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Augmented Reality in A Sustainable Engineering Design Context: Understanding Students' Collaboration and Negotiation Practices

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Abstract: This study reports on the use of augmented reality (AR) within the context of sustainable engineering design education. The objective of this study is to understand students' collaboration and negotiation practices in a sustainable engineering design context using AR. The technology used in this study includes MERGE Cube (a physical cube that acts as a digital canvas for AR) and CoSpaces Edu (an online platform for students to build 3D creations and animate them with code). There have been 48 instances of student participation from upper elementary to middle school in four iterations of this study since February 2022. The research was conducted based on a design-based research methodology, and the data was collected through qualitative methods and analyzed using the intra-action analysis method. This study's outcome revealed that interactions among participant dyads and with the technology shed light on distinct dynamics within collaborative sustainability-oriented learning and design processes. These diverse interactions collectively emphasize the multifaceted nature of collaborative design, where individual experiences, communication styles, and technological proficiency all play integral roles in shaping the collaborative process. In addition, the results of our research showed that the complexities inherent in negotiating ownership and collaboration dynamics are influenced by individual attitudes, timing of involvement, and previous experiences. Given the importance of collaboration in achieving sustainability-oriented goals, these findings are relevant to the field of sustainable engineering education, especially when working with younger children.

Keywords: engineering education; sustainability; augmented reality (AR); sustainable engineering design; learner collaboration; negotiation skills; innovational education

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1. Introduction

Access to low-cost and relevant technologies has resulted in a dramatic increase in the use of technology in everyday life. Merging novel technologies into pedagogical processes using student-centered approaches may support students' academic achievements and help support students who have historically not had access to and been able to develop competence in technology use [1]. An example of a novel technological advancement is augmented reality (AR), which has found application in numerous fields [2–4] including engineering.

Akçayır et al. [5] demonstrated the positive impacts of AR on students' academic performances, and the technology has gained major popularity in various domains, particularly education [6]. For instance, AR has been employed to enhance students' comprehension of many engineering disciplines [7–9] with a particular emphasis on sustainability, a crucial field that aids in the preservation of the environment.

According to United Nations Educational, Scientific and Cultural Organization (UNESCO) [10], Quelhas et al. [11], and Svanstrom et al. [12], the key competencies that are required but understudied regarding students' contributions to sustainable development are systemic thinking, integrated resolution, self-awareness, critical thinking, normative competence, collaboration, and negotiation. Multiple authors argue that the acquisition of such skills is best achieved via interactive learning methodologies [2,13,14]. AR provides an interactive learning environment that enhances the understanding of complex concepts through overlaying digital material such as images, videos, 3D models, animation, and so on over real-world images. According to Sharma and Mantri [15], the use of manipulation and virtual interaction of components can make the concepts more engaging and entertaining for students.

Furthermore, augmented reality (AR) has proven to be an innovative teaching tool for strengthening interpersonal skills, particularly collaboration and negotiation skills, within an academic context. Students can engage in collaborative projects, simulations, and problem-solving activities within augmented spaces, promoting teamwork and interpersonal communication. The immersive nature of AR-driven collaborations encourages active participation, leading to a deeper understanding of diverse perspectives and enhancing collective problem-solving capabilities [15]. Additionally, students can engage in realistic and dynamically simulated negotiation scenarios that imitate true interpersonal obstacles by deploying AR applications. AR enables a sophisticated and contextualized learning experience by immersing participants in augmented settings, allowing them to interact with virtual counterparts, receive immediate feedback, and adjust their negotiation techniques accordingly. Furthermore, the interactive nature of AR platforms promotes iterative practice that allows students to modify and adjust their negotiation strategies in a controlled yet dynamic virtual setting, thus contributing to the development of proficient interpersonal and negotiation skills [16,17].

1.1. Research Aim

This study investigates the use of AR within the context of sustainable engineering design education. The study is based on a comprehensive review of existing literature and explores the affordances of AR technologies for engineering design education with a focus on teaching students in the context of sustainable practices.

Our primary objective is to use AR in a sustainable engineering design context to understand students' collaboration and negotiation practices: more precisely, in what ways do practical engagement in pairs with the MERGE Cube platform foster collaboration and negotiation, which are imperative skills for engineering learning at the K-12, i.e., school level?

1.2. Research Question

How does the use of augmented reality in a sustainable engineering design setting help us understand students' collaboration and negotiating practices?

2. Literature Review

2.1. Engineering Education and Sustainability

Engineering education plays a crucial role in contemporary society for both developing the next generation of engineers and developing important skills and practices attributable to engineering, which are important for most people in the 21st century irrespective of their professional pursuits [18]. According to UNESCO, engineering is one of the most significant activities in the context of sustainable development [10]. Thus, to improve the quality of living for all, future engineers need to integrate sustainability into their practice, and all individuals need to be familiar with sustainable engineering practices. Sustainable engineering practice uses design principles to optimize material and energy utilization to lessen the environmental consequences of products and processes while reducing expenses and improving overall financial performance [19]. In other words, sustainability requires negotiating present and future needs, considering social, environmental, and economic factors, and requires collaboration between multiple stakeholders. This integrated approach to sustainable development allows us to move past a needs-based "growth" debate in a society with finite and non-growing resources. Further, addressing environmental concerns and encouraging sustainable living behaviors necessitates approaching them from a complex systems perspective. They necessitate an understanding of system interdependence and a collaborative effort to address environmental issues [20]. Individualism is regarded as a significant contributor to today's environmental challenges [21]. Scholars have acknowledged the importance of bringing together diverse stakeholders to address these complex and interconnected environmental concerns [21,22]. Individual efforts are insufficient since developing a sustainable way of life is fundamentally a team sport.

2.2. Collaborative Learning in Sustainable Engineering Education

The benefits of collaborative learning have been revealed in several studies [22–27]. Collaborative learning is widely recognized in educational settings to promote student involvement and enhance learning effectiveness [25]. There are several studies in engineering education and the learning sciences that highlight the significance of collaborative learning for various educational achievements, such as problem-solving, long-term engagement in STEM fields, and career readiness, including, e.g., [28–30]. Relatedly, research in sustainability education emphasizes the need to employ collaborative tasks, particularly for young learners [31–33]. Since school-going learners are the upcoming generation and future members of society, efforts should be made to educate and engage them in sustainability education, fostering their understanding and ability to contribute effectively to this field [24].

Prior research, however, has concentrated on macro-level collaborations across organizations, such as those among schools, communities, and local governments [34–37]. A few research studies have particularly investigated micro-level collaborations within the framework of individual and small-group dynamics, especially within the discussion of issues related to sustainability and planning [38–40]. Even when participants are in the same physical location, collaborating requires them to incorporate visualization and communication into their learning activities. Although communication facilitates conventional learning through the dissemination of instructions, peer feedback is equally significant in a collaborative setting. Visualization serves an equivalently critical function in the context of collaboration. Visualizing what their teammates/collaborators communicate is essential to collaboration in sustainable engineering settings [26]. Consequently, it can be stated that using collaborative learning approaches may boost engineering and entrepreneurial abilities and broaden a student's perspective on sustainability [41].

2.3. The Role of Augmented Reality in Sustainable Engineering Education

Scholars emphasize providing active learning environments relevant to learners' daily lives using effective visualization platforms such as virtual reality (VR) or augmented reality (AR) [27]. Several scholars have studied the potential affordances of VR for engaging students in learning [42,43]. However, a drawback of VR is that it necessitates using a head-mounted display (HMD) that is ergonomically unsuitable for extended periods. On the contrary, augmented reality (AR) has a substantially lower barrier to entry, requiring only a camera-equipped device [44] (a smartphone, for instance) to generate a captivating AR experience. Through visual stimulation that learners may interact with, some have proposed that AR allows for more retention of information and material through a hands-on constructivist approach, increasing student motivation and interest by offering an on-site real-world experience that helps them understand their work as relevant [18,23,45].

AR experiences are being utilized more frequently in educational settings across various academic levels, resulting in a significant impact on the whole process of learning [2]. These experiences include several disciplines, such as astronomy [46], anatomy [47], STEM [3], and entertainment [13]. Furthermore, several contemporary AR systems have been developed to accommodate multiple users [3,13,14,48]. However, it is essential to note that none of these studies have evaluated their respective systems about their collaborative efficacy and influence on the learning process, particularly regarding the engineering design process and sustainability-related topics.

A recent study by López-Faican and Jaen [49] examined a multi-user AR game in a school setting through an in-depth user study. Despite the comprehensive nature of the study, the experimental configuration is simplistic, and the collaborative element is notably restricted. This is primarily due to the gamification of the environment, which fosters a sense of competition and renders users' actions highly independent of one another. Hence, deploying AR in an authentic and collaborative learning setting can help understand its potential for teaching students about sustainability topics, which are highly reliant on individuals and larger entities collaborating with one another. Further, to the best of our knowledge, no other existing system has been identified offering a collaborative learning environment using AR to assist students in gaining knowledge about sustainable engineering design.

2.4. Using Complex Systems-Oriented Pedagogy to Teach Sustainability

To address environmental challenges and encourage sustainable living behaviors, it is necessary to adopt a comprehensive systems approach. It is necessary for us to comprehend the interdependence of systems and collaborate as a group to tackle environmental issues [18]. Contemporary environmental concerns are significantly influenced by an individualistic orientation to life [10]. Academics have acknowledged the necessity of involving different stakeholders to collaboratively address these complex and interrelated environmental problems [10,19–21]. Given that the task of establishing sustainable living is inherently a collaborative activity, individual efforts are insufficient. However, despite the involvement of numerous stakeholders, collaboration does not consistently bring the expected positive results [19], as the effectiveness of individual collaboration levels is pivotal in any collaborative undertaking [22].

In the context of the complex systems approach, the term "system" often refers to macro-level systematic relationships and does not usually include micro-level interactions. Academic community members consistently acknowledge the adverse impacts of dysfunctional communication on collaborations that fail across various disciplines, including computer-supported cooperative work (CSCW), computer-supported collaborative learning (CSCL), organizational psychology, and business studies [22,24,25]. In brief, while ideal collaboration can produce revolutionary solutions that are unattainable through individual efforts, its actuality is highly uncommon.

2.5. Employing Emerging Technologies to Enhance Collaborative Learning for Sustainability Education

According to scholars, creating learning settings that are applicable to students' everyday life and developing collaborative learning activities are crucial when it comes to sustainability education [20,50]. As in such settings, students can work together to construct their learning, practice as a community, and interact with real ecological challenges. Place-based learning, which emphasizes forming collaborations between local communities and schools in project design and implementation, is one pedagogical strategy for creating such learning environments [51,52]. Research indicates that educational institutions that establish collaborative partnerships with local communities enable learners to address real-world issues and cater to authentic learning experiences, which consequently enhances their academic performance and community involvement. This contrasts with traditional textbook and lecture methods, which concentrate on imparting theoretical knowledge to learners [51,53].

Providing an environment in the classroom that motivates students to participate in changing the ecological systems of which they are a part and to form connections with one another and their physical surroundings is just as important as assigning them real-world challenges to solve [54]. Design is a technique that focuses on creating solutions to problems and provides chances for students to acquire significant skills including collaboration [55].

It inspires individuals to use innovation and overcome complex problems through iteration. The iterative process contributes to the creation of more equitable teaching strategies and increased involvement of students with diverse needs and interests [56,57].

Research indicates that the rapid advancement of technology holds the capacity to substantially enhance students' learning experiences and enhance their level of engagement [3]. Academics are presently preoccupied with investigating the potential of emerging technologies to enhance students' awareness and ultimately, support them in undertaking additional actions [48] as technological advancements unfold and provide more accessible and novel virtual experiences.

Emerging technologies like augmented reality have the potential to build integrated educational settings that foster new interactive learning approaches. Augmented reality enables students to create knowledge using information they already perceive from the outside world while iterating on multiple solutions in a sustainable manner [13,14,42]. Furthermore, the tool assists the engineering design process in developing a more holistic grasp of the presented difficulties [14]. According to research, technologies such as augmented reality can boost student motivation and engagement by providing on-site real-world experiences that helps students realize why their work is important [13,49]. For example, one study on an augmented reality smartphone application (NetAR) built for engineering students to supplement traditional instruction found that it enhanced student engagement by 11% [49]. AR enables higher retention of information and content through a more hands-on, constructivist approach by providing visual stimulation that students can engage with [48]. The application of developing technologies (particularly those that enable the display of broader realities) has the potential to help learners grasp how their ideas fit into wider ecological systems [50].

As a result, students may move beyond the first sensation of novelty while interacting with AR to reflect on personal experiences and the requirements of their surrounding community in order to better address and eventually, improve their creative solutions. AR is now more accessible and cost-effective than most other developing technologies due to developments in mobile phone technology and internet connections. AR and other extended/virtual worlds allow for the representation of system-level ideas that people frequently do not understand in their daily activities. Further, while students may enjoy an initial feeling of novelty when interacting with AR, the lessons they learn from the learning experiences are equally as crucial, which makes these insights applicable to their everyday lives.

Current research emphasizes how AR may boost interest in and retention of technical information, but there is little evidence on how working with AR can replicate collaboration, negotiation, and innovation. Some research has identified AR as a possible bridge between cognitive and emotional learning but has not investigated its relationship to the engineering design process or sustainability issues.

Consequently, this research employs design-based research (DBR) and investigates the affordances of AR in facilitating informal collaborative engineering learning on the topic of sustainability. Design-based research (DBR) emerged at the beginning of the 21st century and is a practical research methodology capable of effectively bridging the gap between research and practice in formal education [58,59]. Moreover, DBR is a methodological approach that is in line with research methods used in engineering or applied physics education to impact students' learning positively. It involves designing products for specific goals. This approach has been discussed by several authors, such as Brown [58], Joseph [59], Middleton et al. [60], and Kelly [61].

In order to determine the outcome of this investigation, we use an intra-action analysis method. Intra-action analysis refers to the method of examining and understanding the relationships and interactions between elements or components within a system [59]. The term "intra-action" is often associated with the work of feminist physicist and philosopher Karen Barad [62]. Unlike "interaction," which implies that entities exist independently and then come together, "intra-action" emphasizes the idea that entities are co-constituted through their mutual interactions [59].

3. Conceptual Framework

By synthesizing the existing literature that we reviewed in the above section, we present a conceptual framework that investigates the capabilities of AR in a sustainable engineering design context to uncover students' collaboration and negotiation skills, addressing considerable gaps in the current literature on the field (Figure 1). The context of sustainability-related engineering design requires a comprehensive strategy that facilitates students' acquisition and enhancement of collaborative skills. AR enables students to work together in designing the sustainability-related system, facilitating collaborative learning settings. Further, since our deployment is in an informal context, i.e., an afterschool youth club, it provides a low-stakes way for learners to engage in the program.

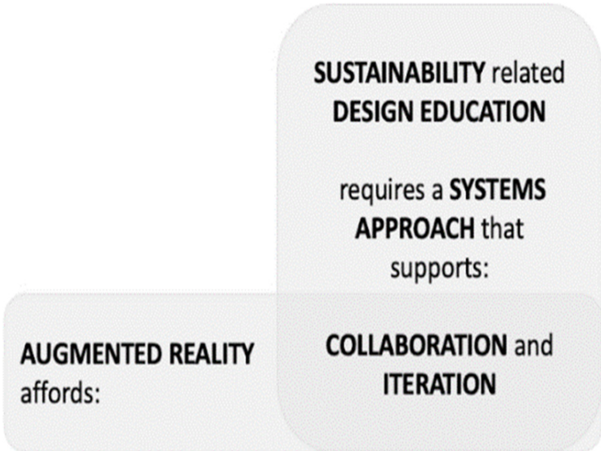


Figure 1. Representation of the conceptual framework [63].

4. Research Methodology

This study is based on a design-based research (DBR) approach. The findings we share here are part of a larger design-based research study that we have run for three iterations since February 2022 and are currently implementing for the fourth time. Each iteration has been developed based on feedback and experiences in the previous iterations. Each iteration has run for 6–8 weeks; for the first two iterations, the program had some interruptions due to COVID-19 infections at the afterschool club and within the research team, who are the authors and facilitators of the study. The workshops took place in a local afterschool club in an urban town in the northeastern United States.

4.1. Participants

As shown in Table 1, there have been a total of 48 participation instances in the broader research project associated with this study, with an average of 12 students in each of the four iterations. This study focuses on an iteration from 2022 with 16 participants who provided informed consent through child assent and parental consent forms. Further, students chose to participate in the workshop voluntarily, so there was no pressure to prioritize it over their other tasks.

Table 1. Demographic information of students (as reported by students on a survey).

	Categories	Frequency
Gender	Male	10
	Female	5
	Other	1
Age	7–9	3
	1012	7
	13–15	5
	16–18	1
Ethnicity	Native American /Alaskan Native	2
	Black/African American	5
	White	3
	Other	4
	Prefer to self-describe	2
Total		16

4.2. Data Collection Tools

The data of the study was collected through audio recordings of pre- and post-interviews, video recordings of the workshop, observations, and the collection of student work.

4.3. Data Analysis Method

To address our research question, we used an intra-action analysis method to understand the interconnectedness between participants, technology, and the educational experience. In the context of research, intra-action analysis involves closely examining the interconnectedness and mutual influence of different elements within a system rather than treating them as separate and distinct entities. Researchers using intra-action analysis seek to understand how these entities shape and define each other through their ongoing relationships [59,64].

4.4. Data Analysis Procedure

In our study, a group of four researchers created content logs for various data types, noting event descriptions and actors within specific time frames. Following the transcription process, we came together to identify recurring themes related to the students' understanding of sustainability, engineering, teamwork, and their workshop experiences. We eventually established the following recurring themes: point system, collaboration, inter-group peer support, design, tool, community care/consideration, and fairness/justice. After this code key was established, each researcher coded their content logs. Finally, we went through the coded content logs and agreed to narrow down the themes to two main focus areas: collaboration and negotiation.

Using intra-action analysis, we cross-examined the various forms of data, including video audio recordings, interviews, and artifacts, to particularly note the emerging moments of conflicts, collaboration, and negotiation. Below, we share some findings focusing on how the technology mediated the students' micro-level collaborations, which, as we established in the literature section, is an understudied area of research.

4.5. Research Context

Table 2 provides an overview of the implementation of the sustainability-oriented engineering design with the AR workshop. The workshop design is grounded in the conceptual framework discussed earlier.

Table 2. Design and implementation procedure of sustainable engineering design with augmented reality.

Duration	Tools	Stages of the Design
Phase 1 (approximately two weeks)	#1- One iPad per dyad #2- MERGE Cube #3- CoSpaces Edu #4- Paper and colored pens, video about sustainability, presentation slides	• General discussion on sustainability • Preliminary survey with questions on sustainability • Explanation of activity + instructor example • Watch role models describe their work with sustainability in videos
Phase 2 (approximately two weeks)	#1- One touchable laptop and iPad per dyad #2- MERGE Cube #3- CoSpaces Edu #4- Pens, paper, presentation slides, point system per dyad	• Instructor provides a recap of sustainability and activity • Instructor explains the point system • Students plan a city on paper in teams of two (referred to as dyads) • Students collaboratively work through laptops and iPads on the same city.
Phase 3 (approximately three weeks)	#1- One touchable laptop and iPad per dyad to design #2- MERGE Cube #3- CoSpaces Edu #4- Pens, paper, point system per dyad	• Students learn to code on the CoSpaces Edu platform (JavaScript) • Students present their cities • Students discuss their ideas of sustainability as a group with the facilitators • Students collaboratively work through laptops and iPads on the same city.

Table 2 illustrates the workshop's duration, which is divided into three sections that each lasts two to three weeks. In the tools section, symbolic numbers serve as identifiers for the following categories: #1 digital device, #2 physical tools, #3 software/application, and #4 materials. The design stages explain the step-by-step plans for each phase.

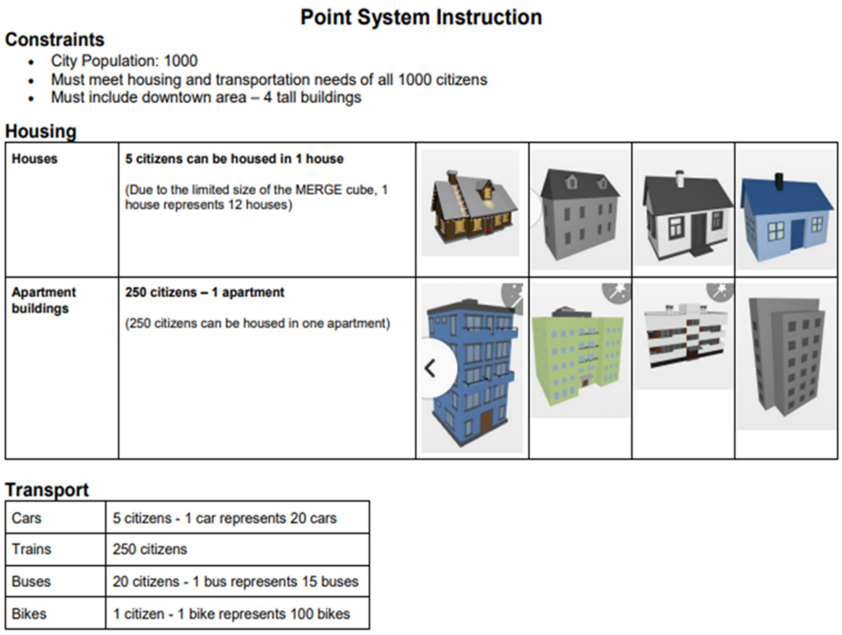
In the workshop, students were provided with interactive devices, including laptops, iPads, CoSpaces Edu (an online platform for students to build 3D creations and animate them with code), and MERGE Cube (a physical cube that acts as a digital canvas for augmented reality) to plan and create sustainable digital cities. In Phase 1, before students started building their cities, they were asked to consider the following:

1. Who are engineers, and what do they do?
2. What role do engineers play in sustainable development?
3. What role does teamwork play in sustainability?

Following that, students were given a brief presentation on sustainable city planning and urban development, with a particular emphasis on engineers' roles in supporting sustainability.

After the presentation, students were introduced to CoSpaces Edu. Initially, they used the same touchscreen laptop to create small-scale sustainable cities that could be visualized with MERGE Cube. Later, each dyad was provided with an iPad and a laptop to observe the effects on their collaboration. The dyads were shown how to find and drag and drop sustainable elements including trees, buses, bikes, and windmills into the CoSpaces Edu environment.

In Phase 2, students were provided with a recap of sustainability and the previous activity. For the next activity where they planned a city on paper, similar to Phase 1, students were divided into teams of two. We developed an end goal with clear requirements for housing, resources, and transportation. We introduced them to a point system to determine the "sustainable impact" of various aspects in their towns, aiming to teach the idea of restrictions in designing for sustainability. Learners were presented with design constraints and objectives (Figure 2) as well as a list of sustainability-oriented elements and their associated scores (Table 3). Their design features could bring positive rewards for environmentally sustainable decisions and negative penalties for excessive energy consumption. The point system scoring (Table 3) is an approximation designed to help young students understand that various housing and transportation options have different impacts on the environment. For example, apartments require more environmental resources, and hence an apartment is assigned a score of −100, as opposed to −50 for a house. However, apartments can house more people. Similarly, different transportation options have varying environmental impacts.



Point System Instruction

Constraints
- City Population: 1000
- Must meet housing and transportation needs of all 1000 citizens
- Must include downtown area – 4 tall buildings

Housing

Houses	**5 citizens can be housed in 1 house** (Due to the limited size of the MERGE cube, 1 house represents 12 houses)	
Apartment buildings	**250 citizens – 1 apartment** (250 citizens can be housed in one apartment)	

Transport

Cars	5 citizens - 1 car represents 20 cars
Trains	250 citizens
Buses	20 citizens - 1 bus represents 15 buses
Bikes	1 citizen - 1 bike represents 100 bikes

Figure 2. Point system instruction.

In Phase 3, students learned to code on the CoSpaces Edu platform. They coded text features explaining why they included the sustainable features they selected after building their cities. Their activity was designed to get them engaged with computer programming and to promote collaboration and negotiation. Students presented their MERGE Cube world to their classmates and provided explanations of their choices after completing their projects.

Example activity. By default, students enrolled in the class used CoSpaces Edu on their computing devices, including laptops and iPads. They saw a cube with a grass background and a windmill placed atop the cube (Figure 3). We placed these features as a baseline for the students' designs. At this point, students dragged and dropped objects from the CoSpaces Edu library, such as residential and industrial buildings, roads, trees, bikes, buses, and solar panels, onto their MERGE Cube to represent their sustainable design choices. It is noteworthy that the number of objects used was not restricted, but the space they had to work with was.

Table 3. Point system items and corresponding scores.

Elements	Points
Green Spaces	+100
Bike	+10
Tree	+200
Windmills	+200
Solar Panels	+100
Bridges	+5
Houses	−50
Apartments	−100
Other Buildings	−100
Cars	−25
Trains	−15
Buses	−15
If the downtown area is close to housing	+55 points
Decorative items (for ex: outdoor furniture like benches, sculptures, lamp posts, etc....)	0 point

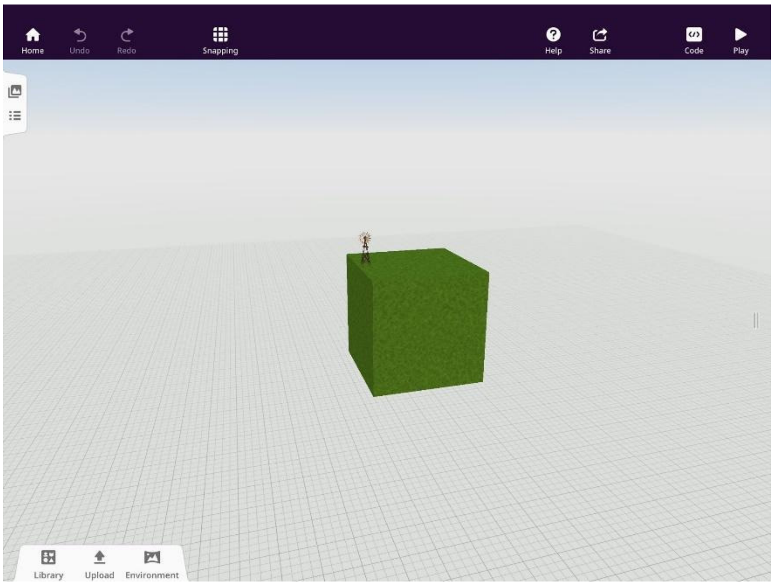


Figure 3. Default workspace created for students in CoSpaces Edu.

After constructing their ideal city, students were required to use animated text boxes that they had coded using the CoSpaces Edu block-programming feature called "CoBlocks" to explain the reasons behind their sustainable design decisions (Figure 4). The students were required to code a function that keeps their design explanations secret until the user touches the text boxes.

The students were able to display their CoSpaces Edu design onto the MERGE Cube (Figure 5) after completing the design and programming parts of the project. By rotating the box on all sides, students could physically interact with their design and view every feature from various proximities and angles. In order to disclose text, students could also tap on their programmed text boxes.

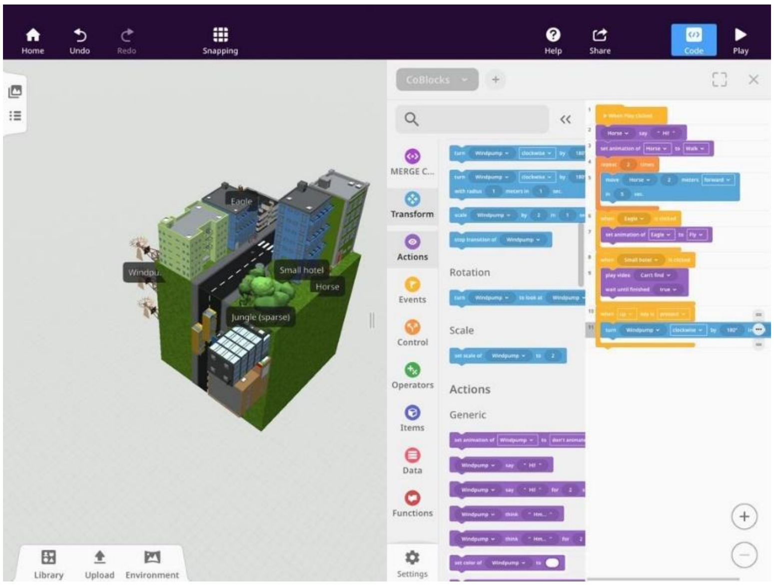


Figure 4. Block programming with CoBlocks.

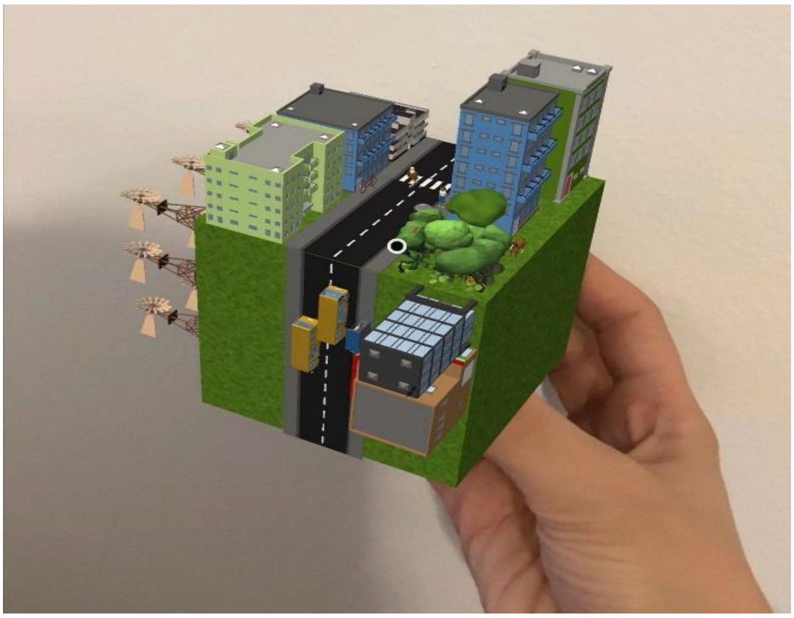


Figure 5. Projected designs on the MERGE Cube when looked at through a tablet.

Afterward, students were asked to answer the following post-interview questions. Questions on the knowledge/perception of sustainability:

4. What new information did you learn from this workshop?
5. Is there any information you learned from this workshop that contradicts what you knew before?
6. After this workshop, would you like to live sustainably? If so, what would you like to do?

Questions related to the engineering design process:

7. What sustainable problem did you identify to solve?
8. What solution(s) did you come up with?
9. What is your design rationale? Or how did you decide on what elements to include when designing a sustainable city?
10. What changes would you make in your next interaction?

11. Are there any constraints in your design? How would you overcome the constraints?

Questions on their extended reality experience:

12. Could you describe your experiences of seeing your design come alive with MERGE Cube?
13. Have you identified any design changes you would like to make after seeing it on the MERGE Cube?

Consequently, instructors collected the answer sheets to signify the conclusion of the activity.

4.6. Trustworthiness

To establish trustworthiness, we examine the credibility, dependability, sincerity, and ethics involved in our research process. [65–67]. We established credibility by performing both data and investigator triangulation. As described above, we collected multiple forms of data, and the findings below were triangulated against observation data and multiple investigators' analyses. At least two researchers were involved in coding the data at different stages; assessment and analysis by the rest of the authoring team provided dependability to the process. We believe that we have been clear about our methods, including a critique of our approach and assumptions laden in asking questions aimed at understanding the positive impacts of educational technology. We believe that these practices bring sincerity to our processes. Finally, approval of the research processes by our institute's review board and following informed consent procedures exemplify the relational and procedural ethics of our work.

5. Results

In the findings below, we share three different cases of participants collaborating and negotiating while working on their projects. For the design process, students employed a laptop for the creation phase and subsequently utilized an iPad integrated with MERGE Cube to visualize the three-dimensional representation. The design decisions were negotiated and mediated through achieving sustainability goals, individual design preferences, tool and technology accessibility, and ownership of the space. The following cases illustrate three vignettes describing how each dyad used technology to design a sustainable city together and how different collaboration and negotiation opportunities emerged from their interaction. The purpose of these descriptions is to familiarize the readers with each dyad, helping them understand the similarities and differences between the dyads' interactions. Ultimately, this provides theoretical insight into what and how dyads interact with each other and with the workshop space and helps answer our research question about how using AR in a sustainable engineering design setting helps us understand students' collaboration and negotiation practices. All student names used are pseudonyms.

5.1. First Interaction: Look at How Much Space We Have!

It was Salvina's first time using the co-spaces platform to design a sustainable city, as she was absent the day before. Her partner, Yacob, had been exposed to the platform the day before, and he felt confident about what he needed to do. He received the laptop (with touch capability) at the onset of the lesson and promptly commenced working on it. Salvina started following Yacob's design and expressed her disagreement with him. Yacob, nevertheless, ignored her recommendations on numerous occasions. Yacob argued that they needed the windmill (an object available in the co-spaces platform) without providing Salvina with an explanation. In order to make room for another object, she proposed positioning the windmill beneath an existing object. Yacob rejected it and replied, "Look at how much space we have!"

During the conversation between Salvina and the facilitator on the point system, Yacob proceeded to add additional objects to the designated area. Salvina redirected her attention to the laptop screen again and asked Yacob, "Why do you have so many? (different new objects that he had placed in their virtual city) Where are you going to put everything else?" Yacob then directed his attention to Salvina and indicated to her that an additional "square" remained available for accommodating objects.

Salvina showed signs of dissatisfaction, to which Yacob responded by stating, "That is what you are supposed to do." (alluding to how incorporating additional sustainable items would help achieve a better rating for a sustainable design.) Salvina nonchalantly raised her shoulders. Yacob told Salvina that he had been present on the previous day. Salvina reacted apologetically, expressing that she was prioritizing more important tasks outside of the club, and that's why she wasn't present. Yacob responded, "I am just saying, I was here yesterday, so I know what to do." He asserted his familiarity with the task, citing his presence on the previous day as evidence.

During this brief vignette, some interesting moments of collaboration and negotiation were noticed between Yacob and Salvina. The initial instance happened when Yacob and Salvina engaged in a discourse on conceptualizing a sustainable urban environment. As the duration and intensity of their disagreement increased, Yacob and Salvina engaged in a process of power negotiation, seeking to determine who had the ultimate authority to provide the final decision regarding the design.

5.2. Second Interaction: That Makes No Sense!

In the second workshop, Mateo and Yara teamed up to work on a joint project, creating a city that reflects the principles of sustainability. Mateo was not present when the CoSpaces Edu platform was introduced; thus, Yara was afforded the opportunity to conceive a sustainable urban center independently. When they started working together for the first time, Yara claimed the iPad and started the process of designing. Despite having a laptop with a touchscreen, Mateo directed his attention to perusing the point system briefly. The workshop facilitator encouraged Mateo to engage in creative activities on CoSpaces Edu. However, he decided to prioritize reading about the point system for a period of time. During this time, the club coordinator informed Yara that Mateo had been absent the previous day. Yara looked at the coordinator and then shifted her attention to Mateo, proceeding to bring the iPad closer to Mateo while holding the device. Yara then posed the question to Mateo, inquiring, "Want to do it on the iPad?" Thus, Yara offered collaboration with Mateo, but she gradually moved the iPad back to herself while finishing her sentence.

After concluding his examination of the point system paper, Mateo discontinued his engagement. Subsequently, Yara extended a suggestion to Mateo, encouraging him to participate in the construction process by setting aside the iPad and engaging in interactive activities within the CoSpaces Edu platform using the laptop. Yara assumed the instructional position and provided Mateo with vocal instructions on how to browse and develop within the CoSpaces Edu platform effectively. For example, Yara would say, "Please hold on, look at this particular item," while she manipulated an object on her iPad and directed her attention toward the laptop screen while moving the item. Mateo looked confused as he operated the laptop.

"Okay, now we should add the trains," Yara said. Mateo continuously interacted with the laptop and tried to find a solution; he informed Yara that a certain object showed immobility. Yara, in response, indicated the laptop and told Mateo to locate the object. "You can find them here." Upon commencing collaboration in CoSpaces Edu, their tensions emerged and were displayed in their verbal and non-verbal conversations. For example, at one point, Yara raised her voice and shouted at Mateo, "Hey, what are you doing with my house?"

Mateo asked Yara to expand the dimensions of the house. Yara responded, "It is a baby house." Then Mateo commented, "That makes no sense," and asked her to increase the size again. "I will," Yara answered. At another point, Mateo added trees on the screen, but Yara deleted them. Mateo argued, "You should put trees," and explained, "Trees are worth 200 points." Yara then pointed at the reward system and suggested they should put a "windmill." It was unclear whether Yara suggested that the windmill was an alternative design idea to trees or a brand new idea. In either case, when Mateo made a design suggestion—"We should put a tree," which Mateo suggested twice—Yara responded, "Wait; we can put a house here." Shortly after, they synchronized their actions by utilizing both the iPad and the laptop. Yara suggested the inclusion of trains and inquired about the potential addition of another house; however, Mateo kept looking at the laptop without responding.

Yara and Mateo, in contrast to the initial dyad, used a greater amount of nonverbal communication, namely through body language, to convey various messages, such as inviting the partner, rejecting, and building jointly. When Yara and Mateo started using a singular digital device to make their designs and modifications, a notable reduction in material disputes was noticed compared to the initial dyad. This dyadic partnership also saw comparable collaboration and negotiation on conceptualizing the sustainable urban environment, including discussions on sizing and modifications. As the participants progressively engaged in collaborative efforts, the issue of individual ownership gained significance within this dyadic relationship, particularly concerning the negotiation of individual and collective design.

5.3. Third Interaction: From Confrontation to Silent Resignation

The final interaction follows the latter half of Salvina and Yacob's collaborative work on city construction. After the initial disagreements they had regarding design implementation and overall authority over the cube, Salvina and Yacob ultimately developed a system and started sharing technology without complaints. Salvina began asking Yacob clarifying questions about specific elements on the cube, such as how to resize an object, as well as questions regarding some of the instructions provided by the facilitators. Yacob gave timely responses to her questions while also focusing on the virtual construction of the city. However, while Salvina sought answers to her questions from Yacob, her efforts were unsuccessful. She would then request an adult facilitator for their response to the same question or for their demonstration of a concept again.

For the remainder of the activity, Salvina and Yacob took turns on the laptop and guided one another in the design process. However, they guided each other the most in the decorative elements of the cube—most of which were not elements listed on the point system sheet. For instance, Yacob modified colors on the surface while Salvina provided guidance, and then Salvina asked for the laptop, to which Yacob agreed and handed over for her to add weather elements—in this case, rain. However, once the iPad and MERGE Cube were given to them alongside the laptop, there was less communication on the design choices. While Salvina cast the city on the iPad and showed it to the facilitator, Yacob maintained a quiet demeanor and added more windmills to their city. After he finished adding the windmills, he proceeded to take the iPad and MERGE Cube from Salvina's hands, to which Salvina picked up the laptop and brought it closer to her.

Salvina did not add any new elements to the cube after she got the laptop, nor did she note Yacob's new addition of the windmills. However, after their short presentation of the city they had built to the class and facilitators, Salvina asked the instructor whether there would be a chance for them to build individual cities based on their own ideas. When the instructor replied yes, Salvina responded, "Yay!"

As time went by in the design process, Salvina and Yacob initially seemed to display a more cooperative relationship where they shared technology, and there were clarifying questions being asked and answered between them. However, they were not discussing elements of the point system to add to their cube; instead, they were collaborating on additional decorative elements for the cube. It was not until Salvina was presenting the city to the facilitator via the iPad and MERGE Cube that Yacob quietly added windmills to the cube. Additionally, Salvina relied a lot more on her interactions with the facilitators, both in wanting re-clarifications on the questions she had originally directed towards Yacob as well as in her question on whether she would eventually get to build her own city.

6. Discussion

In this study, we examined how AR in sustainable engineering design education may help understand students' collaboration and negotiation practices. This section comprehensively analyzes the results on how AR facilitates practical engagement by supporting both visualization and communication between students, making visible practices of collaboration and negotiation.

Our analysis demonstrates that despite students collaborating progressively, the matter of individual ownership significantly impacts their relationship. Their disagreements arose from the pursuit of authority in their design process, which led to their involvement in a negotiation process. Augmented reality can significantly influence the development of negotiation skills in students by offering immersive and engaging learning experiences and providing a tangible medium to engage in conversation over larger system-level phenomena, which, as we discuss in our conceptual framework, is imperative for sustainability education [25]. This is because, in realistic simulations, students can apply negotiation theories in a controlled environment, bridging the gap between theoretical knowledge and practical application. Moreover, AR systems offer real-time feedback, allowing students to assess and refine their negotiation strategies instantly [2]. As a result, this iterative process of experimentation within a risk-free setting accelerates skill development, preparing students for real-world negotiation scenarios. It is also important to mention that since this study was set up in an informal (out of school) learning environment, it was a low-stakes way to engage students where they are more likely to behave authentically as compared to in a formal classroom setting where they might feel that their grades are on the line. Further, we also noticed that students' knowledge related to sustainability improved while they practically engaged in designing sustainable cities, discussing sustainability-related concepts with the facilitators, and visualizing three-dimensional views using AR and MERGE Cube.

As mentioned previously, based on qualitative coding, we established the following recurring themes: point system, collaboration, inter-group peer support, design, tool, community care/consideration, and fairness/justice. Grounded in these themes and to answer our research question, below we discuss two primary dynamics that we observed in our intra-action analysis of the data.

6.1. Ownership

Yacob and Salvina exhibited distinct attitudes toward ownership, which became evident in their post-interview responses. Yacob consistently portrayed a sense of individual ownership, expressing his decision-making process with statements containing the pronoun "I," such as "I just looked at the points" and "I was trying to make our world more sustainable."

In contrast, Salvina's responses reflected a more collaborative stance, emphasizing joint decision-making with phrases that consistently started with the use of "we." For example, she noted, "We were trying to get more houses and a park," and "We started thinking about what people really need." However, while this distinction initially seems like Salvina perceived the project as a joint effort, with decisions and responsibilities shared between both parties, their short presentation of their sustainable city revealed a more complex picture. Note that this was Salvina's solo presentation, where Yacob was quietly adding windmills to the city on the side. When Salvina was asked about a certain design element on the cube by a facilitator, she proceeded to respond, "I don't know; he did it."

We also observed that students often claimed ownership based on their previous attendance and experience. For example, Salvina had missed the first day of activity, which meant Yacob was working on the platform on his own at first. Yacob's negative attitudes towards Salvina were not necessarily in response to questions or lack of participation. Rather, Salvina quickly criticized some of Yacob's design choices, leading him to defend himself by saying he had more knowledge from being present the previous day or insisting that he was doing "what you are supposed to do."

We observed a similar situation within Yara and Mateo's partnership, as Mateo also missed the first day of the activity. When Yara learned of Mateo's absence, she offered to collaborate with him. However, through her body language, she maintained close proximity to the device she was working on, even as she encouraged Mateo to participate in the construction process. As Mateo began operating the laptop and the platform, Yara became agitated as her work was being affected. She used the possessive pronoun "my" to question Mateo about her design choices, saying, "Hey, what are you doing to *my* house?"

The relationship between students feeling ownership over technology and space and their learning outcomes is a complex and context-dependent matter. Generally, a sense of ownership can positively impact learning as it often correlates with increased engagement, motivation, and responsibility [68]. When students feel a connection to the technology and physical environment they use for learning, they may be more inclined to explore, experiment, and take ownership of their educational experiences. However, the extent of this impact can vary based on factors such as the learning environment, instructional methods, and individual student preferences [68–70].

The observed instances with Salvina, Yacob, Yara, and Mateo, where students asserted ownership based on attendance and experience, align with this broader concept. In the broader context, when students feel a sense of ownership over technology and the learning space, as exemplified in collaborative AR-based projects, it substantially impacts learning. In the observed dyads, Salvina's absence led to Yacob working alone initially, and Yara's offer to collaborate with Mateo was accompanied by a sense of control over her working space. These situations illustrate that students may claim ownership based on their previous experiences. This sense of ownership, whether in AR-based projects or real-life scenarios, influences students' actions, attitudes, and engagement levels, highlighting the significance of ownership in shaping learning experiences.

6.2. Negotiation and Collaboration

In contrast to the initial dyad, Yara and Mateo, in the second workshop, showed a heightened reliance on nonverbal communication, which was predominantly conveyed through body language, to express collaboration requests, rejections, and collaborative building efforts. Both Yara and Mateo would physically point at things to get the other's attention. While they initially had several disagreements, they soon became synchronized in their actions, utilizing both the iPad and the laptop.

However, there were also clear examples of dyads engaging in a process of power negotiation. This is evident, especially in Salvina and Yacob's first interaction, where Yacob used the fact that he had one more day of experience with CoSpaces Edu to justify his ultimate authority in making final judgments on design choices. In response, Salvina justified herself, stating that she had "more important tasks outside of the club."

While the physical sharing of a digital tool led to collaboration and the designation of roles, neither dyad presented authentic collaboration and instead became relatively passive towards each other's decisions. On the one hand, even after Yara and Mateo synchronized their actions, Mateo began ignoring Yara's suggestions about including more trains or adding more houses, instead focusing on the laptop. Similarly, Yacob only worked well with Salvina when they were adding decorations to the cube. It was not until Salvina was engaged in another task that he decided to add more sustainable elements without her knowledge.

Consistent with the current research, Radu et al. [71] conducted a study to investigate how AR impacts learning and collaboration while peers engage in robot programming activities. The outcome of the study showed that AR improved overall group learning and collaboration. However, the detailed analysis revealed that AR, in some groups, helped one participant more than the other by improving their ability to learn and contribute while remaining engaged with the robot.

Moreover, a different study by Li and Gu [72] investigated the impact of AR-supported simulation on collaborative learning in physics, comparing it with traditional face-to-face collaborative learning. The effectiveness of collaborative learning was evaluated based on perceived learning effectiveness and learning achievement. The results indicated that collaborative learning fostered an active exchange of knowledge, improved learning efficiency, and heightened engagement and enjoyment. These factors proved beneficial in enhancing the understanding of concepts and solutions. Thus, even though students, much like in our study, have to go through a sometimes uncomfortable process of learning to work together, the benefits outweigh the challenges. This is particularly important in the realm of sustainability, especially since students will be required to collaborate and exhibit systems thinking when it comes to working in this area.

7. Conclusions

This study showed how using AR technologies could help understand students' collaboration and negotiation practices when working on sustainable engineering design projects, which helped unpack the affordances of the technology and also make a case for the importance of learning design and not sole reliance on technology as a panacea for student learning. We shared the cases of three dyads working on sustainable engineering design using AR technologies.

The results showed that the participants negotiated ownership over the technology while using it to communicate and visualize ideas. The outcomes also demonstrated how it looks when participants are collaborating using either "we" language or appearing to work together; they find implicit ways not to truly collaborate on their designs. Eventually, through the post-interviews, we observed a reflection of this lack of authentic collaboration.

In general, the analysis shows that attitudes towards ownership and collaboration varied among the student partnerships. Yacob demonstrated a clear sense of individual ownership in his decision-making process for the sustainable city project. In contrast, Salvina initially presented a collaborative stance, using the pronoun "we" to describe joint decision-making. The concept of ownership was further complicated by students' previous experiences and the timing of their involvement in the project. Similar challenges in ownership and collaboration arose in the partnership between Yara and Mateo. Overall, the study reveals the complexities inherent in negotiating ownership and collaboration dynamics, influenced by individual attitudes, timing of involvement, and previous experiences.

However, the research was only limited to an afterschool club in the northeast of the United States; thus, the results may not be generalizable to other populations. As a result, the research could be implemented in different schools and academic levels. Further, in terms of the implications of this study for broader research on AR use for sustainability education, we believe scholars should consider a few key takeaways: (1) it is essential to look at micro-level collaborations and understand dynamics of students actually working and collaborating with one another as opposed to assuming collaborations because they are sharing technology; (2) while AR and digital technologies provide significant opportunities to support students' learning, it is essential to design learning environments and curriculums that prioritize curriculum as opposed to relying on technology to mediate collaboration.

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