yet assessments traditionally quantify lower-level understanding of subject matter. Therefore, it is often difficult to generate values that lead to conclusively disproving null hypotheses and showing that active learning environments directly create better learning for students. Researchers who question the merits of active environments as a sole source of education still reference the classic study (Judd 1908) that observed that students could not expand upon learning as effectively from purely active learning as those who were in a learning environment with both active learning as well as traditional instruction (Ambrose et al. 2010).

2.2.2 Situated learning theory

Other research suggests that the greatest educational benefits can be obtained through not only active learning components, but situated learning components, where students learn new content within the context where that learning will be applied (Lave and Wenger 1991). Traditional lecture-based learning environments often strip the contextual activity within which the abstract classroom concepts will be applied (Seely Brown et al. 1988). The introduction of situated learning environments in education allows students to learn as they apply knowledge so that they shift from peripheral participation in the discipline to central participation (Hung 1999). This is
believed to be of particular value in the engineering education realm because of the project and problem-based nature of the engineering discipline (Johri and Olds 2011). Some researchers argue that situated learning theorists have overstated the benefits of learning within a particular situation (Reder et al. 1996), but even this work does not go on to suggest that there is not benefit of situated learning, but rather that there is still benefit to other educational environments where students learn out of the situational context.

The prior studies suggest active learning environments have shown benefits over traditional lecture-based learning environments, but they should not be seen as a replacement to lecture-based methods. Instead, active learning environments should be seen as a complement to traditional classroom lectures. In this way, ecoCampus was not seen as a replacement to the traditional sustainable building educational experience, but rather a complement to it. It added a relevant situated learning component to the class, which helped to better understand the benefit that ecoCampus coupled with lectures and tours would offer over the traditional methods alone.

2.2.3 Motivation in education

In addition to understanding the impact of the learning environment, it is also critical to consider how the students will be motivated to learn. Students must be motivated to learn new content by some means or it is simply not possible to achieve any educational benefit (Maehr and Meyer 1997). On the surface, this may seem readily apparent: if a student has no drive to learn a new topic, he or she will not invest any effort in creating a new understanding of a particular concept. Extrinsic motivation incentivizes a person to do a task in order to receive a certain reward and it has been the norm for motivating employees and students to achieve success in the past, but data suggests that it may actually impede progress for certain tasks (Deci et al. 2001). In this research, students are tasked with completing a design problem where the quality of their design does not affect their grade. All students will get credit for simply completing the design activity, thus removing much of the extrinsic motivation to attempt to create the best design possible. The different activity formats were examined to identify any differences observed, which help to indicate the students’ intrinsic motivation to create effective designs.
2.2.4 Design fixation

Engineers who are motivated to create the best design possible for a given design challenge typically need to brainstorm different possible design ideas to determine the strengths and weaknesses of the different design concepts. Many times, these designers blindly adhere to a set of ideas or concepts that limit the output of conceptual design (Jansson and Smith 1991). This occurrence is called design fixation and can hinder design processes. Sometimes people are not even aware that they are experiencing fixation during design (Linsey et al. 2010). This research explores the benefits that an augmented reality-based simulation game can offer in motivating students to consider multiple design ideas before finalizing on one concept.

2.3 Visualization in education

Students’ abilities to solve problems can be greatly affected by how they visualize a given problem, but problem visualization is seldom stressed in education (Finke 1990; Finke et al. 1996; Rieber 1994). Furthermore, within the design disciplines, students have a challenging time visualizing complex building and construction information, thus supporting the need for improved pedagogical methods through implementing proper visualization strategies (Dede and Lewis 1995; Dede et al. 1999). In general, engineering students learn about dynamic spatial and temporal information predominantly through static 2D means. For example, when attempting to convey a building design to students, traditional teaching strategies use 2D paper plans to convey the 3D building concept. This requires students to internalize the information on the pages and mentally construct the three-dimensional representation of the facility. This process tends to be challenging for students and is prone to inefficiencies and inaccuracies in their mental representations (Johnson 1997).
2.4 Augmented reality

To facilitate visualization of course related content related to this research, augmented reality will be used. Augmented reality (AR) is considered to be a subset of the more general term mixed reality. Mixed reality (MR) is defined as a mixing of real and virtual worlds along the virtuality continuum shown in Figure 2-1 (Milgram and Kishino 1994).

![Virtuality Continuum](#)

Figure 2-1: Milgram and Kishino's (1994) Virtuality Continuum shows the range where mixed reality can fall, from just before completely real and completely virtual environments.

In this spectrum, AR would allow a user to view predominantly real world content augmented with some digitized graphical content, whereas augmented virtuality would involve a user viewing predominantly virtual content with some aspect of “reality” incorporated into their view, such as position or viewing direction. This mixing of real and virtual worlds occurs with the use of technological devices to blur the line between reality (what is seen in the purely physical environment) and virtuality (what is seen in the purely virtual environment).

A common example of augmented reality would be the yellow first-down line that can be seen during a televised football game. In this example of augmented reality, a user views a predominantly real view of the world through the camera with a small piece of virtual geometry superimposed onto the screen. Conversely, at the other end of the mixed reality spectrum, a GPS system that is used in a car for navigation would be considered augmented virtuality because it is
predominantly a virtual system with a small piece of reality (a user’s position) incorporated into the user experience.

2.4.1 History of mixed reality

While Milgram and Kishino (1994) are credited with defining and classifying AR as part of the virtuality continuum, the actual term “augmented reality” comes from a study with Boeing (Caudell and Mizell 1992). This study sought to develop an AR system utilizing a head-mounted display (HMD) to allow workers responsible for constructing the 747 aircrafts to see key locations for attaching certain elements during assembly. While Boeing’s “augmented reality” term was a novel concept from this study, the idea and technology behind it was not. Looking even further back through the history of mixed reality, one can see that the first use of augmented reality came in 1968 with Ivan Sutherland’s Head-Mounted Three Dimensional Display (Sutherland 1968). Sutherland’s device used an HMD that would change views as a user would change positions. Looking back further still, before this basic version of AR was developed, there was an even more rudimentary project that would be considered augmented virtuality (Heilig 1962). Morton Heilig’s “Sensorama” system involved a movie that a user would watch and, during the movie, the user would also experience vibrations, gusts of air, 3D sounds, and scents.

2.4.2 Computer vision

While the augmented reality systems have evolved over the years, all AR systems still require a link between the virtual and physical worlds. In creating this link, a computer must possess the ability to automatically recognize what it is seeing in a use case. Once a computer understands what it is viewing in the real world, it can overlay a variety of graphical information on the view of the real world. This process of deciphering meaningful, explicit descriptions of objects from images is known as computer vision (Ballard and Brown 1982).
Computer vision often uses algorithms to predict where a given object is likely to be in a screen. Numerous studies across several disciplines have utilized fiducial markers to achieve computer vision, which are images that a camera can recognize in a space to act as a point of reference for superimposing desired content (Dunston et al. 2003; Kato and Billinghurst 1999; Thomas et al. 2000). In addition to determining a specifically designed marker location, computers can also use algorithms to predict objects by color patterns (Bradski 1998). The Continuously Adaptive Mean Shift (CAMSHIFT) algorithm developed in this research was used to view video of a human face and generate a flesh probability image to predict where a human face was likely to be present in the video. Several studies have also elected to determine a camera view by determining a user’s position and viewing direction with GPS or Wi-Fi location (Behzadan and Kamat 2007; Feiner et al. 1997; Höllerer et al. 1999). This methodology removes the need to analyze the real-time imagery viewed through a device’s camera and opts, instead, to navigate and display appropriate content from a virtual model based on a position input from the location systems mentioned.

Once computer vision is achieved and a link is created between a computing device and the physical world objects, graphical content can be automatically retrieved or generated on top of a user’s view. This process of automation of graphical information generation based on computer vision can offer significant benefit to a user. Whereas mechanical automation of systems tend to offer the most benefit for “grunt work” tasks that are repetitive, physically intensive, require speed, strength, or repetitive motions, or occur in hostile environments (Everett and Slocum 1994), automation of information and graphics generation also would be best suited for informational “grunt work” tasks. In the context of building visualization, this may mean using computers to automatically generate graphics to show what a building design might look like in the context of a real space. This can be a relatively simple task for a computer, but a far more challenging task for inexperienced students to perform accurately (Johnson 1997).

2.4.3 Augmented reality in education

Augmented reality offers the potential for students to improve their understanding of a given problem by allowing them to visualize a design concept in a more intuitive and interactive
The use of AR visualization can motivate learners and help to spur students’ creativity and potentially improve their ability to develop an optimal design (Kosslyn 1994; Pan et al. 2006). Augmented reality has been tested in several educational applications. It has been implemented to allow students to better visualize geometric shapes relevant to math and geometry problems (Kaufmann and Schmalstieg 2003). This marker-based system used AR for visualization of problem data in a collaborative setting where multiple users could see the same geometry at the same time, but were not able to manipulate the virtual content in the real world. Augmented reality was also studied in a basic engineering context (Liarokapis et al. 2004). This study used AR to allow engineering students to visualize relevant models to the course material. Students could browse the web-based AR content to view 3D models of several different engine components, but this virtual content could not be modified by the user.

2.5 Simulation games

In addition to using augmented reality for visualization of building designs, a simulation game has also been incorporated into the ecoCampus experience. Prior research indicates significant potential benefits from using simulation games in education (Aldrich 2005; Nikolic et al. 2010). Simulation games have the potential to engage students in the learning process and, instead of traditional lectures telling students how to create a solution to a problem, they encourage students to experiment in a safe environment to determine the best method for determining a solution for themselves (Gee 2005; Squire 2005). This learn-through-doing approach can offer significant benefits to the learning process (Schank 2002).

2.5.1 Defining simulation games

The term “simulation game” has been created to identify a technology that has both characteristics of a simulation and a game. Simulations are models that attempt to approximate a situation, environment, or set of events to predict, teach, or entertain (Prensky 2004). Games, on the other hand, are defined as: having rules; having variable and quantifiable outcomes; having value assigned to possible outcomes; requiring player effort; requiring a player to become
attached to the outcome; and having negotiable consequences (Juul 2003). Simulation games are, therefore, defined as contests between individuals that move toward specific goals under sets of conditions and constraints that will sufficiently model a real-world situation (Gredler 1994; Jacobs and Dempsey 1993).

2.5.1 Simulation games in general education

The concept of using simulation games in education occasionally receives negative feedback from critics who have negative opinions of these technologies because of bad connotations associated with the term “game”. Furthermore, because the recreational video game industry tends to be on the leading edge of game development technology, the user of a simulation game whether in an educational context or not, is often referred to as a “player” as opposed to a “user” (Bartle 2003). This type of terminology has a way of propagating the belief that simulation games do not belong in the classroom. However, research suggests that one of the key educational benefits that simulation games offer is to frame a problem in terms of a specific situation, which can create an ideal environment for learning and skill acquisition (Aldrich 2004, 2005; Bartle 2003; Brown et al. 1989). This type of engaging learning environment that can be created with simulation games helps to put students in a position to take an active role in their education, which can improve their understanding of systems, decision-making skills, and shift their perspectives based on the results of the simulation game (Galarneau 2004). Compared to traditional lecture-based teaching methods, simulation games may also offer benefit to students in that they provide a chance to engage in learning-through-doing by actively testing decisions and receiving immediate feedback on those decisions (Schank 2002).

2.5.2 Simulation games in engineering education

Building design and construction educators have made several efforts in the past to investigate and validate the merits of simulations and games in the building engineering discipline. The Virtual Construction Simulator 3D (VCS 3D) and Internet-based Interactive Construction Management Learning System (ICMLS) have been developed to determine the benefits of
implementing this type of technology in engineering education (Jaruhar 2007; Nikolic et al. 2009, 2010; Sawhney et al. 2001). These research efforts have focused on developing and implementing a virtual reality interface with a simulation game specifically for educational purposes where students can visualize a construction schedule so that they can optimize the construction planning process. These studies suggest strong educational benefits with utilizing simulation games to illustrate construction scheduling concepts.

2.5.3 Simulation games in conjunction with mixed reality in education

In general, the combination of a simulation game with augmented reality for the purposes of engineering education is not common. Of all of the prior research reviewed, the study that most closely relates to this research used an augmented virtuality interface with a simulation game called “Environmental Detectives” to get college and high school students to play the role of environmental scientist to monitor the spread of a hypothetical toxic spill (Klopfer and Squire 2007). Students would physically walk around a campus where they would attempt to locate high chemical concentration readings with a handheld computing device from the spill. In this study, it was shown that students were highly engaged with the activity, which would suggest it may be able to offer benefits to the learning process as compared to a traditional lecture (Klopfer and Squire 2007).

2.6 Summary

Existing research indicates that engineering students tend to be visual learners who require feedback in the educational process to fully grasp engineering concepts. The traditional teaching methods intended to convey critical engineering content that will eventually be applied to solve real-world problems misses the opportunity to educate students about these concepts in the context in which they will eventually be applied. There is evidence that suggests that the incorporation of new technologies may be able to offer improvement to the learning environment over traditional instructional methods alone. Augmented reality can offer several benefits to students related to visualization of building design content, specifically when viewing that
content in relation to the existing built environment. Furthermore, simulation games, when developed and implemented properly, have the ability to engage students more than traditional teaching methods. Simulation games can provide a learning environment where students learn-by-doing. From a situated learning theory standpoint, this allows engineering students to learn content within the context where it will eventually be applied.

The prior research efforts reviewed have sought to explore the potential benefits that augmented reality and simulation games can offer in several different disciplines. Studies were developed that used AR for visualization of geometry, but did not incorporate the goal-directed component of a simulation game. Studies were conducted to determine the benefit of using simulation games for engineering educational purposes, but did not utilize the visualization aspects of AR to view content in the context of a built environment. Finally, some work has also examined the potential of using augmented virtuality with a simulation game to educate engineering students, but not in a design context.

In conclusion, many different works have suggested benefit in using AR and simulation games for educating students. The benefits suggested of these prior technologies closely align with the educational needs of engineering students as suggested by prior educational theories. Despite the suggested benefits of these tools, there have not been efforts to directly combine the two technologies to target building design students. This research has leveraged these technologies to teach students about sustainability and the design process earlier in their academic careers than previous methods afforded. The key pedagogical findings and best development practices for ecoCampus have been documented from this work to allow future research to leverage the findings to improve engineering education.
CHAPTER 3  METHODOLOGY

This research project studied the effects of incorporating an interactive sustainable design activity with an augmented reality-based simulation game. To study the effects of this technology, Figure 3-1 shows an outline of the approach for achieving the objectives of this

<table>
<thead>
<tr>
<th>Pre-Proposal</th>
<th>Literature review</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fall 2011 Semester</td>
<td>Design participant experience for research</td>
</tr>
<tr>
<td></td>
<td>Develop activity without attributes of application</td>
</tr>
<tr>
<td></td>
<td>Implement with students</td>
</tr>
<tr>
<td>Spring 2012 Semester</td>
<td>Analyze results</td>
</tr>
<tr>
<td></td>
<td>Develop paper-based version of application</td>
</tr>
<tr>
<td></td>
<td>Implement with students</td>
</tr>
<tr>
<td></td>
<td>Analyze results</td>
</tr>
<tr>
<td></td>
<td>Develop ecoCampus prototype</td>
</tr>
<tr>
<td>Summer 2012</td>
<td>Alpha test with graduate students</td>
</tr>
<tr>
<td></td>
<td>Modify ecoCampus based on alpha test</td>
</tr>
<tr>
<td></td>
<td>Initial implementation (T3.1) with AE students</td>
</tr>
<tr>
<td>Fall 2012 Semester</td>
<td>Modify ecoCampus based on implementation</td>
</tr>
<tr>
<td></td>
<td>Second implementation (T3.2) with AE, ARCH, and CE students</td>
</tr>
<tr>
<td>Spring 2013 Semester</td>
<td>Compare results</td>
</tr>
<tr>
<td></td>
<td>Document results</td>
</tr>
<tr>
<td>Summer 2013 Semester</td>
<td>Defend dissertation</td>
</tr>
<tr>
<td></td>
<td>Graduation</td>
</tr>
</tbody>
</table>

Figure 3-1: Flowchart of research methodology
research. The study involves three main experimental treatment activities, labeled “T.1, T.2 and T.3” on the figure. The third treatment, involving the use of the developed ecoCampus application, included two different implementations of the tool. These two implementations are referred to as T3.1 and T3.2 for the first and second implementations, respectively. The processes and treatments listed in this figure are further broken down and discussed in this chapter.

3.1 Literature review

To complete this work, a review of existing literature related to the topics in this research has been conducted, which is included in Chapter 2. The survey of literature highlighted the key aspects of technologies and educational strategies that have been suggested to offer benefits in a variety of contexts based on prior works. This helped to illustrate the current knowledge gap in understanding how new technologies can be used to create a beneficial learning experience to specifically target students learning about sustainable building design.

3.2 Designing the student experience

This research was set up with a quasi-experimental structure to attempt to isolate the different treatment activity format experiences. Figure 3-2 shows the basic process that each student participant followed in this work. Two of the processes listed in the figure had traditionally existed in the first-year AE seminar course. The other activities are new activities related to this research. Other than the “Research treatment activity,” the processes followed by the students were held as constant as possible between all of the treatments. The student experience is described in this section.
3.2.1 In-class sustainability lecture

Students enrolled in AE124S were presented with a 50-minute, in-class lecture and discussion about sustainability in the building context. During this lecture, an overview of the LEED® rating system was covered. This overview included a discussion of the LEED point categories and the theories behind each of the categories. While not every individual LEED point was discussed, the magnitude of how many points can be obtained in each category was covered.

3.2.2 Sustainability tour

Many of the students who participated in this work from the first-year Architectural Engineering seminar course (AE124S) also attended a guided tour of Penn State’s School of Architecture and Landscape Architecture’s (SALA) Stuckeman Family building. These tours were offered to students and counted toward their attendance of one of the five required out-of-class activities for the course. During the tour, guides explained several features of this LEED gold-rated building. The tour guides presented information on the LEED points that were obtained, the rationale behind how these different points were intended to help increase sustainability, and other
interesting facts and anecdotes related to the building’s design, construction, and operation processes.

3.2.3 Research treatment processes

In addition to the traditional sustainability course content offered to students enrolled in AE124S, all students who participated in this research also completed design activities related to this work. These sustainable design treatment activities had not traditionally been a part of the course curriculum. These research treatment activities are described in detail in Sections 3.4, 3.5, and 3.6 in this chapter.

3.3 Designing the assessment tools

To understand the pedagogical value of the ecoCampus experience, it was necessary to collect appropriate data to qualify and quantify the results of the experimental treatment activities. Therefore, assessment tools were developed in conjunction with the development of the application itself. The assessment tools consisted of several different parts intended to elicit data to understand the implications of the implementation of this research. The responses to the assessments helped to answer several questions including:

- How do the design processes differ based on the experimental treatment activity completed?
- How do the students feel about the activity completed?
- Were the students engaged and did they enjoy the activity?
- Was the time commitment for learning appropriate for the skills and information gained?
- How do students feel that the activity needs to be improved in order to maximize learning?
3.3.1 Pre-tests

Students completed pre-tests after the in-class sustainability lecture and also after they had an opportunity to take the guided tour of the SALA Building, but prior to performing the sustainable building design activities. These anonymous quizzes gathered basic background information and helped to determine baseline knowledge of sustainability, LEED, and basic design principles. This test offered both closed- and open-ended problems related to the building redesign activity. Students were also asked questions related to their overall enthusiasm about completing this activity. The pre-tests administered can be found in Appendix J and Appendix K.

3.3.2 Surveys

An online survey was conducted prior to students completing any of the treatments associated with this research. The survey obtained targeted demographic information about the students as well as information related to their background experience with engineering problems and sustainability. The questionnaire provided in this survey also elicited responses about the extent to which students had used mobile computing devices in the past as well as their experience with other related technologies. The responses to these assessment tools helped to better understand the students’ performance in using the developed application. The survey given to students is included in Appendix J.

3.3.3 Post-tests

After the experimental treatment activities were completed, students took in-class post-tests with questions about sustainability as well as questions related to their impression of the experience. As with the pre-test, the post-test included both closed and open-ended questions to better understand quantitatively and qualitatively the levels of feedback and depth of student understanding. These post-test questions sought student feedback on issues related to the format of the activity, perceived value of this activity, and level of enjoyment that students had while completing the activity. This student perspective helped to provide information about how the
different treatment activities were received by the class. The post-test given to students is included in Appendix J and Appendix K.

3.3.4 Reflection questions

After students completed the experimental activity, they were also given several reflection questions to complete in an online quiz. Students were asked questions related to exterior curtain wall designs and also about other building design scenarios to solicit responses of how those scenarios would relate to building sustainability. The questions from this online reflection quiz are included in Appendix J.

3.3.5 Focus group discussions

In addition to asking directed qualitative and quantitative questions in the surveys and tests, student feedback was also generated through discussion focus groups. These focus groups offered a less-structured venue for students to provide their thoughts on their particular treatment activity experience. During these focus groups, students frequently provided formative feedback on the format of a given treatment activity, functionality of the activity, and useful features for future development of the ecoCampus interface. These sessions helped to foster discussion of topics that were not initially covered in the research assessments.

3.3.6 Instructor’s feedback

As the instructor for the first-year AE seminar course in which this research was implemented, information related to the observed learning experience was also developed from an instructor’s perspective. This feedback helped to identify other behaviors observed in the different treatment activities that were not directly collected in the assessments. This will also help to guide future application improvements and identify potential future developments for course-specific learning scenarios.
3.4 Treatment 1: Develop, implement, and analyze design activities without attributes of computer application

To understand the benefits that can be obtained by leveraging augmented reality technology in conjunction with a simulation game, the intended curtain wall redesign challenge was given to first-year engineering students without ecoCampus in the Fall 2011 semester. This helped to illustrate the inherent behaviors of first-year Architectural Engineering students who would not be influenced by a mobile computing experience during their design process. Prior to this in-class design activity, the students were exposed to a basic level of background information related to sustainability in buildings and the design process through the in-class lecture and the SALA Building tour. The events that the students were involved in for this activity are described in chronological order:

3.4.1 Sustainability tour and lecture

As mentioned in Section 3.2.2, many of the AE124S students participated in a guided tour of the SALA Building on Penn State’s University Park campus. During this tour, they were exposed to some background information related to the SALA Building and its LEED gold rating. Students were also presented with a 50-minute lecture and discussion about sustainability in the building context as described in Section 3.2.1.

3.4.2 Pre-activity assessments

Prior to completing the Treatment 1 design activity, students completed the pre-test and survey quizzes described in Sections 3.3.1 and 3.3.2. The survey quiz was administered in the class session prior to the design activity session to allow for more time for designing in the following week’s class. Prior to completing the survey quiz, students were provided with an informed consent sheet to inform them of the research activity being performed. Students were given the opportunity to either allow or not allow their data to be used for this research. Regardless of whether students gave consent to allow their data to be used or not, they were still given the
opportunity to complete the same activities. In compliance with the Institutional Review Board requirements for this project (IRB Protocol ID 37206), students were also given an experimental ID number that would be used to anonymize their responses to the assessments. The list linking experimental ID numbers to student names was not seen by the instructor until after the end of the semester after the grades were finalized and posted. Students submitted both the survey quizzes and pre-tests without listing their names and only listed their experimental ID numbers.

3.4.3 *In-class design activity*

With a basic level of understanding of sustainability concepts, students completed an open-ended, in-class design activity to improve the sustainability performance of a LEED rated building on campus. They were told that the SALA Building, which is tied for the highest rated LEED building on the campus, was to be redesigned to be even more sustainable. The assignment tasked students with redesigning the building’s curtain wall. The students were not told how to complete the design process or specific building design strategies for improving sustainable performance. Instead, students had to determine for themselves the best process for generating a new design concept for the building’s curtain wall to improve sustainable performance.

For this activity, students were provided several blank sheets of paper on which to illustrate their intended design ideas. Additionally they were given a sheet to fill out with questions related to their design process that they used to address the design challenge. The specific handouts provided to students can be seen in Appendix B. The blank sheets provided intentionally lacked any suggestion of a process for beginning to approach this design activity. Instead, students were required to determine a process for themselves. The students had to rely on their prior knowledge obtained through the guided tours, the in-class sustainability lectures, and any information they could ascertain from physical presence and exploration of the existing building space to generate improved design concepts. To understand the intuitive processes that first-year engineers would employ to approach this design project, students were required to document their conceptual ideas via hand sketches and also document their process for designing through a few directed questions about the process they went through to complete the activity.
Students were given approximately 40 minutes to illustrate their design idea and also document their process. During this time, the instructor would answer procedural questions related to the assignment, but would not answer questions related to a suggested design method, optimal material choices, or advantageous geometric layouts, which required students to make the best judgments they could with the knowledge they had. At the end of the 40 minute session, several students had not completed the activity to their own satisfaction. To allow students to fully formulate their thoughts, they were given the opportunity to submit their completed assignment at the beginning of class the following week.

3.4.4 Post-activity assessments

After the activity, regardless of where the students were in their design process when the design session ended, all students were asked to pause/stop their work and complete an anonymous post-test to determine some additional information as described in 3.3.3. Students submitted these post-tests without their names and only their experimental ID numbers to identify them. After class, students also completed a follow-up reflection quiz online. This quiz covered the content described in Section 3.3.4.

3.4.5 Focus group

A few weeks after the activity, several students met for focus group sessions to discuss their perceptions of the activity as discussed in Section 3.3.5. While these sessions were not anonymous, the face-to-face interaction allowed several students to build off of the ideas and thoughts raised by their peers. These sessions served as an opportunity for less structured feedback from the students about the design activity. There were two one-hour sessions held with approximately ten students in attendance at each session.
3.4.6 Analysis

After all of the elements of this activity were completed by the students, the responses to pre-test and post-test assessment questions were coded and compiled. Because of the nature of this design task, the submitted designs varied with regard to detail and quality of documentation, which did limit the level of assessment that could be made about the designs. For example, there was not enough structure in the activity to allow the researchers to quantify thermal performance, cost, or daylighting performance for every single design submitted. Therefore, the submitted designs were examined for major common trends. These common trends were also identified in the assessment questions. The compiled data was then analyzed to determine some conclusions from the work to better understand the innate design processes that were employed by first-year engineering students as well as the educational benefits and challenges associated with this type of educational method. The results of the Treatment 1 implementation can be found in Section 5.1.

3.5 Treatment 2: Develop, implement and analyze activities with paper-based version of application

To better understand the process by which students might want to use a computerized augmented reality-based simulation game, a paper-based approximation of ecoCampus was developed for Treatment 2. The workflow for this activity includes some of the same tasks that would be completed in the computerized ecoCampus format, but without the use of a mobile computing device. Treatment 2 was implemented with two sections of AE124S in the spring 2012 semester.

3.5.1 Develop Treatment 2

This treatment activity was developed to task students with redesigning the exterior curtain wall for the SALA Building to attempt to make it perform more sustainably, similar to the activity described in Treatment 1. Unlike the Treatment 1 activity, where students were not provided with any suggestion for how to complete the curtain wall redesign, this treatment provided
students with multiple images of a typical curtain wall bay of the SALA Building with the existing wall dimmed in the background and also with the wall removed. Students were still responsible to submit their design(s), but they could illustrate their design concepts on the provided images. The two images provided can be seen in Figure 3-3.

![Figure 3-3: Two printed images were provided to students completing the design activity on which to illustrate their design ideas.](image)

In addition to supplying students with the printed images of the curtain wall, students were also given a list of possible building materials to use in their curtain wall redesign. This list of materials was intended to approximate the experience of having the ecoCampus library of materials to choose from when designing. It included a wide range of materials that could be used in a building project, including concrete, brick, copper, drywall, stone, stucco, wood, or architectural glazing choices. Students could select as many of the materials listed as they felt they wanted. To further encourage students to think creatively and challenge the material choices that were used in the existing design, students were also told that they could deviate from the provided list of materials if they felt there was a better material choice that could be used in their design. The specific materials provided in this Treatment 2 activity can be seen in Appendix C.
3.5.2 Pre-activity student experience and assessments

Prior to arriving at the SALA Building for the class session involving Treatment 2, the students who participated in Treatment 2 followed the same process with regard to sustainable background activities described in Sections 3.2.1 and 3.2.2. Students who completed the Treatment 2 activities also completed the same pre-activity assessments described in Sections 3.3.1 and 3.3.2. To keep their responses to these assessments anonymous, the students were all given a unique experimental ID number, which was not known to the instructor of the course until after grades were finalized for the semester.

3.5.3 Implement Treatment 2

When students arrived to the SALA Building to complete the design activity, they were given a brief verbal explanation of the design scenario. They were also supplied with the packet of materials in Appendix C, which also included written instructions for what they were being asked to do. The students were given the packets and told that as they designed, they could use unlimited additional printed images with the backgrounds dimmed or removed as necessary. Extras were supplied in a central location so they could access additional copies as needed. In addition to designing a new exterior curtain wall for the SALA Building, students were also tasked with documenting the process that they followed to complete their design and reflecting on their perceived performance of the materials they selected in their design on the second page of the supplied packet.

Students were given approximately 40 minutes to complete the design activity. Like the Treatment 1 activity, the instructor answered procedural questions related to the activity, but would not provide direct answers related to what building design choice might perform best to achieve a particular design goal. Instead students were forced to use their background knowledge and any information that could be gathered from their physical exploration of the SALA Building to guide their design choices. At the end of the session, students were given the opportunity to either submit their work or take home their design documents and submit them at
the beginning of class the following week if they felt they did not have adequate time to complete the activity in class.

3.5.4  **Post-activity assessments**

At the end of the design session for Treatment 2, students were asked to pause/stop their work and complete a post-test as described in Section 3.3.3. Then after class, students were also asked to complete an online reflection quiz as described in 3.3.4. Both of these assessments were anonymous and students provided only their experimental ID numbers. After completing the post-activity assessments, students were given the opportunity to participate in a focus group session as discussed in Section 3.3.5.

3.5.5  **Analyze data from Treatment 2**

Treatment 2 provided insight into the process that students employed to solve a basic design problem when supplied with only a basic level of guidance on how to complete the activity. This basic process guidance was intended to approximate ecoCampus in a paper format. The designs submitted by the students were analyzed to determine common trends.

Much of the analysis to Treatment 2 sought similar information as what was determined in Treatment 1, such as how many design concepts students would consider during the class session, how many materials students would consider over the course of the design session, if the submitted designs would address some aspect of sustainability, how much students enjoyed the activity, and how students felt about the amount of time and information supplied to complete the activity. Additionally, it was observed in Treatment 1 that several students deviated from the specific building system that was targeted in this design activity. Therefore, it was of interest to determine if the images supplied in this treatment activity would help to keep students focused in their design efforts on the curtain wall system of the SALA Building. The results from the Treatment 2 implementation can be found in Section 5.2.
3.6 Treatment 3: Develop, implement, and analyze activities with ecoCampus

In this third and final treatment, students completed the sustainable exterior curtain wall redesign activity in the SALA Building using the developed ecoCampus prototype on a mobile computing device. The development of ecoCampus is discussed in detail in Chapter 4. The results from this treatment were compared to the prior treatment activities to better understand how the use of augmented reality technology in conjunction with a simulation game can be used to enhance certain aspects of the sustainable design education process. The developed ecoCampus application was pilot tested during the fall 2012 semester with Architectural Engineering students. This first version, called Treatment 3.1, was then further developed based on the feedback from the implementation as described in Section 4.6.2 and is referred to as Treatment 3.2. The Treatment 3.2 version of ecoCampus was implemented in the spring 2013 semester with Architectural Engineering students, Architecture students, and Civil Engineering students. The processes followed during both implementations were similar, but there were a few key differences which are covered in this section.

3.6.1 Treatment 3.1 pre-activity assessments

Students who completed Treatment 3.1 attended the in-class sustainability lecture and SALA Building tour as described in Sections 3.2.1 and 3.2.2. The students were given experimental ID numbers with their informed consent forms in the class session prior to using ecoCampus so they would have adequate time to design with ecoCampus the following week. The students also completed the same anonymous pre-activity assessments as described in Sections 3.3.1 and 3.3.2 prior to beginning the design activity.

3.6.2 Treatment 3.1 implementation

In Treatment 3.1, students were given 40 minutes of the 50-minute class session to complete their designs with ecoCampus. At the beginning of the activity session, students were given a brief, five-minute overview of the ecoCampus workflow so they would understand how to use
the application. After this overview, students were each given a mobile computing device on which to work for the class session. They were told that they must complete a minimum of one design idea, but were free to create more as time would permit. As they would complete different designs using ecoCampus, they were instructed to take screen captures on the provided iPad so that they could later reexamine their work to recall what they had done in each design iteration and what they had learned. During this design session, the instructor would answer procedural questions related to the activity, but would not answer questions related to suggested design methods, optimal material choices, or advantageous geometric layouts. Instead, students had to rely on the visual feedback provided through the AR interface and the simulation feedback received. In the last five to ten minutes of the design activity, students were asked to reflect on their ecoCampus designs. They were asked to review each design iteration along with the feedback generated for each and indicate whether or not they agreed with the provided feedback. If they disagreed with the feedback they were asked to justify why they felt that they may have been right or wrong despite what ecoCampus told them. This reflection form that was completed is included in Appendix F.

3.6.3 Treatment 3.1 post-activity assessments

After students completed Treatment 3.1 and the reflection exercise regarding their designs, they completed the post-test in class as described in 3.3.3. After they completed the anonymous post-tests they completed anonymous, online reflection quizzes as described in Section 3.3.4. Finally, students had the opportunity to participate in a focus group session a few weeks after the design activity as described in Section 3.3.5.

3.6.4 Treatment 3.1 data analysis

After the students had completed all assessments in Treatment 3.1, the collected data was analyzed. The submitted design screen capture files were analyzed to determine how many designs each student explored during the activity as well as how many different building materials they considered while designing. In addition to assessing the designs that students
submitted, the pre- and post-activity assessments were assessed to determine what benefits were observed related to students understanding of sustainability. Additionally, the feedback generated by the students was analyzed to determine how much students enjoyed the activity, how appropriate they felt this interface was for the design activity, and how they felt about the amount of time to complete the activity. The results to this analysis are included in Section 5.3.1.

In addition to analyzing the collected data from a pedagogical point of view, the feedback collected was also examined to determine how the ecoCampus interface might be improved to create a better design experience for future semester implementations. Several suggestions were generated by students that helped to improve ecoCampus for the following implementation. The specific modifications to ecoCampus are discussed in Section 4.6.2.

3.6.5 Treatment 3.2 pre-activity assessments

During Treatments 1, 2, and 3.1, it was observed that some students would occasionally not complete all assessments or would forget their experimental identification number so their responses to the assessments could not be relinked to their submitted designs. Students who completed Treatment 3.2 were comprised of not only students from the first-year Architectural Engineering seminar, but also from a third-year Civil Engineering course and a third-year Architecture course. Because of the added complexity of additional students from a variety of different major courses and the observed tendency for students to forget their ID numbers, the assessments administered in Treatment 3.2 were modified slightly from the descriptions in Sections 3.3.1 - 3.3.4. The Treatment 3.2 assessments were modified to include a single pre- and post-test that would be completed immediately before and immediately following the design activity using ecoCampus. This modified assessment version eliminated the need to complete follow-up assessments online and also made it easier for students to remember their experimental ID number. These modified assessments can be seen in Appendix K.

Prior to arriving at the SALA Building, the students enrolled in the first year AE seminar had the same opportunities to attended the in-class sustainability lecture and SALA Building tour.
described in Sections 3.2.1 and 3.2.2. The students in the Civil Engineering course did not attend the sustainability lecture, but did have the opportunity to attend the SALA Building tour prior to completing the ecoCampus activity. The students in the Architecture course did not attend the sustainability lecture or the SALA Building tour prior to using ecoCampus, but it may be worth noting that the Architecture students’ studio space is located within the SALA Building, so they were still familiar with the facility from working on other design projects there. When students arrived to the SALA Building to complete the Treatment 3.2 activities, they were given an experimental identification number, informed consent form, and a pre-activity assessment, regardless of what background experience they had with sustainability.

### 3.6.6 Implement Treatment 3.2

When students completed the pre-activity assessment and turned in their informed consent forms, they were given approximately 40 minutes to interact with ecoCampus. At the beginning of this time, students were given a brief five-minute overview of how to use ecoCampus and the goal of the assignment. They were told that they had to complete a minimum of one curtain wall design for the SALA Building, but were welcome to complete unlimited additional designs as time would permit. During this time, the instructor would only answer procedural questions and would not give direction as to how to design a curtain wall or what materials to select in a given design. As the students would create their wall design concepts, students were instructed to take screen captures of each design concept that they explored to allow them to later review their different design choices. At the end of the 40-minute session, students were told to stop their work on ecoCampus and review each design iteration screen capture similar to the reflection activity completed in Treatment 3.1. The reflection form that was completed in Treatment 3.2 is included in Appendix H.

### 3.6.7 Treatment 3.1 post-activity assessments

After students completed their design work and the reflection activity using ecoCampus, they completed a modified version of the post-activity assessments, which are included in Appendix
K. Unlike the prior treatments, the post-activity assessments completed in this treatment were completed immediately following the design activity. This eliminated the need for students to complete an online reflection section and made it easier for them to remember their experimental ID numbers. For the students enrolled in the first-year AE seminar course, they also had an opportunity to participate in a focus group session following their completion of the Treatment 3.2 activities as discussed in Section 3.3.5. Because of the way that course credit was offered for attending a focus group session, the students from Civil Engineering and Architecture did not participate in the focus groups.

3.7 Compare results from all experimental treatment activities and document results

The data obtained from all of the treatments was analyzed to determine how the developed ecoCampus prototype benefited students in the learning process. Inherent in this analysis were comparisons of the data obtained in Treatments 3.1 and 3.2 to the results obtained in Treatments 1 and 2. These comparisons helped to isolate the variable of the addition of this computerized AR simulation game tool to determine the added benefit from these technologies and address the core research question for this dissertation. The detailed discussion of the results is included in Chapter 5.

In addition to understanding the pedagogical benefits related to these technologies, this research also sought to understand the process for developing a tool like ecoCampus. To facilitate future developments of new educational design tools like ecoCampus, the process used and best practices for development that were identified throughout this work were documented for others educators at Penn State and other academic institutions. This will serve as a reference for future work to lower the initial effort required to develop and implement similar new educational tools. The detailed description of the ecoCampus development process is included in Chapter 4.
CHAPTER 4  ECOCAMPUS DEVELOPMENT PROCESS

This research aimed to understand the benefits and challenges associated with using augmented reality in conjunction with a simulation game for educating students about sustainable design concepts in the built environment. As a core component of this work, a prototype application, called ecoCampus, was created to help understand the educational value of these technologies. This chapter explores the process of creating ecoCampus. The general process for creating this type of application has been documented in top portion of Figure 4-1. The specific activities performed to develop ecoCampus are shown in the lower process map in Figure 4-1. This chapter explores this detailed process used to create ecoCampus which helps to validate the plausibility of the general application development process map.

![Diagram of ecoCampus Development Process](image-url)

Figure 4-1: Application development process maps for general design education application and ecoCampus application development.
For the initial ecoCampus prototype, one design module was developed to challenge students to redesign an existing building’s exterior curtain wall to attempt to make it perform more sustainably. It is envisioned that ecoCampus will evolve over time to encompass additional design modules for a variety of building types. The curtain wall redesign module was developed to create a proof-of-concept level application that could help to identify the benefits of using augmented reality in conjunction with simulation games for enhancing engineering education. As ecoCampus evolves over future iterations, this same development workflow will be followed as closely as possible to create the additional educational content.

4.1 Identify educational objectives

The first necessary step in developing this new educational tool was to develop a list of educational objectives for the developed ecoCampus experience to facilitate. When ecoCampus was initially being developed, an extensive list of possible educational objectives was created. Because of the broad nature of sustainability in the building context, there are a myriad of different educational objectives that could be targeted by a tool like ecoCampus. Therefore, for this initial ecoCampus proof-of-concept, the created list was analyzed to determine which of the objectives would be the highly targeted objectives in the ecoCampus prototype developed in this work, with the [Targeted in ecoCampus] designation, and which objectives would not be specifically targeted in this first version, but would be potentially advantageous in the future, with the [Future ecoCampus development] designation.

- [Targeted in ecoCampus] Design a new exterior wall to improve sustainability in an existing building.
- [Targeted in ecoCampus] Brainstorm several possible design ideas in the design process.
- [Targeted in ecoCampus] Consider possible building materials other than just those used in the existing design.
- [Targeted in ecoCampus] Consider the visual implications of a wall design in the context of the surrounding space.
- [Targeted in ecoCampus] Recognize examples of building design tradeoffs related to curtain wall redesign.
- [Future ecoCampus development] Recognize examples of building design tradeoffs related to other building systems.
- [Future ecoCampus development] Learn the LEED point categories.
- [Future ecoCampus development] Quantify how many additional LEED points can be obtained by a particular design.
- [Future ecoCampus development] Learn potential drawbacks of the LEED system.
- [Targeted in ecoCampus] Recognize the consideration between initial costs and lifecycle costs for different designs.
- [Future ecoCampus development] Quantify the payback periods for different building design concepts.

The created list of objectives helped to target development efforts toward creating an environment that could facilitate learning these objectives. This is not to say that every student learned every single objective targeted. In a self-directed learning situation, like the one used in this research, students may interact differently with a developed tool and take away different lessons. The point of creating this list was to decide from the beginning what specific things were highly desirable for students to learn so that those learning objectives could drive the development of this initial ecoCampus prototype. For the results, including which of the targeted learning objectives were achieved by ecoCampus, see Chapter 5.

4.2 Develop list of application functional requirements

Along with creating a list of educational objectives, a list of desired features of ecoCampus was developed to help prioritize key application functions that would create an environment that would facilitate the desired learning outcomes. During this initial planning step, different functional requirements that were envisioned to add a certain level of benefit to the user were
identified. For many of these functional requirements, several different levels of detail were identified. The different items were considered to determine which were absolutely necessary, with the [Must Have] designation, and which would be possibly beneficial to the experience, with the [Nice to Have] designation. As this initial ecoCampus prototype was developed, all of the high-priority goals and some of the lower priority goals were implemented and the rest of the goals were left for future developments of the application.

The following items were included in this functional requirement list generated:

- [Must Have] Create engaging, easy-to-use work flow.
  - [Must Have] Allow students to learn how to use application and complete design processes within 50-minute class session.
  - [Must Have] Create a game environment where users are challenged to consider design implications.
  - [Must Have] Create enough challenge to the game experience so a user is incentivized to attempt to improve on prior design ideas.
- [Must Have] Allow users to define materials that they intend to use in design.
  - [Must Have] Allow users to select from predefined materials.
  - [Nice to Have] Allow users to define new materials to be incorporated in the application.
- [Must Have] Allow users to define geometry where they intend to use different building materials.
  - [Must Have] Allow users to select predefined geometry on the exterior wall design to define larger regions of different building materials.
  - [Nice to Have] Allow users to freely define any geometry for building materials on wall.
- [Must Have] Allow users to navigate physical space and see a full scale virtual representation of their design idea through augmented reality (AR).
  - [Must Have] Allow users to examine one typical exterior wall bay.
  - [Nice to Have] Allow users to examine any bay throughout the building to visualize their design.
- [Must Have] Generate tailored sustainability feedback about a given design.
- [Must Have] Provide user with qualitative feedback about their design related to daylighting and thermal properties.
- [Nice to Have] Provide user with updated LEED scorecard that is modified based on design modifications.
- [Nice to Have] Provide user with performance feedback that compares their design to the existing building’s design.
  - [Must Have] Generate tailored feedback about cost implications of a given design.
    - [Must Have] Provide cost for constructing entire wall design.
    - [Must Have] Provide cost for each material in wall design.
  - [Must Have] Generate feedback from different project participant points-of-view.
    - [Nice to Have] Aesthetics
    - [Nice to Have] Constructability
    - [Must Have] Cost
    - [Must Have] Daylight usage
    - [Nice to Have] End-user feedback/functional properties
    - [Must Have] Thermal properties

4.3 Application workflow: ecoCampus curtain wall redesign

After the list of functional requirements was developed and prioritized, storyboard images were generated to strategize a method for achieving the developed functional goals through the planned application workflow. The initial storyboards generated for ecoCampus are included in Appendix D. After these initial storyboard images were developed, the workflow was analyzed to consider the end-user’s experience. From the initial storyboard images, it was determined that the workflow of the application was more complex than it had to be, which could create unintended challenges for the users of ecoCampus. For example, the initial storyboard workflow intended to create one interface for defining building geometry and a separate interface for defining what materials would be used in a design.
The application experience was simplified to three basic steps. The first was the design phase, where a user would define both geometry and materials for their wall design. Then a user would proceed to the visualization phase, where they would view their design concept overtop of the existing building design through the use of AR. Finally, the user would enter the simulation phase of the application, where they would receive tailored feedback about their design.

4.4 Determine development infrastructure for creating application

After the initial storyboards were created and the planned ecoCampus workflow began to take a specific shape, it was necessary to examine the existing tools and technologies that would help to create the application to function as closely as possible to the original workflow intent. When determining the technological infrastructure for developing ecoCampus, it was determined that ecoCampus would need a mobile computing platform on which a user could complete the design activities associated with the application. The mobile computing devices used would need to be lightweight, have a video camera, and adequate computational power to handle the graphical and computational load required for visualizing design content and generating performance values based on a given design. In order to develop on a platform that would lend itself for future expansion, the two possible computing platforms initially identified were Apple iOS and Google Android. Both of these operating systems are becoming commonplace in the world of smartphones and mobile computers. Both operating systems can also be installed on devices that have the necessary video cameras to be able to run the fiducial marker-based ecoCampus application. For this research, the Apple iOS platform was chosen for development, but it was important to develop ecoCampus in a format where it could be expanded to run on both iOS and Android-based devices in the future.

The next key step in the ecoCampus development process was to determine the appropriate environment for developing the application content. The Unity 3D game engine was selected as an appropriate game development platform for this work. It offered a C# and JavaScript-based game development environment that was also capable of exporting a developed game to a variety
of different computing platforms, including both Apple iOS and Google Android as well as many of the other popular video game system and computing platforms.

Unity 3D allows for the development of game content and functions in a given application such as buttons and game objects that can be custom-made, as well as the incorporation of pre-developed plugins created by third parties. To facilitate AR within Unity 3D, an existing Unity 3D add-on was used so that the process of linking game content to a printed fiducial marker would be more seamless. String is a Unity 3D plugin that allows a user to add a camera within Unity with built-in scripts so that the camera constantly searches for a defined image. When the image is identified, String identifies a user’s position by the calculated angle of view of the marker. Then, String can display a Unity 3D game object over the printed marker when viewed through a user’s mobile computing device based on the size and calculated angle of the marker.

In summary, the infrastructure determined for this work used four critical elements that worked in tandem to achieve the ecoCampus performance requirements: String AR plugin for Unity 3D; Unity 3D; XCode compiler; and the Apple iOS mobile operating system. The technical specifications and performance benefits of these components, as well as the computer used for development can be seen in Table 4-1.

4.5 Graphical user interface development

After the development infrastructure was chosen, the graphical user interface (GUI) development began. The GUI development process is fairly straightforward with Unity as it is specifically designed to facilitate game development. The creation of buttons and different scenes to facilitate different user interactions in the game is completed within Unity using either a modified C# or JavaScript code.

The different interfaces envisioned in the early functional requirement brainstorming and storyboarding processes were created by developing different “scenes” within Unity. For example, the design interface was one scene, the AR visualization interface was another scene,
Table 4-1: Components used in ecoCampus development

<table>
<thead>
<tr>
<th>Necessary Component</th>
<th>Chosen Product</th>
<th>Benefits/Reasons for Selected Product</th>
</tr>
</thead>
</table>
| Development Computer | Apple iMac  
- 2.7GHz Intel Core i5 processor  
- 4GB 1333MHz DDR3 Memory  
- AMD Radeon HD 6770M  
512MB Graphics Card  
- Mac OSX Lion 10.7.4 |  
- Mac OSX system necessary for programming on iOS platform  
- Built-in webcam for debugging application before building to iPad |
| Mobile computing platform | Apple iPad  
- (3rd Generation)  
- iOS Version: 6.0 |  
- Lightweight mobile computing platform  
- Touch screen interface  
- Built-in camera  
- Large, high-resolution screen |
| Application compiler | XCode  
- Version 3.5 |  
- Allows created content to be built to iOS devices |
| Graphical user interface (GUI) development environment | Unity 3D Game Engine  
- Version 3.5.4 |  
- High quality graphical rendering  
- Simple GUI development  
- Can export applications directly to XCode compiler |
| Marker-based augmented reality technology | String  
- Version 1-1-3 |  
- Plugin to Unity 3D game engine  
- Real-time tracking of fiducial marker by game camera  
- Beneficial for indoor object registration |

and the simulation results interface was an additional scene. Buttons were developed to allow a user to switch between scenes and each scene would allow for a different camera configuration to affect the user experience. For example, in the design interface and the summary scenes, an ecoCampus user does not have control of the game camera that views GUI content. As a result, the user can only interact/view game content, but cannot manipulate the three dimensional view of the game content, which provides the user with a 2D game experience. In the AR visualization scene, the String plugin for Unity links a game camera to a user’s mobile computer camera so the augmented content changes its position based on the user’s physical view.

4.5.1 Development of design interface

Unity allows for simple material rendering and lighting options within the developed game. Material textures used for rendering can be developed within Unity or can be custom imported
images that can be attached to game objects. When developing ecoCampus, the simple material rendering was a valuable feature for the design interface experience. During development, specific building material choices were determined so that users would be able to choose from one or more of those specific material textures to assign to different pieces of curtain wall geometry as they created their designs.

The curtain wall game object used in the design scene and visualization scene was originally created in AutoCAD. The wall geometry was subdivided into 140 blocks that users would eventually be able to individually modify in ecoCampus. After the model file was created, it was converted to an .FBX file through Autodesk’s 3D Studio Max and then imported into Unity into the design interface scene.

To modify the subdivided curtain wall blocks, buttons were added on the right side of the drawing interface that were linked to each of the chosen material textures. The textures were applied over the buttons so a user could visually see the material choices. As a user would select a given material, it would set that material to the active material through a basic count function. Then, when a user would select a piece of wall geometry, the current material count would render the appropriate material to the appropriate piece of wall geometry.

**4.5.2 Creation of augmented reality experience in ecoCampus**

The process of linking the virtual content defined in the design interface to a marker to be redisplayed in an AR format was relatively simple. String is designed as a plugin to Unity to facilitate marker-based AR and is compatible with the iOS platform. Therefore, linking the model content to a custom marker involved very little development effort. The model file imported into Unity was displayed in a new scene with the materials assigned during design attached to each curtain wall block. The model was then displayed when the camera identified the printed fiducial marker.
While the process of registering the curtain wall model to a fiducial marker was relatively simple, the bigger challenge that arose during the creation of the augmented reality visualization scene was ensuring the augmented virtual content was scaled properly with the existing physical space. Improperly scaled virtual content would not provide the illusion of a fully constructed curtain wall. With a fiducial marker based approach to AR, like the one used in ecoCampus, the size of the augmented virtual content is determined by the size of the printed marker. For the curtain wall design module explored in this research, it was important to determine an appropriate size of printed fiducial marker. Several different marker sizes were examined. Initially, a 60”x80” marker was used. While this marker would allow for stable tracking of augmented content from a distance where a user could view the entire wall, it became more difficult to explore virtual content as a user would approach the wall because of the need to keep the entirety of the marker within a user’s camera view. A second 40”x55” marker was later tested. This marker still allowed for effective tracking, but because of the reduced size, also allowed users to get closer to the augmented content before a portion of the marker would be lost from the camera view and the augmented content would subsequently disappear. These two markers can be seen in Figure 4-2.

![Figure 4-2: Two different fiducial marker sizes were explored during the development of ecoCampus before the smaller marker on the right was chosen.](image)

After an appropriate marker size was determined, a scaled mockup of the actual curtain wall with the actual fiducial marker hung on the wall was created in the computer lab where ecoCampus was developed. There was not sufficient space to recreate the entire curtain wall, so
the brick pier that can be seen below the printed marker was replicated by taping pieces of paper to a wall of the computer lab with the actual marker hung at the appropriate distance above the brick pier. This simple mockup provided a reference to help in scaling the virtual content. While scaling this content, it was not necessary to build the three-dimensional mass of different building elements as the only dimensional concerns were in the X and Y directions. Scaling became a trial and error process to get the virtual content at the right scale relative to the brick pier. One scale would be arbitrarily selected and would then be modified based on whether the augmented model content needed to be larger, smaller, higher, or lower on the wall to match with the brick pier. While this might seem like a tedious process, the simple mockup created within the lab where ecoCampus was being developed greatly helped to speed up this scaling process.

4.5.3 Simulation game development

One of the goals of the ecoCampus workflow was to get students to reflect on their exterior wall designs as they completed their design process. The application uses a simulation game for decision support. While it was not feasible to calculate exact values of all design parameter metrics in ecoCampus, due to hardware and software limitations, the feedback generated by the developed application was intended to reflect realistic numbers to give users an accurate sense of the impact that a given design change would have on a building project. This process of determining appropriate relationships between key building variables required some reduced order modeling to allow for accurate representations of the performance properties which would be impacted by design decisions. In this exterior wall redesign module, there were several performance factors that were included. In the first version of ecoCampus, students were provided with three different design review perspectives including:

- Building owner: This virtual reviewer would provide comments based on the design’s upfront cost. When the simulation interface was opened, the quantity of each material would be counted and multiplied by the unit costs of each material. The costs for different materials were estimated through RS Means construction cost data. The total cost would then be calculated by adding all of the values for the quantities of each
material used in a given design. The owner would then generate comments based on a series of threshold values which were created. These comments would range from very negative comments (“Look, we’re not made of money here. This is a public university. We simply cannot afford the upfront cost of this design.”) to very positive comments (“Wow, that’s cheaper than we had expected.”)

- **Lighting Engineer:** This virtual reviewer provided comments based on the amount of daylight that could enter the building space. These comments were based on the window to wall ratio in the space. This method of generating lighting performance values allowed ecoCampus to easily calculate performance feedback and provide that feedback in a simple way so that students with minimal engineering background could use it to inform subsequent wall designs. When the simulation interface was opened, a count function would count the total amount of glazing on the wall and compare that to the total wall area. The lighting engineer would generate comments for the ecoCampus user based on the window to wall ratio at different threshold values. The lighting engineer would make negative comments if students used little or no glass on their design to allow for daylight (“This design will not allow for any daylight to enter the space. We’ll have to rely solely on interior light fixtures.”) As users added additional windows to the design, the lighting comments would improve (“This design is great. There will be enough daylight entering the space to save some money through a reduction in necessary task lighting.”) After a certain point, the benefit offered by daylighting would begin to diminish and the lighting engineer’s comments decline again (“This design uses a lot of glass. We won’t need to rely on many interior lighting fixtures during the day, but we’ll likely have problems with glare.”)

- **Mechanical Engineer:** This reviewer’s comments to ecoCampus users provided feedback about lifecycle cost associated with heating and cooling a space with a particular curtain wall design. To quantify the lifecycle costs of thermal performance, R-values were calculated for a given design idea to indicate the level of thermal resistance that the design would exhibit. R-values were provided in ft²·°F·h/Btu. R-values are frequently used to quantify the thermal performance, which is why they were chosen as an appropriate feedback unit to use to quantify thermal performance in ecoCampus. While the unit of value for R-values may look relatively complex, it offers a simple, numeric
value that students can use to quickly assess thermal performance by recognizing that the higher the R-value, the more insulated wall assembly will be. When the simulation interface is opened, a count function counts the different materials used and calculates the overall wall R-value based on pre-programmed values for each material choice. The mechanical engineer subsequently generates feedback based on threshold R-values. When a design had a very low R-value the mechanical engineer would provide negative feedback about the design (“That design will cost a fortune in heating and cooling costs.”) When a design had a very high R-value the mechanical feedback would be much better (“Incredible! It will be extremely cheap to heat and cool a building with this design.”)

In the first version of ecoCampus, only these three critiques were provided to students. While these are certainly important viewpoints to consider while creating an exterior wall design, they are not a comprehensive list of design concerns. For example, they do not take into account the opinions of the end users (students and faculty), aesthetic implications, or constructability concerns. While the students who used ecoCampus might be qualified to make judgments about how much they would like the wall design from an aesthetic perspective, they might not inherently have the ability to determine constructability feedback for themselves about their designs. In the early work conducted for this research, it was observed students would not always consider the number of different materials that were incorporated into their designs, the geometry of their designs, or the difficulty associated with procuring different materials in their design. Therefore, for the second implementation of ecoCampus a fourth virtual critic concerned with constructability was added to the simulation game interface.

- **Construction Manager**: This reviewer generated comments for a user based on the number of materials used in a given design. In other words, as students incorporated additional different materials that would need to interface with one another, the construction challenges to build the given design would continue to become more challenging. When the simulation screen was called, a count function would determine the total number of different materials used in a design. The construction manager would generate comments based on the number of materials counted. For simple designs with
only one building material the construction manager would comment, “This is great! I’ll only need to hire one crew to build this design. We might even be able to finish this earlier than expected.” For designs with many materials, the construction manager would say “With this many materials in the design, this will cost substantially more to construct than we had initially discussed.” If students used more than 9 materials in a given wall design the construction manager would become angry and ask, “What is this, some kind of joke?!? Look how many materials are in that design. I can’t build that!”

While it could be argued that several of these virtual critics abstract the views of a real critic, i.e. the owner will care about more than just upfront project cost, for educational purposes these critics helped to illustrate some generalized views from each person. This helped to provide guided feedback to direct the design processes for the ecoCampus users. Additionally, the threshold values also abstract the feedback from a real critic, i.e. adding one more window might bump the lighting engineer comment up to the next level of satisfaction, which may be unlikely to significantly affect a real lighting engineer’s opinion of a particular wall design. Again, for an educational application like ecoCampus, this was deemed to be an acceptable simplification. On any building project, each designer may have slightly different internal ranges of acceptability for a project design. Therefore, the value in these critiques is in their ability to illustrate the competing interests among the different project participants, which is not contingent on having a perfectly precise feedback mechanism.

4.6 Application testing: Identifying and addressing problems with ecoCampus prior to (and after) implementation

While ecoCampus was being developed, several potential problems were identified. Alpha testing was performed with a group of graduate students to further identify other potential application bugs and shortcomings. This section describes the problems that were identified during development and the subsequent activities performed to mitigate the problems that were identified.
4.6.1 Initial alpha testing

After ecoCampus was developed to the point where each of the three (design, visualization, and simulation) interfaces were operating with a basic level of functionality, the application was tested with a small group of graduate students. These students were taken into the SALA Building and given computing devices loaded with ecoCampus on several occasions. They were asked to complete the design activity as the undergraduate students would be expected to do. This activity was completed to identify bugs, workflow problems, and other issues that could arise when using ecoCampus.

Almost immediately after starting the first alpha test, it became clear that there was a major flaw in the application workflow. The first alpha test occurred during the day, when the sun was shining brightly into the existing SALA Building studio space. When the user completed a design in ecoCampus and aimed the iPad camera at the marker on the wall to view the augmented model, the camera would adjust from the amount of daylight entering the space and significantly dim the view to compensate for the high amount of daylight. Unfortunately, in doing this, the printed fiducial marker would become a grayed out rectangle, which prevented image recognition. This made it impossible to register, or subsequently see, any augmented model content. Initially, attempts were made to find a programming solution to tweak the camera settings on the iOS platform, but a solution to this was not readily apparent. Instead, the ecoCampus workflow was tested in the evening after the sun had set, which completely eliminated the backlighting challenges initially observed. Therefore, it was decided that the implementation of ecoCampus would be implemented in the evenings.

A second group of graduate students was brought to the SALA Building in the evening to help with further alpha testing ecoCampus. This group observed no challenges with AR registration, but they did observe an interesting bug with visualization. When viewing their models in the space, it was discovered that their intended design would be mirrored when viewing the augmented model content. Luckily, this was a relatively simple problem that only involved tweaking the coding so the model content would be displayed properly.
Another issue that arose during initial alpha testing was related to the simulation game interface. In the first alpha test, all of the simulation feedback generated by ecoCampus, would appear instantly on the summary screen. The graduate students who helped to test this version of ecoCampus suggested that it was easy for them to avoid reading the performance feedback and the comments from the virtual project critics and only focus on their final numerical score. Several possible fixes to this issue were discussed, including having a button to select “OK” after each bit of simulation feedback was seen before the next portion would appear on the screen. Another suggestion was made to animate the feedback onto the screen to direct a user’s eye to each new piece of information. Ultimately, a hybrid of these two suggestions was used to help force users to read the simulation feedback generated. The ecoCampus workflow was revised to have the R-value and cost information float on to the simulation and then to have the comments from the virtual project critics float on to the screen one by one. This guarantees that a user cannot advance to see his or her score immediately upon entering the summary interface. To further encourage students to consider the simulation information from their designs, after the information floated onto the screen, a button would appear that a user would be forced to click to see their final score. This encouraged a user to keep viewing the simulation interface to see when the final score button would appear on the screen.

In addition to the timing issue on the simulation screen, some of the graduate students who helped to alpha test ecoCampus mentioned that it could be unclear why each of the different virtual building critics would generate the comments that they did. Initially, this was addressed by providing a printed packet of instructions about the application to the students, which included the motivations of each of the virtual project critics. After the first implementation of ecoCampus it was observed that most of the students did not read or even open the printed instructions while using the application. Therefore, the motivation of each of the virtual critics was incorporated into an “information” button on the summary screen in the second version of ecoCampus.
4.6.2 Beta testing: Modifying ecoCampus based on the initial class implementation

After modifying the ecoCampus workflow based on alpha testing with graduate students the application was implemented with engineering students in a first-year course. While this implementation did provide several noteworthy results related to the pedagogical value of the tool, it also provided several key suggestions to improve the workflow for future semesters. One of the key lessons learned from this first implementation was that additional virtual critiques were needed to provide a more comprehensive review of a student’s design. As discussed in section 4.5.3, a fourth virtual critic was added to ecoCampus to provide some basic constructability feedback based on the student’s chosen design.

In addition to the extra virtual project critic, a few other bugs and workflow inefficiencies were observed from this first implementation with engineering students. During the design phase of ecoCampus, students would touch individual pieces of wall geometry to assign the active materials to those pieces. Unfortunately, when students would rapidly touch several pieces of wall geometry, ecoCampus would frequently not register every single piece of curtain wall as having been touched. This became frustrating for several students who suggested that this should be addressed in future ecoCampus versions. This suggestion was addressed by reworking the way that the design interface was developed in Unity 3D. The first ecoCampus version was addressed by creating buttons that would be placed over each piece of curtain wall geometry. When a button would be clicked, the corresponding piece of wall geometry would be assigned the active material. Because of the high number of pieces of curtain wall geometry, the process of registering touches on the 140 buttons over the geometry was very slow and prone to missing screen touches. A different method using ray casting was implemented. In this method, all buttons installed over the pieces of curtain wall geometry were removed and instead, when a user would drag their finger on the screen a “ray” would be “cast” and any geometry that would be struck by this ray would be assigned the active material. This modification not only sped up the process for assigning an active material to wall geometry, but it also allowed users to “swipe” their finger across the screen to assign the active material to all objects in their path, which offered a much faster way to create design ideas in ecoCampus.
The first implementation of ecoCampus rendered all glass the same in the design interface. While all types of glass used may look similar from a distance away in reality, this proved to be frustrating for students to determine what type of glass each piece of geometry might currently have assigned to it while designing. To address this challenge, the second version of ecoCampus used a different material texture for each type of glass applied to geometry in the design interface. The comparison of the old and new glass rendering strategies can be seen in Figure 4-3. This allowed users to visually inspect their design before proceeding to the visualization or simulation interfaces to determine how much of each type of glass they would want to install in their design.

![Figure 4-3: The first version of ecoCampus (left) rendered all glass the same, whereas the second version (right) was modified to render glass differently based on number of panes of glass if the window was fixed or operable.](image)

Students also mentioned that they would like to have additional materials to use in their design process. The first implementation of ecoCampus included 28 different building material choices. The second version was enhanced to include 41 materials, including several different paint color choices for drywall sections. Because of the high number of materials, a new material window format was adopted to allow a user to click on a type of building material and then see a subsequent window with all of the choices for that chosen material category. After a user would select an active material, they could close that window to return to the main list of material categories, which can be seen in Figure 4-3 and also in Appendix G.
The final suggestion that was commonly provided in the first implementation of ecoCampus was to add a button to clear a design to allow a user to start their design from scratch. The first version of ecoCampus would allow users to change a material by selecting an active material and clicking a piece of geometry, which would replace the existing material with the current active material. Many students felt that this was inefficient and, because of the uniform glass rendering in the first ecoCampus version, impossible to know if glass had been correctly changed from one type to another. This was addressed in the second version of ecoCampus by allowing a user to either override a current material on a piece of geometry with the active material or, alternately, by selecting a “clear” button that would reset all geometry to the default blank material.

4.7 ecoCampus: The developed prototype

This section presents the user experience that was created in ecoCampus after following the process described in this chapter. The second version of ecoCampus is presented here. Screen captures of the first ecoCampus version and additional screen captures of this second version can be seen in Appendix E and Appendix G, respectively.

In the initial game screen, users enter an experimental ID number, and then proceed to the ecoCampus design screen, shown in Figure 4-4. This user interface shows the different design categories of materials that a user may select in modifying the curtain wall design. As users explore different material choices and select a particular material, it becomes the active material. When users select a material, they see an icon of the material below the materials library and a description of the material in the white text along the top of the screen. As the users select one or several of the black boxes on the curtain wall, the active material is assigned to those pieces of geometry. A user must then design their initial curtain wall concept by applying some material to every piece of curtain wall geometry, so there are no open pieces of the wall design. While designing, students may experiment with one material layout and decide that they wish to change the layout in this design interface. To modify a design, users may select a new active material and click on the areas of the curtain wall that they wish to modify, which will override the prior
material with the active one. Alternatively, they may select the “clear” button and restart the design process with an entirely blank wall.

![Image of initial design screen](image)

**Figure 4-4: Initial design screen for the curtain wall design educational module.**

As users develop their designs they can see a virtual representation of their wall. An example design can be seen in Figure 4-5. As they select different materials, they can see the type of material currently selected at the top of the screen. This ecoCampus design interface offers users a visual interface that allows them to quickly generate different design ideas. It does not offer a great deal of suggestion for how to design based on cost, thermal performance, constructability, or other performance metrics. This lack of information encourages users to make inferences as to what they believe to be the sustainable advantages and disadvantages of the different material choices. After users create a design that they believe will be successful in improving the sustainable performance of the existing wall, they select “view model.” The application then
takes them to a new interface where the camera on their mobile computing device becomes active.

![Image](image_url)

**Figure 4-5:** Users apply chosen materials to the curtain wall as they create their design.

In this augmented interface, users can point their mobile computing device to see the physical world through the built-in camera. As users point their device to the fiducial marker on the curtain wall of the SALA Building, a virtual representation of their design appears on the real view of the space. This use of AR allows users to get a sense of scale by comparing their full-scale virtual design to the existing curtain wall design. An example of this interface can be seen in Figure 4-6 illustrating virtual design on the real view of a space through AR registration.
After users have examined their design in the augmented reality interface to their satisfaction, they may either elect to go back into the drawing interface as seen in Figure 4-5 to modify their design or they may elect to go to the summary screen shown in Figure 4-7. This summary interface displays simulation results related to their design. The results are animated to float onto the screen one by one. This was done to direct a user’s attention to each result so that they may consider the implications of each piece of information. First the R-value is displayed, indicating the thermal performance of the chosen wall assembly. Then the cost values are presented to indicate the total cost to build the one bay that users redesign as well as the total cost to apply the proportions of the design to every piece of curtain wall in the entire building. Users can also see details about the quantity and cost of each material used in their current design at the top of the
Finally, the four different virtual project participants provide a critique on the users’ designs.

Figure 4-7: After users of ecoCampus have viewed their chosen design, they can run the simulation game interface to receive performance feedback about their design, tailored design critiques, and also a numerical score based on their design’s performance.

After students view the performance feedback and the different critiques about their design, they can select “Show final score.” At this point a numerical score is provided to the students. A high score is based on having a high R-value, a low cost, and positive critiques from the four individuals involved in the project. While this numerical score did not directly offer formative suggestions to users about how to modify their designs, it gave a concise quantification of design performance that would be beneficial in assessing the students’ design processes. After receiving this performance feedback, students can select “Start over” to return to the main menu and begin
the design process again. When students return to the design interface screen shown in Figure 4-5, they may either fine tune their prior design idea or clear the idea and start with a blank wall as they create new design iterations to attempt to beat their prior score.

4.8 Focus groups: Feedback generated for future development

After the version of ecoCampus presented in Section 4.7 was implemented in class, students were given the opportunity to participate in a focus group session. These sessions were held with small groups of 10 students or less. They offered an opportunity for students to discuss their feelings on the ecoCampus experience in an open discussion with their peers. Some of their feedback related to the learning experience of using ecoCampus. This feedback is included in Chapter 5. This section includes feedback generated from the students related to application functionality.

During the focus group sessions, several students mentioned that they would like to review the simulation feedback that was generated from their prior designs while they were completing a new design. In the developed versions of ecoCampus, students documented their work by taking screen captures of each of their designs at each of the three (design, visualization, and simulation) interfaces. Therefore, the only way that students could review their work in the developed versions would be to go into the photographs interface on their iPad and page through the screen captures that they had taken. While this form of review functionality does still allow students to review their prior designs, it would be valuable to look into incorporating a more efficient method for reviewing design iteration history into future versions of ecoCampus.

In the focus group sessions, several students also suggested potential benefit in turning the ecoCampus experience into a competition. There are several ways that students envisioned this competition working. Some suggested benefit in competing against other students to see which student or students could achieve the highest score. One of the potential challenges with this style of competition would be that, when a numerical score is used to quantify the quality of a building design, there are some aspects of the design that may be overlooked. For instance,
aesthetic impact of a wall design was not able to be automatically quantified in this work. If it had been, a design that might achieve a very high score with the existing system, might receive a much lower score because of aesthetics. To potentially skirt this challenge, another student suggested creating a competition environment in ecoCampus by tasking students with “winning” a design job over other virtual designers. This would involve more application development to create other possible designers and designs from which to compare the students’ designs, but could offer an effective means to incorporating competition into the experience.

Some of the students also noted the unrealistic aspect of the different project critics. In other words, students found out through trial and error that one critic might be unhappy with a given design, but by changing only one block or two, would cross a performance threshold and be enough to make the critic happy. This may be solved in future ecoCampus developments by simply adding additional threshold comments and decreasing the size of each critic’s threshold for a given critique. This could allow a designer to switch from very dissatisfied, to somewhat dissatisfied, to marginally satisfied, to somewhat satisfied, to quite satisfied, to fully satisfied, which could make the comments generated feel more realistic in future developments.

4.9 Looking forward: Using the existing ecoCampus platform for future development of augmented reality and simulation game tools

The development of ecoCampus, has shed a great deal of light on the process for creating a new technology for use in education. This section explores how the work done to create ecoCampus can be leveraged for creating educational content for additional educational modules. It is focused on creating a similar type of marker-based wall design application. For other efforts where a substantially different educational game is desired, there may still be value in using certain aspects of ecoCampus as a starting point, but these efforts may require more independent research to determine how to best design these other systems.
4.9.1 Importing geometry into Unity 3D

When creating ecoCampus, the building geometry used to define the curtain wall and the blocks that make up the wall was created in AutoCAD. The default output format of AutoCAD is .DWG. To convert this .DWG file to a .FBX file, which Unity can import, the .DWG file was imported into Autodesk 3D Studio Max. 3D Studio Max can both import .DWG files and export files to .FBX format. If other CAD programs or building information modeling authoring software packages are used for creating building geometry in future game development efforts, it will be necessary to determine an efficient method for converting native file formats to ones that Unity can import.

4.9.2 Developing game GUI within Unity 3D

After the detailed storyboarding process has occurred to define the intended workflow for a planned educational game, the game workflow can be developed within Unity. ecoCampus was developed using a modified version of C#. Unity content can be programmed with a modified version of C# or JavaScript programming languages, but if the String plugin for Unity will be used to facilitate AR registration, C# may be more appropriate to use as String is developed in C#.

For game development that is significantly different from ecoCampus that will use an entirely different method for AR registration, String may no longer be appropriate for facilitating registration. In this case, efforts will have to be made to determine what other methods of registration are possible and what game development environments can use a particular tracking method. When examining registration methods other than marker-based options, it will also be necessary to consider what type of mobile computing device can be used. For example, if GPS-based registration is intended to be used, it will be critical that the intended mobile computing devices used are able to receive a GPS signal and also possess accelerometers capable of tracking viewing angle for accurately augmenting game content.
4.9.3 Building and testing the developed application

When a game, or part of a game, has been created, developers will want to test the application on the chosen mobile computing device. For the development of ecoCampus, the String plugin was used with Unity 3D, which exported content to XCode, which in turn, built the game to an Apple iPad. The specifics of the components can be found in Table 4-1. Due to the high number of different components that played a role in the application development, a major pitfall that was discovered came when upgrading any one of the different components. If one component would be updated to a newer version that was not compatible with all of the other components, the application could not build properly. This became especially challenging when an Apple i-device updated to a newer operating system version as Apple does not allow for a convenient method of reverting back to an older operating system. Therefore, it is recommended that future developers pay careful attention to what version of each component is being used in a chosen workflow. Furthermore, it is recommended that, unless there is a critical update necessary to the game development process, avoid upgrading any of the game design components to avoid this pitfall.

4.10 ecoCampus development conclusions

The development of ecoCampus has offered insight into the process for creating a new educational tool that leverages marker-based augmented reality in a simulation game environment on a mobile computing platform. This chapter identifies the key steps and processes that occurred to create this new tool so that this type of development can not only be repeatable, but also so that it can be expanded by future work. In addition to the steps that have been followed for creating ecoCampus, this chapter has also discussed several actions that lead to problems during development. The suggestions of best practices and practices to avoid described in this chapter have not been compared to alternative paths for game development. The contribution in describing the processes completed in ecoCampus development is in adding to the body of knowledge on creating an educational game using augmented reality. This can offer benefit to future development efforts that seek to create a similar educational game by understanding a workflow that can successfully lead to a workable educational game and also an
understanding of some of the key processes to avoid so that the pitfalls that were observed during ecoCampus development can also be avoided.
CHAPTER 5  RESULTS FROM TREATMENT IMPLEMENTATIONS

This research has sought to better understand the benefits of using augmented reality (AR) in conjunction with a simulation game when applied to the architectural engineering educational context. Several different experimental treatment activities were created and implemented to understand what aspects of students’ learning benefitted as well as which aspects observed no gain from the incorporation of these technologies. All treatment groups tasked students enrolled in a first-year Architectural Engineering seminar course (AE124S) with redesigning a curtain wall in an existing building on campus to attempt to make the building perform more sustainably.

Treatment 1 required students to complete this design in the span of one 50-minute class session with only blank sheets of paper and no added suggestion for how to approach the design challenge. Treatment 2 also used a paper-based design approach, but offered the added resources of printed images of the existing building space on which to illustrate design concepts as well as a list of possible materials that students could consider incorporating in their designs. Treatment 3 implemented the developed ecoCampus application which eliminated the paper-based design component and instead used mobile computing devices to allow students to select materials and geometry in their building designs, view their design ideas in the context of the existing space through the use of AR, and also get automated feedback about their design performance through an added simulation game. This third treatment was implemented over two different semesters with two slightly different versions of the developed ecoCampus application, which are described in Chapter 4. To distinguish between the two implementations, these treatments are referred to as Treatment 3.1 and Treatments 3.2. During Treatment 3.2, not only was ecoCampus tested with students enrolled in the Architectural Engineering (AE) course, but it was also tested with students from Architecture and Civil Engineering (CE) courses. This chapter explores the findings from these different treatment activities.
5.1 Treatment 1: Open-ended curtain wall redesign problem findings

This treatment activity, described in Section 3.4 and included in Appendix B, was implemented in the Architectural Engineering freshmen seminar course (AE124S) in the fall 2011 semester. This exploratory study sought to better understand engineering students’ inherent process for redesigning an existing component of a building through an open-ended design problem. For this treatment students were tasked with redesigning the exterior curtain wall in Penn State’s School of Architecture and Landscape Architecture’s (SALA) Stuckeman Family Building to attempt to make the building perform more sustainably. This activity sought to provide an understanding of: how students would inherently approach the design process; the benefits to this type of open-ended learning method; and the observed behaviors that were not beneficial to students’ learning.

5.1.1 Results

The Treatment 1 activity included several separate assessments described in Section 3.2 and included in Appendix J. Because these different assessments were administered at various times throughout this experimental treatment, some students did not complete every assessment in the experiment or some did not remember their experimental ID number, so their responses to the assessments could not be linked back to their completed design submission. Therefore, in assessing the data gathered in this work, comparisons that required paired data only used responses from students who completed both sets of assessments in question. For comparisons requiring only one data point per student that were compared between the different treatment activities, all students who consented to allow their responses to be used, completed the design activity, and provided data to a given question had their data compared to the different semesters.

The Treatment 1 design activity was completed by 65 students in AE124S. From the survey quiz, 95% of students were first-year students and over 70% were male. From the pre-tests administered, it was also found that 71% of the students had little or no prior experience solving engineering problems and 62% of the students reported having little or no prior experience with sustainability.
5.1.2 Plausibility of submitted designs

The design challenge given to the students required them to develop a new curtain wall design solution to attempt to make the existing SALA Building perform more sustainably. While the level of detail in the submitted designs greatly varied, the submitted designs were generally developed enough to illustrate plausible building designs. Two examples of submitted designs can be seen in Figure 5-1. Most of the submitted designs (85%) appeared to illustrate a design that could be built and would, in some way, address sustainable performance of the building as defined by the LEED® building rating system. Designs were deemed to be plausible if they proposed a solution that made changes only to the exterior wall and if some logic was offered as to why a particular design would improve the existing building’s design. The plausible designs submitted fell into one or more of three categories, with the percentage of designs that fell into each category listed in parentheses: designs to improve building insulation (80%); designs to improve daylight usage (49%); and designs to gain more outdoor air into the space (40%). Some of the submitted designs (15%) deviated from the project guidelines by focusing on the building’s roof, steel structure, or some other system not within the scope of the assignment. Therefore, these designs were determined not to be plausible solutions to this particular design challenge.

Figure 5-1: Example designs submitted during Treatment 1.
5.1.3 Design creativity

While the designs were generally plausible, the submitted designs tended to closely resemble the existing SALA Building design in geometry and also in the materials that students chose to use in their developed designs. After examining the submitted designs, 65% were based on the same materials that were used in the original building design. This may be due to the fact that students were limited by time for this activity. From post-test responses, only 5% of students felt there was more than enough time to complete the activity and 43% felt that there was not enough time to complete the activity. Furthermore, 26% of the students felt that they had not completed their design to their desired level of satisfaction by the end of the class period and elected to finish their design idea after class and submit their design solution before class the following week. Prior works suggest that, in time-constrained situations, students tend to focus on learning about the easiest aspects of a given topic before moving on to more challenging aspects of a given topic (Metcalfe and Kornell 2003, 2005). In the context of this self-directed design activity, it is plausible that the easiest of the sustainable building strategies to learn would be examining the design strategies used on the existing design in which they were physically located.

In addition to time constraints on the activity, students who participated in a focus group discussion mentioned that the lack of structure of this activity tended to force them to use materials that were already present in the existing design. They felt that they did not have a sense of what other materials could be used, so they defaulted to using what was visible in their physical surroundings. In the case of the SALA Building, this largely meant brick, glass, aluminum, and occasionally copper. This effectively limited the ability of students to consider other materials that might offer benefits beyond those offered by the materials in the existing design.

5.1.4 Understanding the students’ design process

Students performed several different design processes in finalizing their wall design concepts. A typical workflow for the students who elected to base their design largely on the existing design
involved drawing what was currently built in the space of interest and then fine tuning the existing design to attempt to be more sustainable. This fine tuning process often involved students defining pros and cons with the existing design and exploring the built environment and then modifying their design based on their discoveries. For example, most of the students (80%) opted to make thermal performance of the new design one of the guiding principles that shaped their design. This activity was performed on a cold morning in November and several of the students who focused on thermal performance walked around the built space to feel different materials to get a sense of their relative temperatures. The existing facility utilizes a substantial amount of glazing separated by aluminum mullions. The students noticed that the metal mullions tended to be much colder than the glazing and, therefore, decided that more glass would make the curtain wall perform better thermally. The students would then create a new design with fewer/smaller aluminum mullions and, in turn, increase the size of the glass window panes in the building. Few students elected to use a material other than glass on the curtain wall to improve the thermal properties of the wall assembly.

After analyzing the submitted designs, it was observed that students tended to start with one design option and modify that first design option until the class period was finished as opposed to starting with several design options and assessing benefits and weaknesses of the different options to determine the best design solution. Of the submitted designs, only 17% included multiple design options for addressing the design challenge involved in this activity. This may be due in part to the time constraints of this class activity, but it may also be due to the concept of design fixation. Previous studies have identified common patterns of fixation in the design process, where designers adhere to ideas and concepts, which, in this case, stem from viewing an initial building design solution that effectively limit the creativity of the designers (Jansson and Smith 1991; Linsey et al. 2010).

5.1.5 Students impression of activity

After compiling the responses to the Treatment 1 assessments, the data was analyzed to determine how the activity was received by the students. Several questions were asked to solicit
responses about the students’ impressions of the activity. Overall, students enjoyed the design activity, with 84% rating the experience as enjoyable or very enjoyable. Despite not having any suggestion for how to approach this design activity or any information related to what materials might be effective choices for an exterior wall design, 59% of the students who completed Treatment 1 felt that they did have enough information to make effective design decisions. Furthermore, 73% of the students felt that they had created a viable design solution to the design challenge provided to them. Overall, the students also felt that the Treatment 1 activity was beneficial to their education.

5.1.6 Focus group session feedback

In the focus group sessions, feedback was obtained from the students in a more open-ended forum than was afforded through the pre- and post-test responses alone. These discussion sessions provided a chance for the students to discuss their perceptions of the activity experience with other students. While these sessions were not anonymous, they allowed students to expand on their peers’ ideas and also to disagree with their peers’ opinions. From the discussions held, there were a wide variety of opinions expressed about what worked and what did not work in the activity. Many of these opinions were in direct opposition to one another, which serves to illustrate the variety of learning preferences that students can possess as suggested by prior research (Felder and Silverman 1988).

One of the questions posed to the students to spur discussion was related to the time that was given to complete the activity. While over half of the students responded that 40 minutes was enough time or more than enough time to complete the activity on the in-class post-test, students at the focus group expressed nearly unanimous feedback that they felt they did not have adequate time to complete the activity to their level of satisfaction. Part of the frustration with the time constraint was that several students felt they did not have enough background on sustainability or the LEED system, so addressing the challenge of generating design concepts to improve building sustainability was difficult for them.
The groups of students were asked to discuss their feeling on the level of information and their level of preparedness to tackle the given design challenge. The first student to respond to this question argued that it was good that the assignment given offered minimal suggestion of how to complete the activity or what materials to select because it allowed him to be more creative in his choices. The follow-up comment by another student strongly disagreed saying that not offering material choices to students from which to select for their design lead to students making unrealistic designs. This also illustrated the variety in learning preferences among the students.

5.1.7  **Self-directed learning**

One of the challenges discussed with this type of activity is that the basic level of background information provided to students prior to the activity does not fully prepare them to complete the design. Therefore, students must rely on prior personal experiences in the built environment, knowledge developed in other related courses, and information that they can gather from exploration of the existing building. This occasionally leads to incomplete understandings or outright misunderstandings of sustainability.

A student in one of the focus group sessions mentioned that he liked the experience of being able to explore an existing facility to learn about how to make it more sustainable. He felt that the “tactile sense of touching materials made a difference in thinking.” This process of exploring the building allowed students to get a physical sense of how different building materials perform thermally simply by touching them. Generally, this is seen as a valuable activity, so students have a more real-world understanding of building materials. However, some of the conclusions that were drawn by the students from this type of exploration generated incomplete understandings of sustainability. For example, many students felt that the aluminum curtain wall mullions were much colder than the glazing on the wall. Therefore, students frequently decided that the best way to make the curtain wall perform better thermally was to reduce or remove the mullions entirely and create larger window panes. While it may be true that in this instance, the glass appears to perform better thermally than the aluminum mullions, there may have been another building material that may not have been used on the built facility that would insulate the
Another student mentioned that in exploring the building, he felt it was a bit strange that LEED would award points for the building being green in color. The case study building used for this work gained some points for its green exterior not because of the green patina color, but because the copper used to clad the building was recycled. This student may have remembered that the building’s green exterior helped in getting LEED points from the building tour, but forgot exactly the rationale behind why this received credit during the design activity exploration. This illustrates one of the key potential pitfalls with this type of open-ended, self-guided instruction.

5.1.8 Treatment 1 conclusions

This treatment explored the process of tasking students in a first-year AE seminar course with redesigning an existing building element to attempt to make the building perform more sustainably. The activity was designed with minimal structure so that students were forced to determine the best way to address the design challenge on their own. Through this process of self-exploration, several insights into the advantages and disadvantages of this type of education method were identified.

Despite the fact that students were not given detailed instructions or information about different materials’ performance data, they were successfully able to synthesize building designs that addressed one or more aspect of LEED and sustainability in general. Furthermore, the designs they submitted generally appeared to be plausible designs with current building technology, although they closely resembled the existing LEED-rated SALA Building design. Additionally, students tended to enjoy completing this activity. Nearly all students said that the activity was either enjoyable or very enjoyable and they also felt that the activity was beneficial for their education.
This Treatment 1 implementation also highlighted some challenges with this format for design. While nearly all of the designs submitted did address topics in LEED, the designs were somewhat uncreative. Over half of the submitted designs used very similar geometric layouts to the existing design with identical building materials. This may be largely because of the time constraints associated with this work. When time is constrained, students tend to put effort toward learning the easiest concepts first (Metcalfe and Kornell 2003, 2005). In this case, this meant that students spent more time determining how to best tweak the existing design that they could quickly assess rather than trying to determine alternate strategies to improve sustainability. This does not necessarily mean that there was no value in this type of self-directed, open-ended design problem for increasing student creativity. While 65% of students used the materials that were incorporated into the existing design into their final design idea, 35% of the students did experiment with different design materials during their concept development process.

This activity allowed students to explore a physical space in conjunction with their redesign assignment. This allowed students to use their senses in the physical space to better understand how the existing building functions and how the current design could be improved to function more sustainably. During this exploration period, some students ascertained misinformation. Because there was no form of real-time feedback while students were completing the Treatment 1 activity, incorrect assumptions sometimes guided students’ decisions in directions that were largely unintended.

From a process standpoint, the findings from this treatment activity echo the findings of other research efforts that show that students often fixate on one design idea when an example design to a given design problem is presented (Jansson and Smith 1991). In the case of this activity, the students were physically in a building that did meet the basic design requirement of functioning as an exterior curtain wall. As a result, students did not take time to identify several design choices, determine strengths and weaknesses of each choice, and then select a final design choice.
5.2 Treatment 2: Paper-based augmented reality activity findings

This treatment offered students a similar experience to the Treatment 1 activity in that it required them to generate a new exterior curtain wall design for the SALA Building to make it perform more sustainably, but this implementation also gave students a few additional resources to use to help them complete the design challenge. The additional resources included printed images of the existing exterior curtain wall on which to illustrate their designs and also a list of possible building materials they might consider while designing. Two different printed images were supplied to students. One image had the existing curtain wall dimmed and the other image had the curtain wall completely removed from the image. The resources supplied to students can be seen in Appendix C and the process followed for implementing Treatment 2 is described in Section 3.5.3.

5.2.1 Results

During the Treatment 2 activity, 23 students enrolled in AE124S participated in the design activity. During the spring 2012 semester when this treatment was implemented, one participant was a second-year student and the rest were first-year students. Four of the participants were female and all participants were between the ages of 18 and 20 years. Half of the students reported having little or no background in solving engineering problems in general and more than half reported little or no background in sustainability.

On the day of the design activity, students were given the Treatment 2 activity to complete as described in Section 3.5.3. They were given approximately 40 minutes to complete their designs. At the end of class, students were given the option to take their packets home with them to complete their designs if they felt they had not had enough time to complete their designs in class. While several students who completed Treatment 1 elected to finish their designs after class, none of the students who completed Treatment 2 opted to do this.
At the end of the design session students submitted their exterior wall designs. The design submissions were analyzed to determine common trends. Figure 5-2 shows two examples of designs that were submitted by students to illustrate a general level of design completion. Additionally, this figure shows how different students elected to use different images to illustrate their design. The image on the left shows the work of a student who elected to use the image with the dimmed background and the image on the right shows the work of a student who elected to use the image with the background removed. In addition to the analysis of the submitted designs, the completed pre- and post-tests were examined to identify elements of the experience where significant changes in the students’ performance perceptions were observed and also elements of the experience where little or no evidence of change was observed.

**Figure 5-2:** Examples of design submissions by students, including an example where a student used the image with a dimmed background (left) and one with the image with no background (right).

### 5.2.2 Design process analysis

In building design, students are generally encouraged to create design solutions through the exploration of several possible design concepts. This process allows students to weigh the pros and cons of each concept, and after this analysis, refine their design to one concept. For this work, it was initially hypothesized that the multiple provided images would encourage students to explore more than one design concept in arriving at their final design choice. This was largely not the case. The majority of the students (70%) completed this design activity through the
creation of only one design concept. In the Treatment 1 implementation, 83% of the students completed the design activity through the creation of only one design concept. While this percentage of students who created only one design in Treatment 2 was lower than the proportion of students who created only one design in Treatment 1, the small Treatment 2 sample size did not show conclusive evidence of significance of improvement.

In Treatment 1, it was observed that some students deviated from the design assignment. Some of these students designed building systems other than an exterior wall in their attempts to redesign the existing curtain wall. During Treatment 2 it was observed that none of the students deviated from the wall design assignment, which suggests that the addition of the provided images may have helped to focus students’ design efforts on the targeted building element.

In analyzing the submitted designs, the different background images that students used were also examined. Design submissions from the students were grouped into one of three categories: students who used the image with the dimmed background; those that used the image with the background removed; and those that used both images to illustrate their design ideas. It was found that 43% of the students used the image with the dimmed background, 39% of students used the image with no background, and 18% of students used both images. This, nearly even, split between the proportions of students who used each of the two provided images did not indicate any significant preference to one over another.

5.2.3 Students’ feedback about the design activity

In addition to the results that were generated through analysis of the submitted student designs and the assessment of pre- and post-test questions, data was also obtained from the students based on their impressions of the design activity. Several Likert scale questions were asked to students to determine to what extent they agreed or disagreed with particular statements. Based on the results of these questions, it was observed that 76% of students enjoyed completing the design activity and none rated it as actively not enjoyable. Furthermore, 57% of the students said that completing the Treatment 2 activity generated more interest in sustainability and 76% said it
generated more interest in the building design process. 75% of students felt that they had enough information provided to them to make effective design decisions and 76% felt that they created a viable solution to the design challenge. While a large proportion of the students were confident in their designs, it was interesting to note that a large portion of the students (43%) also suggested that they did not have enough time to complete the activity.

5.2.4 Conclusions from Treatment 2

The data collected in this research was analyzed to identify key learning aspects related to building sustainability and the building design process where students appeared to improve and also aspects where no improvement was observed. While there was not a significant benefit observed in students’ understanding of building sustainability practices and the LEED point system, there did appear to be some improvement in the students’ design process that they employed to arrive at their design solutions. As compared to Treatment 1, students tended to focus more on the design problem at hand with the addition of the provided images. This may be due to the printed images provided assignment materials. Finally, Treatment 2, like Treatment 1, offered the benefits of engaging students with sustainability and the design process in a way that was enjoyable for the participants.

5.3 Treatment 3: ecoCampus application implementation findings

Treatment 3 involved a similar design activity as the activity described in Treatments 1 and 2, but this treatment activity provided students with a mobile computing device running the developed ecoCampus application to use while designing. ecoCampus was designed to help students: brainstorm different “what if” design scenarios to determine the best possible design solution to the given design challenge; visualize full-scale virtual prototypes of their design ideas through AR; receive tailored feedback through a simulation game to shape their thought processes for subsequent design iterations; and, ultimately, learn sustainable design concepts through these actions. This treatment involved two different implementations as described in
Section 3.6, which are referred to as Treatment 3.1 and Treatment 3.2. The findings from these implementations are discussed in this section.

5.3.1 Treatment 3.1 results

During this first ecoCampus implementation, 47 students enrolled in a first-year Architectural Engineering (AE) seminar completed the design activity. Of these 47 students, 30 were male and 17 were female. All but one of the participants was a college freshman. Students were also surveyed to find out their intended majors. In this Fall 2012 semester, 31 students indicated that they were interested in pursuing AE and 17 students listed some alternate major as their current preferred choice. After analyzing the submitted files from all of the students, several noteworthy observations were made.

The screen captured images of the students’ designs were examined to identify how many design iterations that students explored during the activity. It was found that students completed between 3 and 19 different design iterations with a mean of 9.3 design iterations during the class session. The number of design iterations created by the students who used ecoCampus was compared to the number of iterations created by students who completed Treatments 1 and 2. The number of iterations with ecoCampus was significantly higher than both prior activity formats (p<0.001). Figure 5-3 shows the percentage of students in each treatment that explored a given number of design iterations in the 40-minute time period.

In addition to examining the number of design iterations that were explored by students during Treatment 3.1, it was also of interest to examine how many different building materials students considered during their design process. It was noted in prior implementations that students generally did not deviate from the existing building design with regard to material selection and geometric layout when attempting to create their more sustainable design. On average, students who used ecoCampus used 9.3 different materials throughout their design creation process, which is substantially more than the 3 main materials currently used on the existing section of
Figure 5-3: Graph showing the number of design iterations for each of the experimental treatments.

curtain wall. This was also significantly more than the number of materials that students used in prior semesters with paper-based formats (p<0.001). The numbers of materials that students experimented with in their design processes from the different activity formats can be seen in Figure 5-4.

5.3.1 Treatment 3.1 analysis of student perception of activity

In addition to analyzing the designs that were submitted, the responses to pre- and post-activity assessments from this work were examined to understand the learning and perception of the activity among the students. Students generally felt that the format of ecoCampus was effective, with only 6.4% of students reporting it as either “not very effective” or “not effective at all.” Students generally also found the activity to be interesting. For example, 63% of the students
felt that it specifically increased their interest in sustainability and 70% indicated that it made them more interested in the building design process.

Students were also asked open-ended questions to solicit their overall perceptions of the activity. Most of the responses to these questions were positive. Some of the noteworthy comments included:

- “I really liked this activity. I think it was very beneficial for me as I learned more than I would have learned just reading about it. It was a great practice for sustainability design of a building.”
- “I really enjoyed this activity. I was shocked to see the technology; I did not think something like this could be done on an iPad app. Very interesting and made you think about numerous design aspects and see them come to life ‘almost’.”
• “I liked this experience and trying to figure out ways to improve our designs as we got feedback from the app.”
• “It was great to see the augmented picture. Designing something is one thing but having the ability to see it roughly right away is a great feature.”
• “It was really great... no other way to put it. I learned some new things about sustainable design such as having a mix of materials on a wall. At first glance it seems that having all glass or all brick is good. (For daylighting for the former and insulation for the latter). However I realized that having a balance of the two is more effective for sustainable design. That was really cool to discover through this app.”

While the majority of responses to this activity were very positive, not every student felt that it was as beneficial to their education. A few students provided negative comments such as:
• “It was interesting but not too beneficial. I still am not sure what materials are better insulators than others. I really didn’t have a plan and all of my adjustments were made thru trial and error. I also didn’t have a chance to try out all the different materials”
• “It was fun, but I didn't learn why the building owner and the engineers said what they did.”

5.3.2 **Treatment 3.1 unintended use of ecoCampus**

From the instructor’s perspective, some unintended learning outcomes were also observed during the Treatment 3.1 implementation. For example, when certain students were using ecoCampus, they tried to design with the intent of receiving the highest score possible. While this might initially sound like a good approach, in this initial ecoCampus version, the only factors that affected the score were initial cost, daylight usage, and thermal efficiency. Therefore, students may have achieved very high scores, but did not necessarily create the best possible design for the particular design challenge because of ignoring important design considerations not included in the initial ecoCampus scoring algorithm, such as constructability, aesthetic impact, or functionality of the wall for serving the students who use the SALA Building studio space.
5.3.3 Treatment 3.1 conclusions

After implementing Treatment 3.1 with a class of students enrolled in AE124S, several noteworthy observations were made. Students completed this activity through the creation of between 3 and 19 design ideas over the course of the 40-minute design period with ecoCampus. This indicates a shift among students to generate more design ideas than prior paper-based treatments. This suggests that this type of mobile game environment can serve as a catalyst to encourage students to brainstorm different design possibilities in a self-directed design context and resist the tendency toward design fixation.

The students who used ecoCampus also considered more possible building materials in their design process as compared to prior treatments’ students where the application was not used. This could be due in part to the fact that some first-year students are not yet aware of possible different building materials that could be used in a design, but even when comparing the number of materials considered with the Treatment 2 students, who were supplied with a list of possible building materials, the Treatment 3.1 students still explored more materials in their designs. When considering this finding with the increased number of design iterations completed, this may suggest that ecoCampus can enable students to design more quickly than with a paper-based method and, therefore, experiment with more design and material options.

5.3.4 Treatment 3.2 results

This second implementation of ecoCampus was performed in the spring 2013 semester as described in Sections 3.6.5 - 3.6.7. A modified version of ecoCampus was used for this implementation as discussed in Section 4.6.2. In addition to the modified implementation process and modified ecoCampus prototype, the students who completed the design activity consisted not only of students enrolled in AE124S, but also third-year Architecture students enrolled in a required Architectural Engineering course (AE424) and a class of predominantly third-year Civil Engineering students (CE 370). In total there were 108 students participating in the Treatment 3.2 implementation. In the AE seminar there were 34 students who participated, of which 82%
were male. Of the 34 students in this course, 23 students said that they intended to pursue AE as their major. There were 27 students who participated from the third-year CE course, of which 70% were male. Of the 27 students from this course, 16 intended to pursue CE as their major. Lastly, 47 students participated in the third-year AE course for Architecture majors, of which half were male, half were female, and one student preferred not to respond. All of the students in this course intended to pursue Architecture as their major.

5.3.5 Treatment 3.2 student impression of activity

After students completed the Treatment 3.2 design activity, it was of interest to understand their impression of the experience. Overall, the students enjoyed completing the activity with 82% of students in the AE course, 96% of students in the CE course, and 79% of the students in the Architecture class reporting it as actively enjoyable. The students also felt that the activity was beneficial for their education with 94% of the students in the AE course, 93% of the students in the CE course, and 87% of the students in the Architecture course rating it as beneficial.

Students were asked to what extent they felt that the ecoCampus activity increased their interest in the building design process and sustainability. The students in the AE course reported being more interested in sustainability and the building design process by 79% and 82%, respectively. The students in the CE course reported being more interested in sustainability and the design process by 85% and 89%, respectively. The students in the Architecture course reported the lowest increase in interest in sustainability and the design process, but still had 53% and 51%, respectively reporting an increased interest in these topics.

The students who completed the Treatment 3 activity generally felt that they had enough information provided to them to complete the activity with 75% of AE’s, 82% of CE’s, and 80% of Architects reporting having enough information. They also felt that they were successful in creating a viable design solution to the design challenge with 74% of AE’s, 89% of CE’s, and 85% of Architects reporting that they had created a viable design solution. The students who completed Treatment 3.2 also tended to feel that there was sufficient time to complete this
activity with only 9% of AE’s, 11% of CE’s, and 9% of Architects saying they did not feel they had enough time. During the paper-based treatment activities, 43% of Treatment 1 students and 43% of Treatment 2 students felt they did not have adequate time to complete the activity. This suggests a shift in the perception of the amount of time students felt was necessary to complete this design with ecoCampus.

5.3.6 Treatment 3.2 design process analysis

The students who completed Treatment 3.2 took screen captures in the same way as the students who completed Treatment 3.1. The captured images were compiled and analyzed. Collectively, students from all disciplines who completed Treatment 3.2 completed a mean of 9.5 designs during the 40-minute design session. This is approximately the same as the average number of designs explored in Treatment 3.1. The students enrolled in the AE course completed a mean of 8.3 iterations; Students enrolled in the CE course completed a mean of 11 design iterations; And the students in the Architecture course completed a mean of 9.5 design iterations. The design iterations completed by the Treatment 3.2 participants can be seen in comparison to all other treatments in Figure 5-5.

As Treatment 3.2 was being developed from the ecoCampus version used in Treatment 3.1, one of the pieces of feedback that was obtained from the students was that the design interface did not allow for a fast recognition of screen touches to modify building materials. The second version of ecoCampus was redesigned to allow for a user to “swipe” their finger across the design screen to apply the active material to all building objects that their finger crossed as discussed in Section 4.6.2. This feature sped up the process for creating wall designs and was predicted to increase the number of iterations that students would complete while using ecoCampus. This was not backed up by the observations in the Treatment 3.2 implementation, which suggested that, while ecoCampus can significantly increase the number of designs a student would create as compared to a paper-based design (Treatments 1 and 2), after a certain point of development, the time to create new wall designs was no longer the limiting factor in the students’ design behavior.
In addition to analyzing the number of design iterations that students created while using ecoCampus, it was also of interest to examine the number of materials that students explored during design. When comparing all students completing Treatment 3.2 to those who used 3.1, there was statistical significance that the 3.2 students used more materials in their design process ($p=0.029$). However, when considering the students from different courses individually, none of the groups individually showed statistical significance of using more materials. Figure 5-6 shows the percentage of students who explored different numbers of materials through the different treatment design activities. This observation may be due in part to the fact that the Treatment 3.2 version of ecoCampus offered more material choices than the Treatment 3.1 version, but it may also be due to students using ecoCampus in ways that were not intended, which are discussed in Section 5.3.7.
5.3.7 Treatment 3.2 unintended use of ecoCampus

During Treatment 3.2, some students used ecoCampus in ways that were not intended. For instance, in Treatment 3.2 a virtual construction manager was added to provide construction feedback on designs based on the number of materials used. This was added to the ecoCampus experience to make students recognize and consider the constructability benefits of a simple design. Ironically, the addition of a critic intended to simplify designs spurred several students to try to see how much they could upset the critic. While students would not typically use more than 9 materials in a given design, in a few groups of students someone would use more materials. When they would do this, they would receive a very negative critique from the construction manager (“What is this, some kind of joke?!? Look how many materials are in that design. I can’t build that!”) Students would be amused at the response and tell other students completing the activity how the construction manager really hated their design. This would lead other students in the group of participants to also try to “break” the game to see the construction
manager’s angered response. An example of this type of design is shown in Figure 5-7. This type of design behavior appeared to be more prevalent among the Architecture and Civil Engineering students. For example, in the AE course only 8.1% of students experimented with more than 15 materials over the course of the design session, while 14.8% of the CE course students and 17.0% of the Architecture course students used more than 15 materials.

From an instructor’s perspective, it was observed that, on several occasions, certain students who completed designs did not take the design process seriously for some of the time. For example, in one of the design sessions with a group of students in the Architecture course, students decided to experiment with the novelty of designing their initials into their curtain wall design. What further encouraged this type of novelty design was the fact that these designs often received very high scores from ecoCampus. With a design like the one shown in Figure 5-7, most of the non-glazing materials are relatively inexpensive compared to glass options and they also have relatively good insulation properties. The glass included in the novelty drawing or initials would let in some daylight, and with only 2 materials used, the virtual construction manager would also be satisfied with the design. This combination of performance traits leads to a relatively high score and it illustrates one of the shortcomings with the existing ecoCampus simulation feedback.

Figure 5-7: Students using ecoCampus occasionally tried to upset the construction manager with their designs (left) or create novelty design with drawings or letters (right).
approach. In reality, these types of novelty designs would likely cost a substantial amount of money to construct because of the irregular material layouts and would also not be approved for construction by a building owner, but this was not calculated during the ecoCampus simulation.

5.3.8 Treatment 3.1 and 3.2 critical assessment of design tradeoffs and sustainable building performance

During both of the ecoCampus implementations, students completed several design iterations of the sustainable design activity with the use of ecoCampus. It was of interest to observe how the students’ scores improved throughout the process of creating these design iterations. When the first scores received by the students were compared to their highest scores, it was found that the highest scores were significantly higher than their first scores (p<0.001). It was also observed that the iteration on which students scored their lowest score was significantly lower than the iteration on which they scored their highest score (p<0.001). This suggests that students’ initial designs were not generally their best designs. It also illustrates the trend that students tended to create better designs as they complete additional design iterations.

Ideally, the performance results from Treatments 3.1 and 3.2 would be compared to Treatments 1 and 2, but because Treatments 1 and 2 were paper-based, the designs could not have automatic simulation feedback and scores generated to compare. While this is an inherent limitation of the open-ended nature of Treatment 1 and 2, it is worth noting that the students who used ecoCampus did create significantly more design iterations than those who completed Treatments 1 and 2 and the ecoCampus students also tended to do better in their design performance as they created these additional iterations. The students who used ecoCampus also tended not to score their highest score on their first design. As a point of comparison, most students in Treatment 1 and 2 only completed one design iteration. Even when considering that the scoring mechanism for ecoCampus may possess certain flaws for rating designs as discussed in Section 4.5.3, the fact remains that any design project would still have different critics with different criteria for what will satisfy them in a given design scenario. The students who completed a paper-based treatment with no feedback mechanism incorporated into the experience effectively missed the
opportunity to critically assess their work to ultimately produce a better exterior wall design through the creation of additional design iterations. This further suggests the value in using ecoCampus for helping students.

5.4 Conclusions and future work from treatment implementations

This research has explored the pedagogical benefits of using an augmented reality-based simulation game to help students in the Architectural Engineering and related disciplines learn about sustainable design in the built environment. The benefits of using these technologies were observed through the implementation of the developed ecoCampus prototype as well as more traditional, paper-based design approaches. Three different treatment activities were implemented over 4 semesters. From the data collected, several noteworthy conclusions can be drawn. The conclusions drawn and related future work suggestions are grouped to address each of the detailed research questions listed in Section 1.4.

5.4.1 Conclusions related to students engagement with course content

Overall it was observed that students enjoyed the design activities, regardless of their format. The students in all treatments generally liked the experience of designing a new exterior curtain wall for the SALA Building. Therefore, the conclusion that ecoCampus can boost students’ enjoyment more than paper-based methods cannot yet be drawn. Part of the reason that a clear preference to one design format over another cannot be drawn is that students in different treatments were only given the option to complete one particular design format. Future work may explore the tendency of students to choose one format over another or possibly explore using multiple design formats to create their wall designs.

The students who completed all treatments also reported similar levels of increased interest in the design process and sustainability. In all of these treatments over half of the class reported being more interested in both sustainability and the design process. As a result, the conclusion that ecoCampus leads to increased engagement with course content as compared to paper-based
methods cannot be drawn, but it is encouraging to see that the use of ecoCampus still maintains the high level of engagement that was observed through the paper-based methods, while offering certain benefits that were not observed through the paper-based methods.

5.4.2 Conclusions related to design fixation

Design fixation has been defined as the blind adherence to a set of ideas or concepts limiting the output of conceptual design (Jansson and Smith 1991). This was observed in Treatments 1 and 2. In both of these paper-based treatments more than two thirds of the class arrived at their design solution through the creation of only one design concept. In most cases the materials and geometry that these students used in their designs closely resembled the design of the existing curtain wall installed in the SALA Building.

The use of ecoCampus was effective at breaking the tendency toward design fixation in this self-directed, time-constrained design scenario. In Treatments 3.1 and 3.2 students were given the application and not told specifically how many designs they had to create, but only that they must complete at least 1 design. The developed application allowed for simple creation of design concepts and supplied students with tailored performance feedback about their design concepts. This allowed students to use the feedback provided to create multiple design concepts before arriving at their final design concept.

Part of the reason why students may have been able to resist the tendency toward design fixation in Treatments 3.1 and 3.2 is because ecoCampus allowed students to generate design ideas more quickly than the paper-based methods. Not only were students able to create more design ideas in the same amount of time with ecoCampus, but they were also less likely to report feeling that had not had enough time to complete the overall design activity. Since time was more of an issue for the paper-based treatment versions, design fixation was more prevalent as students tended to focus their efforts on tweaking the existing SALA Building design. This effectively eliminated the consideration of many other possible design options by the students in Treatments 1 and 2.
5.4.3 Conclusions related to higher level thinking skills to critically assess designs

The students who completed this design process in all treatments were successful in analyzing their curtain wall designs to some extent. In all treatments students created designs that somehow addressed a concept related to sustainability. However, the students who completed the design activity with ecoCampus and received performance feedback were able to use this information to critically assess their design concepts. This allowed them to modify their designs to attempt to achieve the best overall wall performance. The students who completed Treatments 1 and 2 did not receive simulation feedback about their designs, so they were more likely to attempt to create a design to optimize performance of one aspect of design, which was frequently at the detriment of another design aspect. Furthermore, because the Treatment 1 and 2 students did not have the ecoCampus design interface, they rarely considered materials other than glass to increase thermal efficiency.

5.4.4 Conclusions related to aspects of ecoCampus that did not offer educational benefits

While ecoCampus did offer several benefits to students, there were also a few observations made where the benefit of this tool was less evident. Most students used the 40-minute design session to make a serious attempt at creating a more sustainable exterior curtain wall design, but some of the students took part of the 40-minutes to create novelty designs. These novelty designs incorporated either drawings or letters into the curtain wall design. While this type of behavior is not necessarily wrong, the developed simulation feedback processes used in ecoCampus does not quantify a design based on geometric layout. Therefore, the feedback students receive in these novelty designs is not necessarily realistic. From a learning point of view, this diminishes the benefit that ecoCampus can offer in providing formative design feedback to users.

In addition to not quantifying constructability performance based on geometric layout, the developed ecoCampus version also did not quantify aesthetics of a given design in the simulation feedback interface. This places the responsibility on the student to determine what they believe
to be an aesthetically acceptable wall design. The potential problem with this is that, for students who do not consider aesthetics in their design, high numerical scores can be obtained indicating a successful design, yet it might be unrealistic to expect a project owner to ever accept the design for construction in reality.

5.4.5 Overall conclusions

The results obtained suggest that ecoCampus was a beneficial tool that did offer educational benefits that were not observed with paper-based design approaches. Students enjoyed completing the design activity as much with the use of ecoCampus as they did with the paper-based approaches and they were also able to resist the tendency toward design fixation as well as critically assessing their designs with the feedback provided through the developed application in ways not observed in the paper-based approaches. The broader conclusions, contributions, limitations, and directions for future work based on the results from this work are discussed in Chapter 6.
CHAPTER 6 CONCLUSIONS AND CONTRIBUTIONS

This study has provided insight into the pedagogical value of using a simulation game that leverages augmented reality (AR) technology to educate engineering and design students about the building design process with a focus on sustainability. The contribution from this research includes the documentation of key aspects of the learning process that were observed to offer the most opportunity for benefit from the use of this technology as well as identifying aspects of the learning process where no significant benefit was observed. This understanding will help future educators and application developers target key learning aspects in future program development efforts.

In addition to the contributions related to the educational benefits of AR and simulation games to teach design processes related to sustainability, this research has also helped to add to the body of knowledge about creating a simulation game technology for the purposes of education. The process used in developing of ecoCampus has been documented to help future researchers to develop other educational applications and avoid some of the potential pitfalls associated with this type of application development.

6.1 Conclusions

To help understand the pedagogical value of using a simulation game with augmented reality for sustainable design education, the ecoCampus augmented reality educational game was developed. This application was tested with Architectural Engineering students as well as with Architecture and Civil Engineering students to identify educational areas of benefit. This section discusses the conclusions from this work related to the pedagogical value and also conclusions related to the application development process.
6.1.1 Conclusions related to the pedagogical value of ecoCampus

Throughout the research process, students who were involved with this research completed one of three different experimental treatment activities. The findings from these different treatment activities are described in detail in Chapter 5. After collecting data on all of the treatment activities, several noteworthy conclusions can be drawn.

Design fixation has been defined as the blind adherence to a set of ideas or concepts limiting the output of conceptual design (Jansson and Smith 1991). Design fixation is a common trend not only among students, but also among faculty and industry members and can be limiting when trying to determine the best possible design for a particular scenario (Linsey et al. 2010). It was observed that students who used ecoCampus were more likely to experiment with multiple possible design options within a time-constrained, self-directed design scenario. In the context of design fixation, students who were asked to complete a design activity in an existing space without the use of ecoCampus, were more likely to create only one design, which typically resembled the existing building’s design. It was observed that ecoCampus lowered the amount of effort required to generate multiple designs and also provided information that might not have been known or considered by students who completed the activity without the application. Therefore, it is concluded that this type of technology can help to break the common tendency toward design fixation in a time constrained, self-directed learning situation.

Situated learning theory states that the best way for students to learn is to teach them in the context in which that knowledge will be eventually applied (Lave and Wenger 1991). The ecoCampus platform was developed to allow students to learn the process of design through actually designing. Students who completed the ecoCampus experience were able to demonstrate understanding of several key design competencies in their submitted work. Students tended to receive low scores on their first designs while using ecoCampus, but their scores tended to increase as they subsequently used the application. This suggests that students’ initial guesses as to what design would best meet the needs of the virtual project critics may have been inaccurate. By using ecoCampus, students were able to test a design hypothesis, fail quickly in assessing their initial hypotheses, and modify their behavior based on their assessments in a design context.
This tendency to change the design to modify performance was not observed in the designs submitted by students who were given a paper-based design activity instead of ecoCampus. This suggests that ecoCampus facilitated critical assessment of design ideas by the students. The increasing trends in scores illustrates that students were generally able to negotiate between the building tradeoffs to allow for natural daylighting to enter the built space while not using so much glass that the resulting R-value or cost is overly impacted or so many materials that construction processes could suffer. Therefore, it is concluded that augmented reality in conjunction with a simulation game can facilitate critical assessment in the design process to learn key principles while completing the process of design more than paper-based design methods can in a time-constrained, self-directed context.

In addition to the observations related to the students’ performance during the different design activities, self-reported feedback from the students about their experiences was also obtained. The feedback obtained by the students was very positive, with approximately 85% of the students rating the experience as actively enjoyable. When considering this result with the high number of design iterations that students created with ecoCampus, this suggests that this mode of interaction can motivate students to experiment with course content in a way that is not typical from paper-based methods.

Some of the self-reported results generated by the students who used ecoCampus did not illustrate the same level of clear-cut benefit over the more traditional design methods. For example, while students did report the activity as being highly enjoyable using ecoCampus, the responses did not illustrate significantly higher ratings than traditional, paper-based formats. Prior to implementing the activity, it had been hypothesized that students would report the level of enjoyment of completing the ecoCampus experience more highly than they would report the paper-based versions. While this hypothesis is not backed up by the collected data, this may not be a drawback per se. It may more appropriately suggest that, for educators looking to engage students and make them enjoy the learning process, incorporating design activities in any format can effectively engage students. Therefore, for the specific purpose of engaging students in the learning process, ecoCampus cannot be concluded to offer a significant benefit over traditional methods. For this conclusion, it is important to note that this finding compares two different
samples of students who did not complete the other format of activity. It is possible that if students had been exposed to both design activity formats and asked which format they found to be more enjoyable, they may have self-reported a particular preference of one format over another.

6.1.2 Conclusions related to the development process of ecoCampus

Over the course of this research, a substantial amount of effort went into creating a functional sustainable design game using augmented reality technology for visualization. The effort to develop ecoCampus has provided a great deal of insight into understanding the process associated with this type of application development. A detailed explanation of the development process followed is described in Chapter 4. Essentially, the process followed involved: brainstorming a wish list of functional requirements for the application to achieve the desired learning outcomes; storyboarding a desired user experience to achieve the intended functional wish list goals; selecting a development infrastructure to achieve the desired performance; creating an initial prototype using the chosen development infrastructure; testing and debugging the prototype; piloting the prototype in desired course; and fine tuning the application based on feedback from students. While the process used was not validated through comparison with other possible development strategies, it was successful in generating a functional proof-of-concept level application that was successfully able to offer insight into the pedagogical value of the tool, thus addressing the targeted research question. Therefore, it is concluded that this process does offer a sound method for developing an educational simulation game using marker-based augmented reality for a mobile computing platform.

6.2 Limitations

While this research has provided insight into several beneficial aspects of using an augmented reality-based simulation game to educate students about sustainable building design, there were also several limitations associated with this initial work. This section explores the limitations associated with this ecoCampus development and implementation.
6.2.1 Limitations related to learning outcomes

In order to understand the pedagogical benefits of using an educational simulation game in conjunction with augmented reality, ecoCampus was developed as a proof-of-concept application. The implementation of this prototype was intended to answer a few basic research questions. Several observations made during this work suggest that students may benefit from this type of technology in a time-constrained self-directed learning environment. For example, it was observed that students were willing and able to explore more possible design options with the use of ecoCampus as compared to a paper-based design activity. While this is seen as a benefit for the curtain wall design activity implemented, this does not necessarily suggest that students will transfer this behavior of design brainstorming to future design work, where ecoCampus is not present. Therefore, it is difficult to conclude that the completion of the ecoCampus experience directly causes students to learn the value of brainstorming alternative design options and resisting the pitfall of design fixation.

This research explored the benefits of using augmented reality in conjunction with a simulation game. It was of particular interest to explore how these two technologies might be able to help students visualize and assess design content. A specific attempt was not made to isolate the two technologies as individual variables. The targeted class of students had not had a substantial amount of design experience, which could make both the processes of visualization and analysis difficult. Therefore, ecoCampus was intended to help lower the hurdles associated with completing both of these tasks through the use of both AR and a simulation game. Based on this, it is not possible to quantify the value of just one of these two technologies.

6.2.2 Limitations related to the ecoCampus prototype and implementation

The developed ecoCampus prototype has helped to explore the educational benefits associated with using augmented reality in conjunction with a simulation game. Because ecoCampus was developed as a proof-of-concept prototype, there are some limitations associated with the application and implementation of this tool in the classroom.
One of the educational goals associated with this work was to educate students about tradeoffs in building design to understand that as one aspect of design might improve, it may adversely impact another aspect of the building design. In the context of the curtain wall design problem, a tradeoff that students would be expected to encounter would be related to balancing the amount of glazing used in a design to allow for adequate daylight while minimizing the amount of thermal losses. One of the limitations of this work from a development point of view was related to the camera function in the mobile computing devices that was used. When sunlight would shine into the building space, the camera on the mobile computing device would darken to adjust for the abundance of light entering the view. As a result, the fiducial marker used for this work, would no longer be visible to the camera. Specific camera adjustments to override this dimming function were not able to be programmed into this initial prototype, which meant that the activity had to be performed in the evening. This created a potential source of bias where students might design more for thermal performance than daylight performance as very little light entered the building space in the evenings when they were completing the activity.

An additional limitation to this work was that only one building design module was created. Initially, several design modules were envisioned, but the complexity of the prototype development process limited the amount of design modules that could be created for implementation. This limitation reduced the scope of design content to which students were exposed. This also limited the amount of content to which students were exposed related to performance relationships between the design of one building system and other related building systems.

6.3 Contributions

The research presented in this work contributes to the existing body of knowledge related to the pedagogical value of augmented reality and simulation games in education as well as the process for creating this type of new tool.
6.3.1 Understanding of the pedagogical value of AR-based educational simulation game

Through implementation of ecoCampus and also more traditional, paper-based methods of design, this research has helped to expand the current understanding of pedagogical value of simulation games and augmented reality in design education. It has observed several key benefits and challenges to using this type of technology. Future research will benefit from the identification of the aspects of the learning process that were benefitted through the use of this technology as well as the aspects of learning where no benefit was observed. This will allow future educators to develop AR-based simulation games to target the specific educational experiences where the greatest benefits were observed and explore alternative methods for achieving the learning outcomes for which ecoCampus was less effective.

6.3.2 Documentation of ecoCampus development process

The development process used for creating ecoCampus has been detailed in this research to help future research efforts create new educational design games that attempt to leverage AR technology. While the application was only developed as a proof-of-concept, the documentation of the process used to create this prototype application helps to illustrate a functional process for developing a new educational tool like ecoCampus. In addition to documenting the process used for creating ecoCampus, several limitations and pitfalls associated with the chosen development process have also been discussed. These will help future educators avoid some of the potential problems observed and/or restructure learning modules to avoid some of the limitations observed in this work. Finally, in addition to the documentation of the process used for creating ecoCampus, all assessments administered are included in the appendix of this document as well as detailed screen captures to illustrate the specific ecoCampus application interface.
6.4 Future work

The research presented has provided several contributions to the body of knowledge related to the pedagogical understanding of technology in engineering, but also has several limitations. This section explores possible directions for future work based on the findings of this research.

6.4.1 Further development of ecoCampus

Future work will further develop the ecoCampus prototype created in this work. Much of the feedback and comments received by students encouraged future development for future implementations of this type of learning interface. Students specifically suggested including more materials and construction assemblies in the curtain wall design module. Some students mentioned that they would like to have been able to design with cutting edge building materials, such as solar photovoltaic panels and living walls, as well as alternate wall assemblies, such as double skin facades. More consideration into different possible methods for creating an exterior wall will be considered and incorporated into future iterations of ecoCampus.

In addition to the need for more building materials and assemblies, students also mentioned that the current development of ecoCampus was lacking in realism in certain aspects. For example, many students recognized that there was no built-in aesthetic component to the design review simulation. Future iterations of ecoCampus will incorporate additional virtual critics to encompass even more possible design criteria that would be relevant to an exterior wall redesign scenario. These additional virtual critics may include: Architect to judge aesthetics of a design; An architecture student to judge the functionality of a given design related to the ability to access an operable window near their studio desk; And additional construction critics to assess constructability based on how difficult certain building materials may be to obtain or how far they must be shipped to arrive on site. While these additional critics will likely add to the challenge of ecoCampus, there is a value in making the design process as real as possible to illustrate the real-world challenges that exist when attempting to make a new building design.
Future work will also expand ecoCampus beyond the exterior wall design module into other building design modules that will challenge students to think about design considerations outside of the scope of an exterior wall design. Possible additional design modules may include: An interior material redesign; A parking lot redesign; Or the creation of an addition to existing building to determine the best orientation and site logistics. These different design modules will be developed to tie into the same ecoCampus gaming experience so students can also understand the impact that the design they create in one module will have on their design of a building component in another module.

### 6.4.2 Further implementation of ecoCampus

In addition to the future work related to furthering the development of ecoCampus itself, there are also opportunities to further examine new ways to implement the tool. This research identified benefits from using ecoCampus, but some of the limitations will open the door to future opportunities. For example, one of the key findings from this implementation was related to the students’ tendencies to create multiple design ideas through the completion of ecoCampus. This finding illustrates the intrinsic motivation observed in this type of application in encouraging students to brainstorm to identify the best possible way to solve a design challenge. It would be of particular value for future work to examine this tendency beyond the ecoCampus experience to determine whether or not students who completed ecoCampus could transition their behaviors performed in the activity into design habits that they could use in future design projects where a computerized simulation game interface is not provided.

Additionally, it would be of value for future work to target other disciplines of students in further ecoCampus implementations. This implementation targeted three related majors including Architectural Engineering, Architecture, and Civil Engineering. Future work could also examine the benefits of using this type of tool for Landscape Architecture, Mechanical Engineering, Electrical Engineering, as well as for incoming or undecided college students who may still be trying to determine their desired major. These additional implementations could determine how this type of tool might encourage students in a wide variety of fields to take an interest in
sustainability. It may also help to determine the benefits that ecoCampus may offer in teaching students about the tradeoffs that occur between different building systems for students in majors that may have more focused curricula where the interaction between different design disciplines is not highly stressed.

6.4.3 Leveraging findings for use outside of academic education.

Through informal discussions with different building industry practitioners about ecoCampus, a common question that frequently was raised was related to whether this technology could be used to offer benefit in industry applications. This could prove to be a valuable direction for future research. While the ecoCampus platform developed was intended to educate students in academia, the lessons learned from this research may be able to be transitioned to educate designers and owners about the implications of a specific building design. This could allow owners to more directly provide design suggestions for what they would like in a building project. It may also help to illustrate tradeoffs that may exist with a particular design. This could help to create more informed building owners and designers who may be less likely to be surprised to find that a given design possesses critical flaws after it is constructed.

6.5 Closing remarks

The experience of developing and implementing a new technology for use in education has been greatly rewarding. The findings from this initial development of ecoCampus are highly encouraging for the potential of further exploring augmented reality and simulation games in education. This work has made a first step toward advancing these technologies for use in an engineering education context to educate the future cohort of building designers about sustainability and building design. After completing this work, it is clear that much more can be done and future developments will certainly determine other beneficial aspects of these technologies not only for engineering students, but for other disciplines as well. As computing technology continues to evolve, the possibilities for the use of existing tools in education will
only increase. It is exciting to consider how this work may serve as a starting point for some of these new and innovative methods for education.
REFERENCES


APPENDIX A  DEFINITIONS OF TERMS AND ABBREVIATIONS

Accreditation Board for Engineering and Technology (ABET) – Organization responsible for ensuring that educational institutions meet certain educational standards related to the engineering and technological disciplines.

Augmented reality (AR) – A subset of the more general mixed reality, where graphical content is superimposed on the real view of a physical space of interest.

Computer vision – The process of deciphering meaningful, explicit descriptions of objects from images.

ecoCampus – An augmented reality-based simulation game designed to allow students to design new building components for existing facility to attempt to make the building perform more sustainably.

First-year seminar (FYS) – One credit courses that incoming freshmen Penn State students complete. For this research, the particular FYS of interest is Architectural Engineering 124S.

Game engine – A system designed for the development of video game environments that may include a graphics engine, physics engine, scripting, animation, and artificial intelligence capabilities.

Head-mounted display (HMD) – A system for viewing augmented reality content that rests on a user’s head and covers the user’s eyes with a screen that displays information based on their viewing position.

Leadership in Energy and Environmental Design (LEED) – This is a design metric developed by the United States Green Building Council (USGBC) to quantify the level of sustainability of a give facility.

Mixed reality (MR) – The mixing of the real and virtual worlds by superimposing graphical content on the real view of a physical space of interest.

School of Architecture and Landscape Architecture’s (SALA) Stuckeman Family Building – This building, located on Penn State’s University Park campus is the facility that will be examined in-depth on this project.

Simulation game – Goal-directed contest between individuals that move toward specific goals under sets of conditions and constraints.

Software development kit (SDK) – Existing tools designed for software developers to facilitate the creation of (in this research case) augmented reality content.

United States Green Building Council (USGBC) – This organization is responsible for creating the LEED scoring metric, which is a key learning component associated with this research.
AE 124S: Sustainable Design Activity

For this assignment, your design services are needed. The Pennsylvania State University is looking to improve its sustainability image by retrofitting its flagship green building with an even better design to improve its sustainable performance. Your assignment is to redesign a key aspect of the School of Architecture and Landscape Architecture’s (SALA) Stuckeman Family Building to make it more sustainable. You understand that a significant amount of building energy efficiency can be saved or lost through the building envelop and so you have elected to target the building’s curtain wall as the particular building system of interest for this project.

**Deliverables:**

**Design documents** – Because of time constraints you are not contracted to deliver fully completed design documents that account for every possible detail, but you are responsible for developing a coherent drawing/sketch/set of drawings and sketches to convey your design idea and any unique features or building materials that you intend to use. For this activity, you should worry less about exact geometry and dimensions and focus more on the general design principles and how you foresee improving the sustainable performance of the SALA Building with your design.

The University recognizes that this substantial design task can take time to complete, so while your design can be submitted at the conclusion of class, you may elect to submit it at the beginning of next week’s class should you need more time.

**Process documentation** – You and the University both understand that the importance of design is not only in the final product that is created but also the process for creating that design. If Penn State’s owners decide that they want to make changes to your initial design, they need to be assured that you as the lead designer possess the ability to use a sound design process to adapt a given design to accommodate new design requests. Therefore, to demonstrate to the University that you are up to the challenge, you are responsible for submitting the process sheet that is attached to indicate your thought process for arriving at your final design from this activity.

**Assessment Completion**

- Completed before activity:
  - Pre-test in class
  - Survey quiz on ANGEL
- Completed during class:
  - Post-test
- Completed after class:
  - Reflection questions (on ANGEL)
  - Optional discussion focus group (Will meet out-of-class and count toward your out-of-class requirements for this course)
Name:

Describe the sequential steps that you took to arrive at your final design: __________________________

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List the key decisions that you made during your design process: ________________________________

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List the different factors that affected your design decisions: _________________________________

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AE 124S: Sustainable Design Activity

For this assignment, your design services are needed. The Pennsylvania State University is looking to improve its sustainability image by retrofitting its flagship green building with an even better design to improve its sustainable performance. Your assignment is to redesign a key aspect of the School of Architecture and Landscape Architecture’s (SALA) Stuckeman Family Building to make it more sustainable. You understand that a building’s performance is significantly affected by the design of its exterior walls and building enclosure and so you have elected to target the building’s curtain wall as the particular building system of interest for this project. While improving the building’s sustainability performance is the primary design goal, you should also consider the implications that your design has on aesthetics, cost, constructability, and function of the space.

**Deliverables:**

**Design documents** – Because of time constraints you are not contracted to deliver fully completed design documents that account for every possible detail, but you are responsible for developing a coherent design concept that illustrates your design idea and any unique features or building materials that you intend to use. Two similar, but slightly different, images have been provided so that you may illustrate your design in the context of the existing building space. You may draw your design on either or both of the images provided. When you need additional images for testing other design ideas, please see the instructor for extra copies. Each image shows a typical curtain wall bay. Unless you specifically state otherwise, your design for one bay will be assumed to be replicated in all others in the building. A library of possible design materials has been provided to you in this packet. You may select to use any number of materials in your curtain wall redesign.

The University recognizes that this substantial design task can take time to complete, so while your design can be submitted at the conclusion of class, you may elect to submit it at the beginning of next week’s class should you need more time.

**Process documentation** – You and the University both understand that the importance of design is not only in the final product that is created but also the process for creating that design. If Penn State’s owners decide that they want to make changes to your initial design, they need to be assured that you as the lead designer possess the ability to use a sound design process to adapt a given design to accommodate new design requests. Therefore, to demonstrate to the University that you are up to the challenge, you are responsible for submitting the process sheet that is attached to indicate your thought process for arriving at your final design from this activity.

**Assessment Completion**

- Completed before activity:
  - Pre-test in class
  - Survey quiz on ANGEL
- Completed during class:
  - Post-test
- Completed after class:
  - Reflection questions (on ANGEL)
  - Optional discussion focus group (Will count toward your out-of-class requirements for this course)
Describe the sequential steps and key decisions that you made in arriving at your final design:

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List the different factors that affected your design decisions:

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List each material you selected in your final design and (at least) one pro and con for each material:

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<th>Material</th>
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Material Library

Architectural Concrete

Brick

Concrete

Copper

Painted Drywall

Stone

Stucco

Material Library

Wood

Glazing Options:

Specify:

- Single, double, or triple-paned
- Fixed or operable (able to be opened)
- Location of window separations/mullions
- Tint, color, frit pattern, or photo voltaic technology incorporated into the design.

The choices you make can significantly impact building performance, cost, functionality, and aesthetics.

Other Options:

You have the freedom to use materials other than those specified in this library of materials. If you choose to deviate from this list, be sure to indicate what materials you will be using and why you chose to use those materials over the ones listed.
Description of AR tool
This tool was created to help in the creation of building design ideas and also to help understand the performance implications of a particular design. For this assignment, you will be attempting to redesign a curtain wall system. You will develop a design idea for one section of this curtain wall and that idea will be duplicated along the entire length of curtain wall.

Start
Define Materials

Material 1
Masonry ½ running bond: This has historically been a standard material on Penn State’s main campus.

Define New Material  Cancel Changes  Confirm Changes

Define Materials

Material 1
Material 2
Triple Pane Glazing: This glass has a high insulation (R-value) relative to other glass, but tends to cost

Define New Material  Cancel Changes  Confirm Changes
Define Geometry

Material 1

Material 2

Attach Material to Geometric Area

Define Area
Modify Area
Delete Area
Cancel Changes
Confirm Changes

Define Geometry

Divide window / Add mullions

Define Area
Modify Area
Delete Area
Cancel Changes
Confirm Changes

125
APPENDIX E   TREATMENT 3.1 ECOCAMPUS APPLICATION

This section includes screen captures of each screen with which a user may interact and all simulation content illustrated for the first version of ecoCampus.
The Pennsylvania State University is looking to improve its sustainability image by retrofitting its flagship green building with an even better design to improve its sustainable performance. Your assignment is to redesign a key aspect of the School of Architecture and Landscape Architecture’s (SALA) Stoeckeman Family Building to make it more sustainable. You understand that a building's performance is significantly affected by the design of its interior walls and building enclosure and so you have elected to target the building’s curtain wall as the particular building system of interest for this project. While improving the building’s sustainability performance is the primary design goal, you should also consider the implications that your design has on aesthetics, cost, constructability, and function of the space.
Materials Used
- Brick: 190,460 sq ft
  - Cost of Brick: $400,800.44
- Copper: 42,700 sq ft
  - Cost of Copper: $128,860.46
- Double Glazed Glass: 170,890 sq ft
  - Cost of Double Glazed Glass: $425,880.00

R-value = 0.184 Degrees F ft² hr / Btu

Total Cost of Construction Per Bag: $29449.89
Total Renovation Cost: $69368.06

Owner Comment: We should be able to afford your design.
Lighting Engineer Comment: This design will let in a lot of light. We can probably reduce our intended number of interior light fixtures.
Mechanical Engineer Comment: This design should perform fairly well. It will not cost too much to heat and cool the building with this design.

Final Score: 22587

Show Final Score
Start Over
Experimental ID number: 13
Reflection Sections:

Design 1:
What comments did you receive for this design from each person (you may paraphrase each comment)?

**Owner comment:**

**Lighting engineer comment:**

**Mechanical engineer comment:**

How would you respond to each of these comments? Your response might be a description for how you plan to modify your design to make a given person happier. Conversely you can also choose to respond with an explanation as to why your design should be left as it is and why a particular person should be satisfied with the existing design.

**Your response to owner:**

**Your response to lighting engineer:**

**Your response to mechanical engineer:**

Design 2:
What comments did you receive for this design from each person (you may paraphrase each comment)?

**Owner comment:**

**Lighting engineer comment:**

**Mechanical engineer comment:**
How would you respond to each of these comments? Your response might be a description for how you plan to modify your design to make a given person happier. Conversely you can also choose to respond with an explanation as to why your design should be left as it is and why a particular person should be satisfied with the existing design.

Your response to owner:

Your response to lighting engineer:

Your response to mechanical engineer:

Design 3: What comments did you receive for this design from each person (you may paraphrase each comment)?

Owner comment:

Lighting engineer comment:

Mechanical engineer comment:

How would you respond to each of these comments? Your response might be a description for how you plan to modify your design to make a given person happier. Conversely you can also choose to respond with an explanation as to why your design should be left as it is and why a particular person should be satisfied with the existing design.

Your response to owner:

Your response to lighting engineer:

Your response to mechanical engineer:
Design 4:
What comments did you receive for this design from each person (you may paraphrase each comment)?

**Owner comment:**

**Lighting engineer comment:**

**Mechanical engineer comment:**

How would you respond to each of these comments? Your response might be a description for how you plan to modify your design to make a given person happier. Conversely you can also choose to respond with an explanation as to why your design should be left as it is and why a particular person should be satisfied with the existing design.

**Your response to owner:**

**Your response to lighting engineer:**

**Your response to mechanical engineer:**

Design 5:
What comments did you receive for this design from each person (you may paraphrase each comment)?

**Owner comment:**

**Lighting engineer comment:**

**Mechanical engineer comment:**
Design 6:
What comments did you receive for this design from each person (you may paraphrase each comment)?

**Owner comment:**

**Lighting engineer comment:**

**Mechanical engineer comment:**

How would you respond to each of these comments? Your response might be a description for how you plan to modify your design to make a given person happier. Conversely you can also choose to respond with an explanation as to why your design should be left as it is and why a particular person should be satisfied with the existing design.

**Your response to owner:**

**Your response to lighting engineer:**

**Your response to mechanical engineer:**
Design 7:
What comments did you receive for this design from each person (you may paraphrase each comment)?

**Owner comment:**

**Lighting engineer comment:**

**Mechanical engineer comment:**

How would you respond to each of these comments? Your response might be a description for how you plan to modify your design to make a given person happier. Conversely you can also choose to respond with an explanation as to why your design should be left as it is and why a particular person should be satisfied with the existing design.

**Your response to owner:**

**Your response to lighting engineer:**

**Your response to mechanical engineer:**

Design 8:
What comments did you receive for this design from each person (you may paraphrase each comment)?

**Owner comment:**

**Lighting engineer comment:**

**Mechanical engineer comment:**
How would you respond to each of these comments? Your response might be a description for how you plan to modify your design to make a given person happier. Conversely you can also choose to respond with an explanation as to why your design should be left as it is and why a particular person should be satisfied with the existing design.

Your response to owner:

Your response to lighting engineer:

Your response to mechanical engineer:
APPENDIX G  TREATMENT 3.2 ECOCAMPUS APPLICATION

This section includes screen captures of each screen with which a user may interact and all simulation content illustrated for the first version of ecoCampus.

The Pennsylvania State University is looking to improve its sustainability image by retrofitting its flagship green building with an even better design to improve its sustainable performance. Your assignment is to redesign a key aspect of the School of Architecture and Landscape Architecture's (SALA) Steckman Family Building to make it more sustainable. You understand that a building’s performance is significantly affected by the design of its exterior walls and building enclosure and so you have elected to target the building’s curtain wall as the particular building system of interest for this project. While improving the building’s sustainability performance is the primary design goal, you should also consider the implications that your design has on aesthetics, cost, constructability, and function of the space.
The Pennsylvania State University is looking to improve its sustainability image by retrofitting its flagship green building with an even better design to improve its sustainable performance. Your assignment is to redesign a key aspect of the School of Architecture and Landscape Architecture’s (SALA) Stuckeman Family Building to make it more sustainable. You understand that a building’s performance is significantly affected by the design of its exterior walls and building enclosure and so you have elected to target the building’s curtain wall as the particular building system of interest for this project. While improving the building’s sustainability performance is the primary design goal, you should also consider the implications that your design has on aesthetics, cost, constructability, and function of the space.
Select a building material from the menu and start designing!
Materials Used
Brick: 196.46 sq ft
Cost of Brick: $6080.44
Copper: 42.70 sq ft
Cost of Copper: $1381.46
Double Fixed Glass: 170.00 sq ft
Cost of Double Fixed Glass: $1458.00

R-value = 0.184 Degrees-F ft² hr / Btu
Total Cost of Construction Per Bag: $21949.89
Total Renovation Cost: $491546.06

Owner Comment: We should be able to afford your design.
Lighting Engineer Comment: This design is great. There will be enough daylight entering the space to save some money through a reduction in necessary task lighting.
Mechanical Engineer Comment: This design should perform fairly well. It will not cost too much to heat and cool the building with this design.
Construction Manager Comment: My crews will be able to build this, but with this many materials, it may take a bit longer than expected to complete.

Final Score: 20301

Experimental ID number: 13
APPENDIX H  TREATMENT 3.2 REFLECTION SECTION

ecoCampus Reflection Sections: Experimental ID Number:__________________

Design 1:
What comments did you receive for this design from each person (you may paraphrase each comment)?

Owner comment:

Lighting engineer comment:

Mechanical engineer comment:

Construction manager comment:

How would you respond to each of these comments? Your response might be a description for how you plan to modify your design to make a given person happier. Conversely you can also choose to respond with an explanation as to why your design should be left as it is and why a particular person should be satisfied with the existing design.

Your response to owner:

Your response to lighting engineer:

Your response to mechanical engineer:

Your response to construction manager:

Design 2:
What comments did you receive for this design from each person (you may paraphrase each comment)?

Owner comment:

Lighting engineer comment:

Mechanical engineer comment:

Construction manager comment:
How would you respond to each of these comments?

Your response to owner:

Your response to lighting engineer:

Your response to mechanical engineer:

Your response to construction manager:

Design 3:
What comments did you receive for this design from each person (you may paraphrase each comment)?

Owner comment:

Lighting engineer comment:

Mechanical engineer comment:

Construction manager comment:

How would you respond to each of these comments?

Your response to owner:

Your response to lighting engineer:

Your response to mechanical engineer:

Your response to construction manager:

Design 4:
What comments did you receive for this design from each person (you may paraphrase each comment)?

Owner comment:

Lighting engineer comment:

Mechanical engineer comment:

Construction manager comment:
How would you respond to each of these comments?

Your response to owner:

Your response to lighting engineer:

Your response to mechanical engineer:

Your response to construction manager:

Design 5:
What comments did you receive for this design from each person (you may paraphrase each comment)?

Owner comment:

Lighting engineer comment:

Mechanical engineer comment:

Construction manager comment:

How would you respond to each of these comments?

Your response to owner:

Your response to lighting engineer:

Your response to mechanical engineer:

Your response to construction manager:

Design 6:
What comments did you receive for this design from each person (you may paraphrase each comment)?

Owner comment:

Lighting engineer comment:

Mechanical engineer comment:

Construction manager comment:
How would you respond to each of these comments?

Your response to owner:

Your response to lighting engineer:

Your response to mechanical engineer:

Your response to construction manager:

Design 7:
What comments did you receive for this design from each person (you may paraphrase each comment)?

Owner comment:

Lighting engineer comment:

Mechanical engineer comment:

Construction manager comment:

How would you respond to each of these comments?

Your response to owner:

Your response to lighting engineer:

Your response to mechanical engineer:

Your response to construction manager:

Design 8:
What comments did you receive for this design from each person (you may paraphrase each comment)?

Owner comment:

Lighting engineer comment:

Mechanical engineer comment:

Construction manager comment:
How would you respond to each of these comments?

Your response to owner:

Your response to lighting engineer:

Your response to mechanical engineer:

Your response to construction manager:
INFORMED CONSENT FORM FOR SOCIAL SCIENCE RESEARCH

Title of Project: Improving collegiate education of first year design and construction students through the use of augmented reality.

Principal Investigator: John I. Messner jmessner@engr.psu.edu
Associate Professor, Dept. Architectural Engineering
The Pennsylvania State University
104 Engineering Unit A
University Park, PA 16802
(814) 865-4578

Co-investigator: Steven K. Ayer ska124@psu.edu
Graduate Research Assistant, Dept. Architectural Engineering
The Pennsylvania State University
104 Engineering Unit A
University Park, PA 16802
(814) 865-5022

1. **Purpose of the Study**: The purpose of this study is to gather information about the value of using augmented reality in conjunction with simulation games as a tool to improve visualization of sustainable building design content.

2. **Procedures to be followed**:
   - As an assignment for AE 124S, you will be asked to complete a sustainable design activity.
   - As part of this assignment, you will be asked to complete a series of assessments before and after the sustainable design activity.
   - You will also be asked to give the researchers permission to use the responses from the assignment, assessments, and any photographs taken during this activity for research purposes. All identifying information will be removed from all assignments so that individuals cannot be associated with responses.

3. **Benefits**:
   - You may learn more about the design process through this research activity.
   - This research may provide a better understanding of the pedagogical value of using augmented reality and simulation games within the engineering domain.

4. **Duration/Time**: Completion of the class assignment will take 1 class session to complete plus the time necessary to complete out-of-class assessments related to the activity (approximately 2 hours total).

5. **Statement of Confidentiality**: Your participation in this research is confidential. If this research is published, no information that would identify you will be written. Your name will not be associated with any data in any manner. Both the content you create and the feedback you provide will be stripped of any link to your name, so your instructor and teaching assistants will not be able to identify your specific responses until the end of the semester after final grades are posted. All the data and recordings will be stored securely on a password protected computer in the co-investigator’s office. The file identifying the link between an individual’s name and experimental ID number will be stored on a password protected drive on the graduate research assistant’s computer and will not be shared with the course instructor until the close of the semester, after grades have been recorded. Only the principal and the co-investigators will have access to the data collected. All identifying information will be removed from student assignments and survey responses. Your confidentiality will be kept

---

APPENDIX I

INFORMED CONSENT FORM

The Pennsylvania State University

Research ID#: 

INFORMED CONSENT FORM FOR SOCIAL SCIENCE RESEARCH

Title of Project: Improving collegiate education of first year design and construction students through the use of augmented reality.

Principal Investigator: John I. Messner jmessner@engr.psu.edu
Associate Professor, Dept. Architectural Engineering
The Pennsylvania State University
104 Engineering Unit A
University Park, PA 16802
(814) 865-4578

Co-investigator: Steven K. Ayer ska124@psu.edu
Graduate Research Assistant, Dept. Architectural Engineering
The Pennsylvania State University
104 Engineering Unit A
University Park, PA 16802
(814) 865-5022

1. **Purpose of the Study**: The purpose of this study is to gather information about the value of using augmented reality in conjunction with simulation games as a tool to improve visualization of sustainable building design content.

2. **Procedures to be followed**:
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   - You will also be asked to give the researchers permission to use the responses from the assignment, assessments, and any photographs taken during this activity for research purposes. All identifying information will be removed from all assignments so that individuals cannot be associated with responses.

3. **Benefits**:
   - You may learn more about the design process through this research activity.
   - This research may provide a better understanding of the pedagogical value of using augmented reality and simulation games within the engineering domain.

4. **Duration/Time**: Completion of the class assignment will take 1 class session to complete plus the time necessary to complete out-of-class assessments related to the activity (approximately 2 hours total).

5. **Statement of Confidentiality**: Your participation in this research is confidential. If this research is published, no information that would identify you will be written. Your name will not be associated with any data in any manner. Both the content you create and the feedback you provide will be stripped of any link to your name, so your instructor and teaching assistants will not be able to identify your specific responses until the end of the semester after final grades are posted. All the data and recordings will be stored securely on a password protected computer in the co-investigator’s office. The file identifying the link between an individual’s name and experimental ID number will be stored on a password protected drive on the graduate research assistant’s computer and will not be shared with the course instructor until the close of the semester, after grades have been recorded. Only the principal and the co-investigators will have access to the data collected. All identifying information will be removed from student assignments and survey responses. Your confidentiality will be kept
to the degree permitted by the technology used. No guarantees can be made regarding the interception of data sent via the Internet by any third parties.

6. **Right to Ask Questions:** You may ask questions about the research. Contact John I. Messner at 865-4578, or Steven K. Ayer at 865-5022 with questions, complaints or concerns about this research.

7. **Voluntary Participation:** Participation is voluntary. This research study is part of regular classroom instruction and everyone will receive the same instruction, regardless of the decision to participate in the research study. Your course grade will not be impacted by your participation in this study. You can withdraw your content and responses from the study at any time by notifying the principal investigator. You can decline to answer specific questions on the surveys.

You must be 18 years of age or older to consent to participate in this research study.

You will be given a copy of this consent form to keep for your records.

If you agree to the conditions and statements noted above, please select the appropriate options below:

☐ I agree to give the researchers permission to use the content I generate during the sustainable design activity and the responses to the surveys and assessments associated with this assignment.

☐ I DO NOT agree to give the researchers permission to use the content I generate during the sustainable design activity and the responses to the surveys and assessments associated with this assignment.

In addition, please select the response which reflects your agreement with the researchers’ use of the photographs:

☐ I agree to allow images from AE 124S to be released to the principal investigator and the research team of this study for the purpose of research. In addition, these may possibly be shown in a presentation setting with names removed.

☐ I DO NOT agree to allow my images from AE 124S to be released to the principal investigator and the research team of this study for the purpose of research. Please complete the section below:

<table>
<thead>
<tr>
<th>Student Name</th>
<th>Signature</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investigator Name</td>
<td>Signature</td>
<td>Date</td>
</tr>
</tbody>
</table>
APPENDIX J  ASSESSMENTS FOR TREATMENTS 1, 2, AND 3.1

Pre-test:
This section seeks to determine some baseline understanding and motivation levels for completing the work associated with this experimental activity. For all of the following questions, students’ course grades will NOT be affected by whether or not their responses are deemed correct.

Motivation level:
1. Are you looking forward to this design activity?
   - Not at all
   - Not very
   - Somewhat
   - Very Much

2. How useful do you believe this activity will be?
   - Not at all
   - Not very
   - Somewhat
   - Very Much

3. How important do you feel it will be to do well on this exercise?
   - Not at all
   - Not very
   - Somewhat
   - Very Much

4. How pleasant do you expect this activity to be?
   - Not at all
   - Not very
   - Somewhat
   - Very Much

5. How much effort do you plan to put into this activity?
   - Not at all
   - Not very
   - Somewhat
   - Very Much

6. How successful do you believe you will be in completing this activity?
   - Not at all
   - Not very
   - Somewhat
   - Very Much
Content understanding:
1. To the best of your understanding, explain what LEED is and its purpose is in one or two sentences.
   ____________________________________________________________

2. Are there any drawbacks to LEED? If so what are some examples?
   ____________________________________________________________

3. To the best of your understanding, define sustainability in one or two sentences.
   ____________________________________________________________

4. What is an example of sustainability in the architectural discipline? How does it address sustainability?
   ____________________________________________________________

5. What is building lifecycle cost and how does it differ from initial building cost?
   ____________________________________________________________

6. Multiple Select (Circle all that apply): What general aspects of building performance related to sustainability could be affected by an exterior curtain wall redesign?
   a. Thermal efficiency
   b. Daylighting usage
   c. Energy usage
   d. Water usage
   e. Material reuse/minimization
   f. Emissions introduced into the external environment from the building
   g. Emission levels in interior building spaces
   h. Emission levels from building occupant transportation

7. Which aspects of LEED (which categories) would you potentially be able to affect through an exterior curtain wall redesign?
   ____________________________________________________________
8. Multiple Select (Circle all that apply): What general aspects of building performance related to sustainability could be affected by a parking lot redesign?
   a. Thermal efficiency
   b. Daylighting usage
   c. Energy usage
   d. Water usage
   e. Material reuse/minimization
   f. Emissions introduced into the external environment from the building
   g. Emission levels in interior building spaces
   h. Emission levels from building occupant transportation

9. Which aspects of LEED (which categories) would you potentially be able to affect through a parking lot redesign?

10. Multiple Select (Circle all that apply): What general aspects of building performance related to sustainability could be affected by an interior material selection redesign?
    a. Thermal efficiency
    b. Daylighting usage
    c. Energy usage
    d. Water usage
    e. Material reuse/minimization
    f. Emissions introduced into the external environment from the building
    g. Emission levels in interior building spaces
    h. Emission levels from building occupant transportation

11. Which aspects of LEED (which categories) would you potentially be able to affect through an interior materials selection redesign?
Pre-activity Survey

1. What is your experimental ID number? (This was the number written in the upper right corner of the packet you received in class. You need this number in order to get credit for completing this quiz. If you lost your number, let me know and I will put you in touch with the research assistant who has access to your numbers.)

2. Please indicate your age.

3. Please indicate your gender.
   a. Female
   b. Male
   c. Prefer not to answer

4. Indicate your intended major as of now.

5. Indicate your academic standing.
   a. Freshman
   b. Sophomore
   c. Junior
   d. Senior
   e. Graduate

Engineering Background:

6. Indicate your level of experience with solving engineering problems in general.
   a. None
   b. Very Little
   c. Some
   d. Substantial

7. What types of engineering problems have you worked on in the past?

8. Indicate your level of knowledge related to sustainable concepts in general.
   a. None
   b. Very little
   c. Some
   d. Substantial
9. Indicate your level of experience with alternative energy.
   a. None
   b. Very little
   c. Some
   d. Substantial

10. Indicate your level of experience with energy use minimization.
    a. None
    b. Very little
    c. Some
    d. Substantial

11. Indicate your level of experience with water use minimization.
    a. None
    b. Very little
    c. Some
    d. Substantial

12. Indicate your level of experience with recycling reuse of materials.
    a. None
    b. Very little
    c. Some
    d. Substantial

13. Have you had any other experience with aspects of sustainability? If so, what?
    ________________________________________________________________

Technical Background:

14. Please estimate the number of hours per week that you use a computer for coursework.
    _____________________________________________________________

15. Estimate the number of hours per week that you use a computer for leisure activities
    (personal email, chat, games, movies, shopping, etc.)
    _____________________________________________________________
16. Do you own or regularly use a mobile computing device (Apple iOS devices such as the iPhone, iPad, iPod Touch; Android devices; Blackberry Playbook; HP Touchpad; etc.)? If so, which device(s) do you own or regularly use?

17. Estimate the number of times that you have used a mobile computing device (Apple iOS devices such as the iPhone, iPad, iPod Touch; Android devices; Blackberry Playbook; HP Touchpad; etc.)
   a. Never
   b. Once or twice
   c. Less than 5 times
   d. Less than 20 times
   e. More than 20 times

18. Estimate the number of years or months of experience you have with CAD software applications. Please specify years or months. Enter 0 for no experience.

19. Estimate the number of years or months of experience you have with video games. Please specify years or months. Enter 0 for no experience.

20. Please list your 5 favorite video games. If you do not play video games, leave blank or indicate that you do not play video games.

21. Augmented reality involves merging the virtual world with the real world through the use of computerized technologies. An example of augmented reality that can help to illustrate this type of merging of real and virtual worlds could be the yellow first down line that appears on the screen of a televised football game. This type of technology is common in mobile computing applications. Estimate the number of years or months of experience you have with augmented reality applications. Please specify years or months. Enter 0 for no experience.

22. Please list up to 5 of your favorite augmented reality applications.
Content understanding:

23. Are there any building design strategies that add LEED points to a project, but have little or no effect on building sustainability? If so, list an example or two.

24. Are there any building design strategies that create a more sustainable building that do not necessarily achieve LEED points? If so, list an example or two.

25. What is an example of a design tradeoff between different building systems? (As one system is modified to increase performance, another system performs worse.)
Experimental ID number:_______________

Post-test

The responses you provide on this quiz will not affect your grade for this course. Some questions may be challenging. If you do not know an answer for a particular question, just take your best guess or simply state that you don’t know the answer.

User Experience:

1. How valuable did you feel that this design activity was to your education?
   - Not at all
   - Not very
   - Somewhat
   - Very much

2. How effective was the format of this activity?
   - Not at all
   - Not very
   - Somewhat
   - Very much

3. Please indicate your level of agreement: I found this activity to be interesting.
   - Strongly disagree
   - Somewhat disagree
   - Neither agree nor disagree
   - Somewhat agree
   - Strongly agree

4. Please indicate your level of agreement: I am more interested in sustainability after completing this activity.
   - Strongly disagree
   - Somewhat disagree
   - Neither agree nor disagree
   - Somewhat agree
   - Strongly agree
5. Please indicate your level of agreement: I am more interested in the building design process from this activity.

<table>
<thead>
<tr>
<th>Strongly disagree</th>
<th>Somewhat disagree</th>
<th>Neither agree nor disagree</th>
<th>Somewhat agree</th>
<th>Strongly agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

6. Please indicate your level of agreement: I enjoyed completing this design activity.

<table>
<thead>
<tr>
<th>Strongly disagree</th>
<th>Somewhat disagree</th>
<th>Neither agree nor disagree</th>
<th>Somewhat agree</th>
<th>Strongly agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

7. Please indicate your level of agreement: I put in a significant effort in completing this design activity.

<table>
<thead>
<tr>
<th>Strongly disagree</th>
<th>Somewhat disagree</th>
<th>Neither agree nor disagree</th>
<th>Somewhat agree</th>
<th>Strongly agree</th>
</tr>
</thead>
<tbody>
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<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

8. Please indicate your level of agreement: I successfully created a viable design solution to the design challenge described in this activity.

<table>
<thead>
<tr>
<th>Strongly disagree</th>
<th>Somewhat disagree</th>
<th>Neither agree nor disagree</th>
<th>Somewhat agree</th>
<th>Strongly agree</th>
</tr>
</thead>
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<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>
9. Please indicate your level of agreement: I had enough information provided to me to make effective design decisions during this activity

<table>
<thead>
<tr>
<th>Strongly disagree</th>
<th>Somewhat disagree</th>
<th>Neither agree nor disagree</th>
<th>Somewhat agree</th>
<th>Strongly agree</th>
</tr>
</thead>
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</tr>
</tbody>
</table>

10. How did you feel about the amount of time to complete this activity? (Circle one)

- Not enough time
- Just enough time
- More than enough time

Content Understanding:

1. Identify as many LEED categories as you can. Then rank the categories according to how many points are associated with the category (1 has the most points, 2 has the second most, 3 has third most, and so on).

   Category: ___________________________ Rank: _____
   Category: ___________________________ Rank: _____
   Category: ___________________________ Rank: _____
   Category: ___________________________ Rank: _____
   Category: ___________________________ Rank: _____
   Category: ___________________________ Rank: _____
   Category: ___________________________ Rank: _____

2. Are there any drawbacks to LEED? If so what are some examples? ___________________________
   ___________________________
   ___________________________
   ___________________________
   ___________________________
   ___________________________
   ___________________________
3. What are some examples of building design practices that attempt to address sustainability?

4. What is an example of a design tradeoff between different building systems? (As one system is modified to increase performance, another system’s performance decreases.)

5. What is building lifecycle cost and why/how does it differ from initial building cost?


**Post-activity reflection quiz**

1. What is your experimental ID number? (This was the number written in the upper right corner of the packet you received in class. You need this number in order to get credit for completing this quiz. If you lost your number, let me know and I will put you in touch with the research assistant who has access to your numbers.)

2. Which of the following building design appears to be the most sustainable according to LEED? (Make sure that you keep an eye on which choice you check. The choices you select are at the bottom left of each image.)

   ![Building Designs](image)

   a. A.  
   b. B.  
   c. C.  
   d. D.  
   e. E.  
   f. F.  

3. For the question above (most sustainable building design), what assumptions did you make to justify your answer? 

   
   


4. From the building images listed above, which design appears to be the least sustainable according to LEED?
   a. Choice A
   b. Choice B
   c. Choice C
   d. Choice D
   e. Choice E
   f. Choice F

5. For the question above (least sustainable building design), what assumptions did you make to justify your answer? _______________________________________________________________________

6. For the least sustainable building, what specific recommendations could you suggest to alter the design to make it more sustainable according to LEED? _______________________________________________________________________

7. What general aspects of building performance could be affected through an exterior curtain wall redesign?
   a. Thermal efficiency
   b. Daylighting usage
   c. Energy usage
   d. Water usage
   e. Materials reuse/minimization
   f. Emissions introduced into the external environment from the building
   g. Emission levels in interior building spaces
   h. Emission levels from building occupant transportation

8. Which aspects of LEED (which categories) would you potentially be able to affect through an exterior curtain wall redesign? ________________________________________________________________
9. What general aspects of building performance could be affected through a parking lot redesign?
   a. Thermal efficiency
   b. Daylighting usage
   c. Energy usage
   d. Water usage
   e. Materials reuse/minimization
   f. Emissions introduced into the external environment from the building
   g. Emission levels in interior building spaces
   h. Emission levels from building occupant transportation

10. Which aspects of LEED (which categories) would you potentially be able to affect through a parking lot redesign?

11. What general aspects of building performance could be affected through an interior material selection redesign?
   a. Thermal efficiency
   b. Daylighting usage
   c. Energy usage
   d. Water usage
   e. Materials reuse/minimization
   f. Emissions introduced into the external environment from the building
   g. Emission levels in interior building spaces
   h. Emission levels from building occupant transportation

12. Which aspects of LEED (which categories) would you potentially be able to affect through an interior material selection redesign?
13. Are there any aspects of the LEED system that contribute points, but have little or no effect on building sustainability? If so, list an example or two.

14. Are there any sustainable building practices that do not necessarily achieve LEED points? If so, list an example or two.
APPENDIX K  TREATMENT 3.2 ASSESSMENTS

ecoCampus Pre-test

The responses you provide on this quiz will not affect your grade. Some questions may be challenging. If you do not know an answer for a particular question, just take your best guess or simply state that you don’t know the answer.

Background Questions:
Experimental ID number:______________
In what course are you enrolled where you heard about this activity?_______________________
Please indicate your age: _______________
Please circle your gender: Male Female I’d prefer not to answer
What is your intended major as of now?__________________________________________
What is your current academic standing?
Freshman Sophomore Junior Senior Graduate

Motivation Questions:
1. To what extent are you looking forward to this activity? (circle one)
   Not at all Not very much Somewhat Very much
2. How useful do you believe this activity will be for your education? (circle one)
   Not at all Not very much Somewhat Very much
3. How important do you feel it will be to do well on this activity? (circle one)
   Not at all Not very much Somewhat Very much
4. How pleasant do you expect this activity to be? (circle one)
   Not at all Not very much Somewhat Very much
5. How much effort do you plan to put into this activity? (circle one)
   None at all Not very much Some Very much
6. How successful do you believe you will be in completing this activity? (circle one)
   Not at all Not very Somewhat Very much
Engineering Background questions:
1. Indicate your level of experience with solving engineering problems in general. (circle one)
   None    Very little    Some    Substantial
2. What types of engineering problems have you worked on in the past?
   ____________________________________________________________________________
   ____________________________________________________________________________
3. Indicate your level of knowledge related to sustainable concepts in general. (circle one)
   None    Very little    Some    Substantial
4. Indicate your level of experience with alternative energy. (circle one)
   None    Very little    Some    Substantial
5. Indicate your level of experience with energy use minimization. (circle one)
   None    Very little    Some    Substantial
6. Indicate your level of experience with water use minimization. (circle one)
   None    Very little    Some    Substantial
7. Indicate your level of experience with recycling/reuse of building materials. (circle one)
   None    Very little    Some    Substantial
8. Have you had any other experience with other aspects of sustainability? If so, what?
   ____________________________________________________________________________
   ____________________________________________________________________________

Technological Background Questions:
1. Estimate the number of hours per week that you use a computer for coursework:___________
2. Estimate the number of hours per week that you use a computer for leisure activities (personal
   email, chat, games, movies, shopping, etc.)___________________________
3. Do you own or regularly use a mobile computing device (Apple iOS devices such as the
   iPhone, iPad, iPod Touch; Android devices; Blackberry playbook; HP Touchpad; etc.)? If so,
   which device(s) do you own or regularly use?
   ____________________________________________________________________________
   ____________________________________________________________________________
   ____________________________________________________________________________
4. Estimate the number of times that you have used a mobile computing device (Apple iOS devices such as the iPhone, iPad, iPod Touch; Android devices; Blackberry playbook; HP Touchpad; etc.) (circle one)

Never  Once or twice  Less than 5 times  Between 5 and 20 times  More than 20 times

5. Estimate the number of years or months of experience you have with CAD software applications. Please specify years or months. Enter 0 for no experience.

6. Estimate the number of years or months of experience you have with video games. Please specify years or months. Enter 0 for no experience.

7. Please list your 5 favorite video games:

8. Augmented reality involves merging the virtual world with the real world through the use of computerized technologies. An example of augmented reality that can help to illustrate this type of merging of real and virtual worlds could be the yellow first down line that appears on the screen of a televised football game. This type of technology is common in mobile computing applications. Estimate the number of years or months of experience you have with augmented reality applications. Please specify years or months. Enter 0 for no experience.

9. Please list up to 5 of your favorite augmented reality applications.

Sustainable Content Questions:

1. To the best of your understanding, explain what LEED is and its purpose is in one or two sentences.
2. To the best of your understanding, define sustainability in one or two sentences.

______________________________________________________________________________
______________________________________________________________________________

3. What is an example of a sustainable design strategy in the architectural discipline? How does this example address sustainability?

______________________________________________________________________________
______________________________________________________________________________

4. Are there any building design strategies that add LEED points to a project, but have little or no effect on building sustainability? If so, list an example or two.

______________________________________________________________________________

5. Are there any building design strategies that help to create a more sustainable building that do not necessarily achieve LEED points? If so, list an example or two.

______________________________________________________________________________

6. What is building lifecycle cost and how does it differ from initial building cost?

______________________________________________________________________________

7. What is an example of a design tradeoff between different building systems? (As one system is modified to increase performance, another system performs worse.)

______________________________________________________________________________
**ecoCampus Post-test**

The responses you provide on this quiz will not affect your grade. Some questions may be challenging. If you do not know an answer for a particular question, just take your best guess or simply state that you don’t know the answer.

Background Questions:
Experimental ID number:_______________
In what course are you enrolled where you heard about this activity?_______________________

Opinion Questions:
1. How valuable did you feel that this design activity was to your education? (circle one)
   - Not at all
   - Not very much
   - Somewhat
   - Very much

2. How effective was the format of this activity? (circle one)
   - Not at all
   - Not very much
   - Somewhat
   - Very much

3. Please indicate your level of agreement: I found this activity to be interesting. (circle one)
   a. Strongly disagree
   b. Somewhat disagree
   c. Neither agree nor disagree
   d. Somewhat agree
   e. Strongly agree

4. Please indicate your level of agreement: I am more interested in sustainability after completing this activity. (circle one)
   a. Strongly disagree
   b. Somewhat disagree
   c. Neither agree nor disagree
   d. Somewhat agree
   e. Strongly agree

5. Please indicate your level of agreement: I am more interested in the building design process from this activity. (circle one)
   a. Strongly disagree
   b. Somewhat disagree
   c. Neither agree nor disagree
   d. Somewhat agree
   e. Strongly agree
6. Please indicate your level of agreement: I enjoyed completing this activity. (circle one)  
   a. Strongly disagree  
   b. Somewhat disagree  
   c. Neither agree nor disagree  
   d. Somewhat agree  
   e. Strongly agree

7. Please indicate your level of agreement: I put in significant effort in completing this activity. (circle one)  
   a. Strongly disagree  
   b. Somewhat disagree  
   c. Neither agree nor disagree  
   d. Somewhat agree  
   e. Strongly agree

8. Please indicate your level of agreement: I successfully created a viable design solution to the design challenge described in this activity. (circle one)  
   a. Strongly disagree  
   b. Somewhat disagree  
   c. Neither agree nor disagree  
   d. Somewhat agree  
   e. Strongly agree

9. Please indicate your level of agreement: I had enough information provided to me to make effective design decisions during this activity. (circle one)  
   a. Strongly disagree  
   b. Somewhat disagree  
   c. Neither agree nor disagree  
   d. Somewhat agree  
   e. Strongly agree

10. How did you feel about the amount of time to complete this activity? (circle one)  
     Not enough time Just enough time More than enough time
Sustainability Understanding Questions:
The following questions on this page relate to the following images. Select the image letter that you feel best answers the questions that follow:

1. Which of the following building design appears to be the most sustainable according to LEED? (write the letter of your choice in the blank) ______________

2. For the question above (most sustainable building), what assumptions did you make to justify your answer?
______________________________________________________________________________
______________________________________________________________________________
______________________________________________________________________________

3. From the building images listed above, which design appears to be the least sustainable according to LEED? (write the letter of your choice in the blank) ______________

4. For the least sustainable building, what specific recommendations could you suggest to alter the design to make it more sustainable according to LEED?
______________________________________________________________________________
______________________________________________________________________________
______________________________________________________________________________
5. What general aspects of building performance related to sustainability would be affected by an exterior curtain wall redesign? (circle all that apply)

A. Thermal Efficiency  
B. Daylighting usage  
C. Energy Usage  
D. Water Usage  
E. Material use/minimization  
F. Emissions introduced into the external environment from building  
G. Emission levels in interior building spaces  
H. Emission levels from building occupant transportation

6. Which aspects of LEED (which categories) would you potentially be able to affect through an exterior curtain wall redesign?

______________________________________________________________________________
______________________________________________________________________________

7. What general aspects of building performance related to sustainability would be affected by a parking lot redesign? (circle all that apply)

A. Thermal Efficiency  
B. Daylighting usage  
C. Energy Usage  
D. Water Usage  
E. Material use/minimization  
F. Emissions introduced into the external environment from building  
G. Emission levels in interior building spaces  
H. Emission levels from building occupant transportation

8. Which aspects of LEED (which categories) would you potentially be able to affect through a parking lot redesign?

______________________________________________________________________________
______________________________________________________________________________

9. What general aspects of building performance related to sustainability would be affected by an interior material selection redesign? (circle all that apply)

A. Thermal Efficiency  
B. Daylighting usage  
C. Energy Usage  
D. Water Usage  
E. Material use/minimization  
F. Emissions introduced into the external environment from building  
G. Emission levels in interior building spaces  
H. Emission levels from building occupant transportation
10. Which aspects of LEED (which categories) would you potentially be able to affect through an interior material selection redesign?

______________________________________________________________________________

______________________________________________________________________________

11. What is an example of an architectural design strategy intended to increase sustainability? How does this example address sustainability?

______________________________________________________________________________

______________________________________________________________________________

12. Are there any aspects of the LEED system that contribute to points, but have little or no effect on building sustainability? If so, list an example or two.

______________________________________________________________________________

______________________________________________________________________________

13. Are there any sustainable building practices that do not necessarily achieve LEED points? If so, list an example or two.

______________________________________________________________________________

______________________________________________________________________________

14. Do you have any suggestions for how this activity could be improved for future semesters' students? If so, please explain.

______________________________________________________________________________

______________________________________________________________________________

______________________________________________________________________________
15. Please list any other thoughts you had about this experience.
________________________________________________
________________________________________________
________________________________________________
________________________________________________

Thank you for your responses!
Steven K. Ayer, E.I.T.

**Education:**


*Concentrations:*

The use of mixed reality technologies to improve:

1. Engineering education
2. Building operation / facility management

*Dissertation:* Sustainability Education of Engineering Students Using Augmented Reality and Simulation Games


**Teaching Experience:**

2009 – 2013 Instructor: AE124S - Introduction to Architectural Engineering

2012 – 2013 Invited Guest Lecturer:
AE597F – Virtual Facility Prototyping
IE424 – Process Quality Engineering
CE370 – Introduction to Environmental Engineering

**Selected Publications:**


**Service:**

2012 – 2013 The Student Chapter of the Partnership for Achieving Construction Excellence (S:PACE). Graduate advisor/representative