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Schools as Living Laboratories for Architectural Engineering Research Experiences for Teachers

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Schools as Living Laboratories for Architectural Engineering Research Experiences for Teachers

Abstract

Through a collaboration between the Department of Architectural Engineering and the Center for Science and the Schools (CSATS) at Pennsylvania State University, the *Building Education RET* project launched a strategic approach to address global challenges in energy, ecological systems, and human health through transformational integration of technical research into precollege curriculum. Schools are critical instruments for advancing knowledge about sustainability, and they provide the ideal context for active research and teaching in sustainability-focused topics designed to cultivate a new generation of STEM leaders. Our strategy involves engaging teachers and students with their school facilities as "Living Laboratories" to provide a place-based context for math and science education. The *Building Education RET* site at Pennsylvania State University has immersed teachers in both fundamental and applied research on building science topics including indoor air quality, lighting effectiveness, thermal comfort, and energy efficiency and automation. Systems Thinking is an increasingly recognized competency in sustainability and serves as the overarching learning objective of the *Building Education RET* program. To date, 12 secondary teachers were prepared to utilize experimentation on air quality, lighting systems, and energy use in their respective school buildings as hands-on and applied STEM-based teaching modules. In the spring of 2020, the *Building Education* team decided to implement the RET program remotely with teachers conducting research in their homes or in their schools. Teachers from multiple states were able to participate in the program. To engage in research projects, we equipped teachers to collect data through instruments and observations about the quality of lighting, indoor air quality, occupant thermal comfort and health, building automation, building energy consumption, etc. in their teaching environments and other spaces in their school building, or their homes, and they learned different methods to analyze the results. We also engaged teachers in the mapping and evaluation of control systems in either their school facilities or their homes to manage heating, cooling, and fresh air. They learned state-of-the-art data analysis methods to identify opportunities to reduce energy demand. To translate their research into curriculum, science education faculty from CSATS engaged teachers in professional development focused on engineering practices. Weekly sessions supported teachers in identifying engineering practices that were translatable to secondary classrooms. As a culminating product, the teachers developed a classroom research project plan for their students to complete in the academic year.

Introduction

Schools and school buildings are critical instruments for advancing knowledge about sustainability. Active research, teaching, and outreach activities in sustainability-focused topics offer a strategic and innovative approach to cultivate a new generation of STEM leaders. To leverage these facilities, we established a

Building Education Research Experience for Teachers (RET) program. This RET site was pursued as a regenerative strategy for developing unique teacher-led research in their school facilities to: (1) engage teachers and students in the use of data collection and management practices related to building performance and occupant health; (2) provide a tangible and sustainability-focused context for science and math education; and (3) involve teachers and students in the active improvement of building conditions related to energy efficiency of their respective schools. The *Building Education RET* launched a strategic approach to address global challenges in energy, ecological systems, and human health through transformational integration of technical research into precollege curriculum.

Our strategy involves engaging teachers and students with their school facilities as "Living Laboratories" to provide a place-based context for math and science education. Research activities in multiple domains of building science were utilized to engage teachers across multiple levels and disciplines in a way that offers *Education for Sustainability* as a unifying and energizing theme. *Education for Sustainability* is built on the notion of sustainability as "meeting human needs today in such a way that future generations can meet their own needs" [1]. This approach aims to educate students through systems thinking to understand the interconnectedness of the environment, the economy, and society, so that they are motivated to live sustainable lives [1]. Requiring the consideration of each of these three interconnected facts, building engineering research provides an opportunity for students to understand the complex issues of sustainability.

Systems Thinking is an increasingly recognized competency in sustainability and served as a second overarching learning objective of the *Building Education RET* site. Wiek et al. [2] defined sustainability-related systems-thinking as "the ability to collectively analyze complex systems across different domains (society, environment, economy, etc.) and across different scales (local to global), thereby considering cascading effects, inertia, feedback loops and other systemic features related to sustainability issues and sustainability problem-solving frameworks" (p. 207). Providing students with the opportunity to approach ill-defined sustainable engineering problems requires systems thinking to design a solution [3]; therefore, engaging students in solving engineering problems within disciplinary classrooms is a way to highlight and problematize the interdisciplinary nature of sustainable engineering solutions.

Engaging in research experiences requires RET participants to understand the day-to-day thinking structures and technical activities that drive the work of researchers. With the release of the Next Generation Science Standards (NGSS) [4], these day-to-day activities that scientists and engineers use to conduct their work have been termed as the science and engineering practices (SEPs). Figure 1 shows the 8 SEPs identified by the NGSS. Out of the 8 practices, 2 of the practices specifically call out engineering-focused practices: Defining Problems and Designing Solutions. To elaborate on these 8 practices for the work of engineers, Cunningham and Kelly [5] identified sixteen epistemic practices of engineering for education (Figure 2).

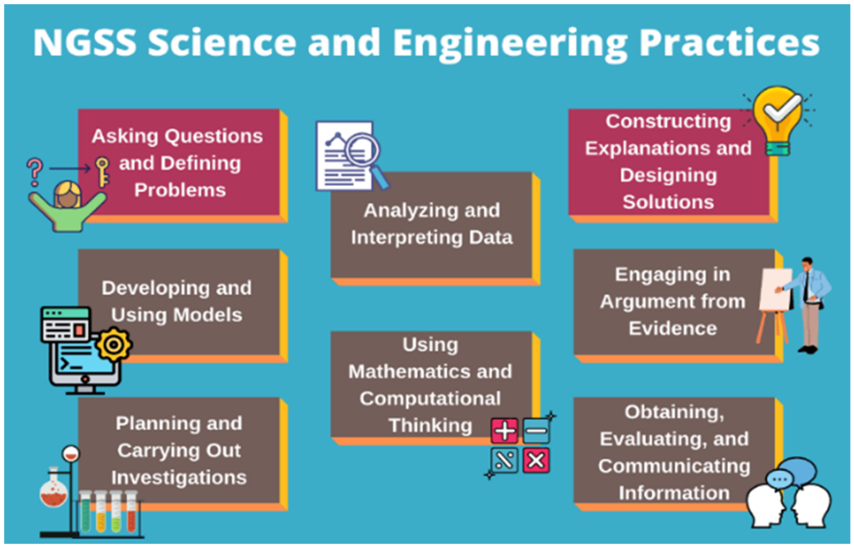

Figure 1 *NGSS Science and Engineering Practices [4].*

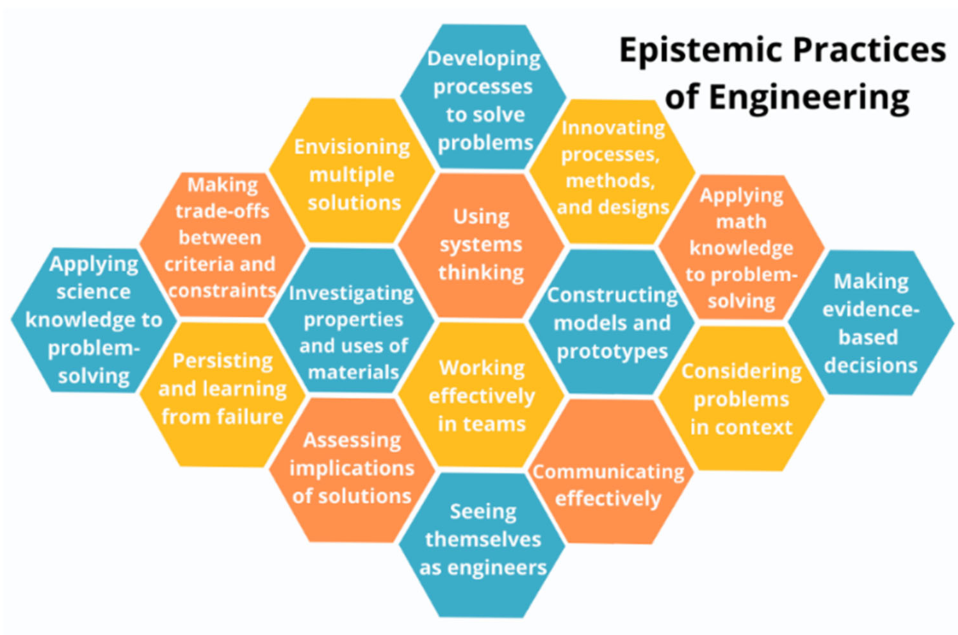

Figure 2 *Epistemic engineering practices [5].*

The *Building Education RET* site is a collaboration between engineering faculty in Architectural Engineering and science education faculty at the Center for Science and the Schools at Penn State University. As designed, the program emphasizes the intersection of sustainability, systems thinking, and the practices of engineers to provide a holistic understanding of the nature of engineering research. In this paper, we describe the structure of the *Building Education RET* program from the teachers' technical research to curriculum development, and finally curriculum implementation. The level of integration of the engineering practices into secondary curriculum based upon the teachers' research experiences is explored. We present an exemplar case of a teacher who is currently using his school as a "Living Laboratory" to highlight how this particular teacher conducts authentic research with his students and to share the curriculum planning tools that we use with teachers to facilitate their translation of research to the classroom.

Context

The *Building Education RET* site has immersed teachers in both fundamental and applied research on architectural engineering topics. Despite originally intending to implement the program in-person, during the spring of 2020, the *Building Education* team decided to implement the RET program remotely with teachers conducting research in their homes. Not only did this allow the program to continue through the pandemic, but the virtual implementation also allowed teachers from outside of the state to participate in the program for the first time. Over the past two summers, we have had teachers from 11 different states participate in the RET program. To date, 12 secondary teachers have been mentored by Penn State Architectural Engineering researchers to measure and interpret various aspects of sustainable building practices. Teachers also engaged in professional development with science education faculty at the Center for Science and the Schools (CSATS), housed in the College of Education at Penn State University. CSATS faculty have developed a specialized series of experiences and interventions that support teachers to translate their research into curriculum appropriate for secondary students (Figure 3).

Technical Research
Prior to teachers' arrival, the active projects taking place in the research labs were discussed by the engineering and science education team. Based upon this ongoing work, related projects were designed for the teachers to engage in summer research. The *Building Education RET* lead team was intentional in avoiding projects that were merely tangential to the research or too intensive to be completed in a seven-week period. The designed projects enabled the teachers to directly contribute to the research efforts of the engineering labs and participate in regular lab meetings.

Teachers were equipped to collect data through instruments and observations about the quality of lighting, indoor air quality, occupant thermal comfort and health, building automation, and building energy consumption in their homes. We also engaged teachers in the mapping and evaluation of control systems in their homes to manage heating, cooling, and fresh air. They learned state-of-the-art data analysis methods to identify opportunities to reduce energy demand. For classroom implementation, the intent was for the teachers to use their schools as 'living laboratories' and scale the research they conducted in their own homes to their school facilities.

Initial research activities were designed to build teachers' content knowledge of both disciplinary conceptual understandings and engineering practices. Over the course of the summer research, CSATS supported teachers to make these concepts and practices explicit by through iteratively construct concept maps and research diagrams representing their projects. We used concept mapping to help the teachers identify the concepts required to carry out their research projects and articulate the ways in which these concepts are connected. To help the teachers organize the context of their research in the broader scope of their lab's research goals, the teachers created a Modeling Authentic Science, Technology, and Engineering Research (MASTER) Model [6].

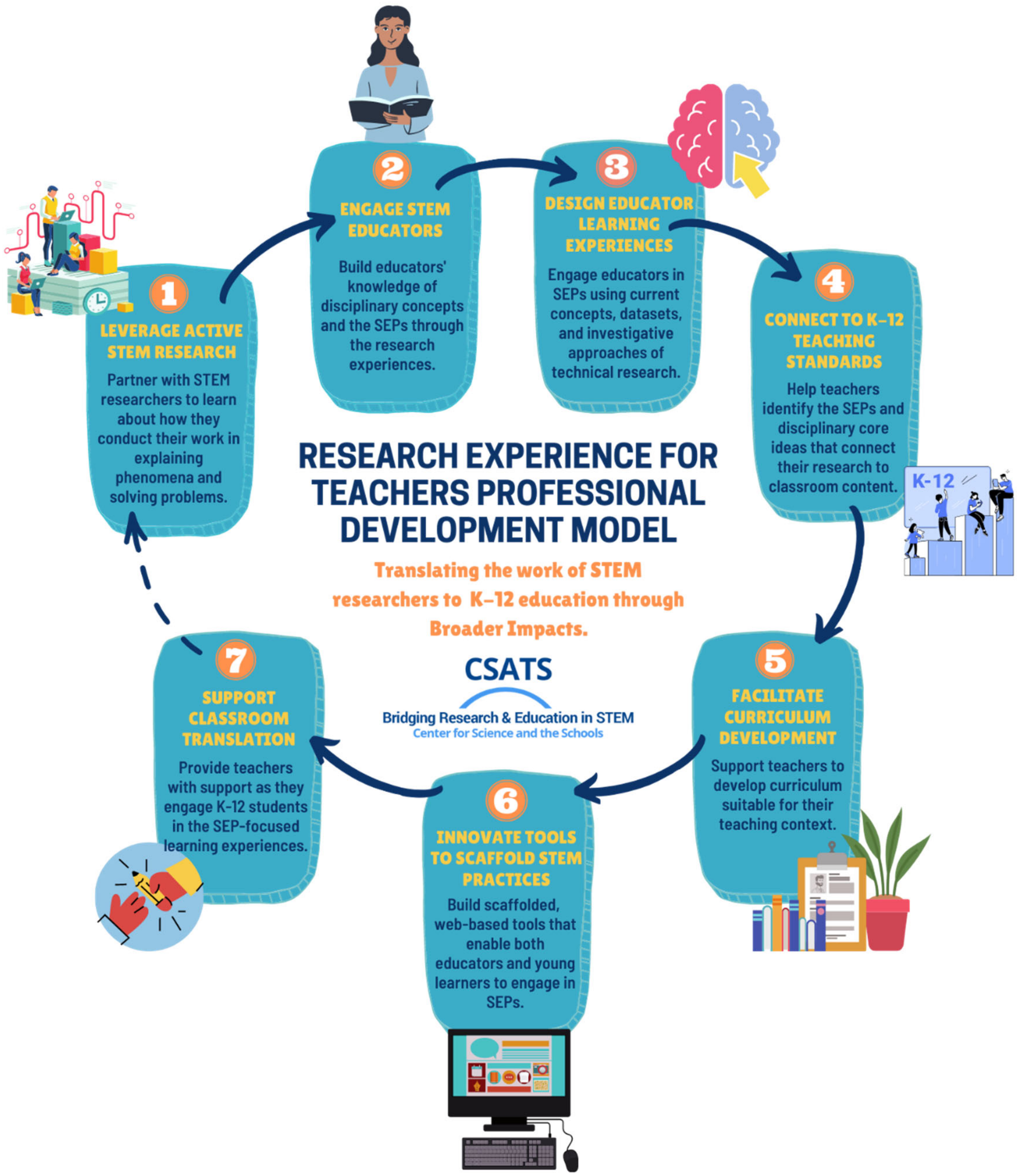

Figure 3 *CSATS' Research Experience for Teachers professional development framework.*

The MASTER Model is a diagram that takes a leveled approach to communicate the research goals and primary research activities that are currently being investigated in a research lab. The first level of the Model is the phenomenon under study in the research lab. The second level is the overall research goal (or problem, in the context of engineering). The Model then narrows focus as it communicates multiple sub-questions at the third level and then investigation approaches at the lowest level. These investigations may even give rise to new questions that emerge as new knowledge is constructed. The teachers used this tool to identify and communicate the research questions and approaches they are conducting in their technical research. Then, they use the MASTER Model to identify the research questions and practices that are applicable to their own classrooms. An example of a concept map and MASTER Model generated by a teacher can be found in the appendix below.

Weekly sessions supported teachers in identifying disciplinary content and engineering practices that were translatable to secondary classrooms. CSATS engaged the teachers in multiple practices, including *Developing and Using Models* and *Designing Solutions* [4], through scaffolded pre-designed activities. CSATS provided examples of concept maps and MASTER Models that related to these modules and discussed how they related to actual research taking place in engineering labs on campus. These activities served to support teachers in bridging cutting-edge technical research and secondary classroom instruction.

Curriculum Development
As a culminating product, the teachers developed a classroom research project (CLRP) that included a series of applied STEM-based teaching modules. The CLRP integrated applicable aspects of their technical research into their existing curriculum for the academic year. The CLRP curriculum may be focused on the content of the technical research project, but more importantly, the CLRP is intended to engage students in the practices that engineers use to conduct their day-to-day work.

The professional development of the *Building Education RET* program included scaffolds and a framework for teachers to organize their understanding of their technical research and how to translate it back to the classroom. Teachers used their concept maps as a tool for integrating their technical research into their CLRPs by identifying the specific concepts and connections that aligned with their relevant secondary STEM class. These concept maps enabled teachers to identify the gradient of conceptual learning from basic to more sophisticated disciplinary ideas. Teachers also used the MASTER model as a framework for planning the classroom activities and incorporate the engineering practices appropriate for their teaching context.

Since many Pennsylvania school districts have outdated computer resources or have purchased less expensive devices (e.g., Chromebooks, iPads), secondary students are often limited to class projects that require limited to no computing power. This is counter to the work involved in engineering research. With the secondary teachers conducting research that involved sophisticated engineering practices, such as analyzing large datasets and building and running simulations, equipment and computational tools were identified or created to support engaging younger learners in the same or similar practices. VR headsets, laptop computers, micro-processors, and sensors were purchased for teachers to use as a means of making their school a "Living Laboratory." In addition, web-based computational tools were identified or developed for teachers to successfully implement their CLRPs with students.

Curriculum Implementation
During the academic year following their summer research experience, the teachers implemented their CLRPs with their students. Some teachers implemented the curriculum with a single class while others implemented with all their students. In the past two academic years, we have had eight classroom research projects implemented with students. Table 1 shows a summary of each

of the CLRPs developed and implemented by the *Building Education RET* teachers. Of the eight projects, two projects are being implemented for the second time by teachers who participated in the RET program during two consecutive summers.

Along with content translation, the teachers focused on integration of the SEPs and epistemic engineering practices in their classroom research projects. Figures 4 and 5 show the frequencies of SEPs and epistemic engineering practices, respectively, that appeared in the teachers' CLRP plans.

Table 1 *Technical research and associated classroom research projects developed by teachers*

Technical Research Focus	CLRP Focus	Course and Grade Level
Using virtual reality software to develop virtual landscapes – used by the researcher to develop engineering safety training environments	Students use the virtual reality software to design an environment and code the game to have a rover explore the environment	General Science, 9
Measuring home energy use and indoor air quality with Purple Air sensors and HOBO data loggers	Consider trade-offs between school energy usage and indoor air quality	Environmental Science, 10-12
Conducting a literature review to see what is known about contaminants attached to particulate matter and their effects	**Collect energy usage and indoor air quality data and recommend modifications to building design**	**Environmental Science, 10-12**
Development of a cost-effective sensors design for in situ measurement of window efficiency	Heat from buildings escapes through windows	7th Grade Science
Optimizing building design and glazing for energy reduction	Understanding how design implications minimize building energy use	Environmental Science, 9
Explore how a person's STEM affinity score affects their engagement with a building design challenge	**Understanding the design implications of minimizing building daylighting, energy use, and structural weight through computational design thinking**	**Environmental Science, 9**
Development of a Brainwave-Driven Human-Robot Collaboration framework to create communication between workers and robots using EEG signals	Designing robots with biosensors to solve a problem related to human physiological monitoring	Robotics Competition Prep, 11-12
Using thermal imaging to detect energy leakage in existing windows	Designing a bearded dragon living structure while keeping the classroom cool	7th Grade Science

Note. Bolded CLRPs are extensions to a teacher's second year of participation in the program.

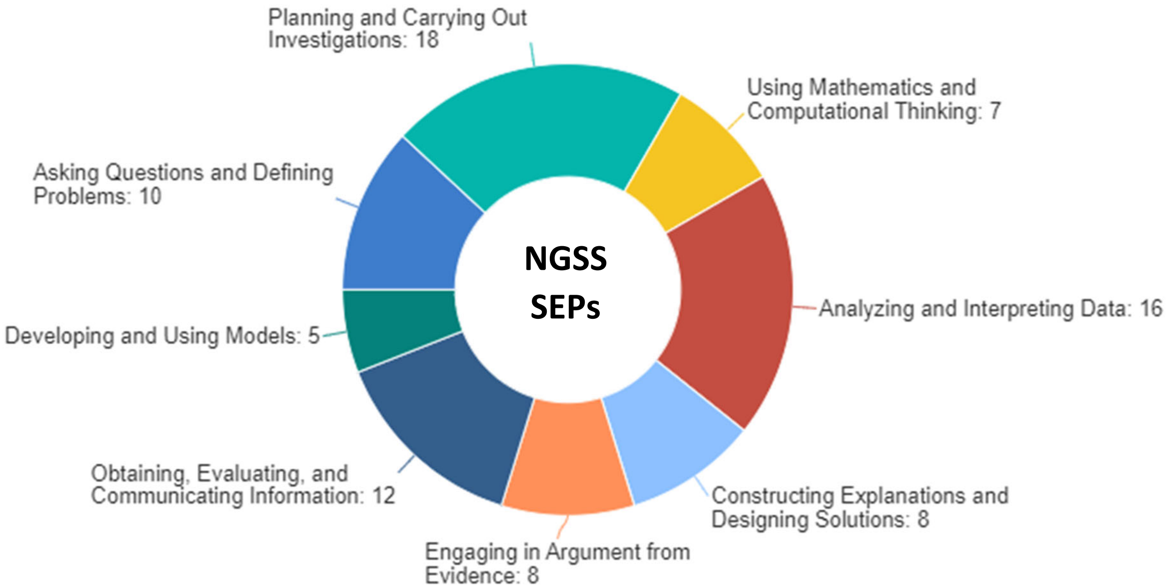

Figure 4 *The number of times the NGSS SEPs [4] appear in the teachers' classroom research projects. Note: Some practices appear more than one time in a classroom research project based on the proposed activities.*

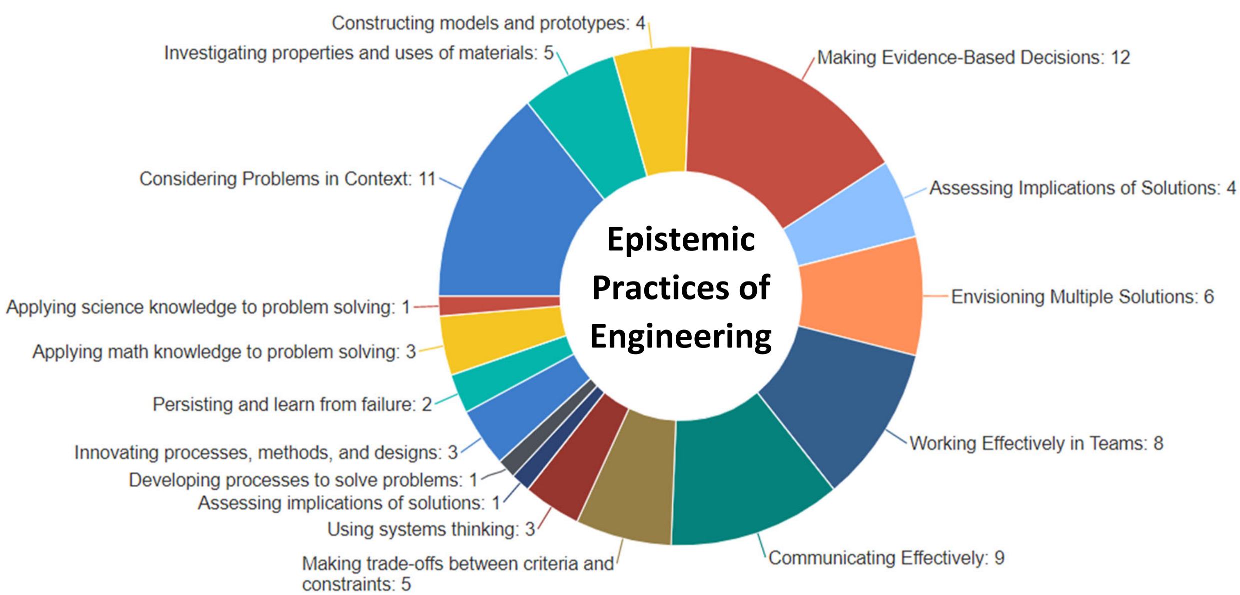

Figure 5 *The number of times the epistemic practices of engineering [5] appear in the teachers' classroom research projects. Note: Some practices appear more than one time in a classroom research project based on the proposed activities.*

Teachers were encouraged to conduct action research on their classroom research projects to evaluate the effectiveness of the technical research-focused curriculum and to make enhancements for future years of implementation. Science education faculty at CSATS provided professional development for the teachers to perform action research in their classrooms, as most teachers had not previously conducted action research as a method of professional improvement.

An Exemplar Case of a "Living Laboratory"

Although there have been eight successful classroom research project implementations during COVID-19, our discussion will focus on one teacher, John (pseudonym), who translated his research into a classroom research project that effectively embodies the goal of the *Building Education RET* program to use schools as "Living Laboratories" for sustainability education. During the summer 2020 RET program, John's research was planned to take place in his school building, but without being able to enter the building due to COVID restrictions, John completed an energy audit and assessed air quality in his home. His research mentor provided him with Purple Air sensors [7] and HOBO data loggers [8] to measure air quality in different home spaces. John decided where to place the sensors based on his understanding of the background literature that cites that many energy efficiency measures negatively impact indoor air quality. Translating his research to the classroom, John was able to develop a classroom research project that planned to engage the students in multiple engineering practices, including considering problems in context, making trade-offs between criteria and constraints, and designing solutions.

John was able to implement parts of his classroom research project with his AP Environmental students after their end of the year exam in 2021. John's students placed the Purple Air sensors and HOBO data loggers he used to conduct his technical research in different locations around the school to collect data about the school's air quality. The students collected data, but with the end of the school year schedule, and inconsistent student attendance due to COVID, the students were unable to fully complete their data analysis or design solutions to the potential issues of air quality in their schools. Unfortunately, they were not able to use their data as evidence to provide recommendations on air quality to the school.

During summer 2021, John returned for a second year in the RET program to build out the complexity of his air quality research and build upon his previous year's classroom research project. John worked with the same research mentor and built out his research interest in indoor fine particulate matter. This research was in its beginning stages during John's 2021 summer placement; therefore, John was involved in laying the groundwork for the particulate matter study. John expanded the scope of his 2021 CLRP to include the new focus on particulate matter. Figure A (see appendix) shows how John integrated the engineering concepts related to his course content into his curriculum using concept mapping. The concept map shows only a small section of his larger concept map, which included a multitude of concepts related to his research that he already teaches. The focus here is how John built out the engineering concepts related to sustainability, a concept he already teaches, to provide a place-based context for learning by actively engaging the students in considering the economic, environmental, and human-related implications of building design decisions in a context that is relevant to the students.

During spring 2022, John's students will pilot his mentor lab's new sensors in his school building to see how fine particle matter becomes aerosolized due to movement of occupants and HVAC systems operations. The students will monitor and analyze particulate and carbon dioxide levels in chosen locations around their schools. The students will compare the energy use and air quality data and make evidence-based recommendations for solutions to improve indoor air quality while maintaining energy efficiency. Figure B (see appendix) shows the details of John's MASTER Model, which he created to organize the CLRP's research questions and investigations. Based on their recommendations, the students will have the opportunity to work with their school's facilities department to make reasonable adjustments to their building to test the effectiveness of their design solutions.

Conclusions

The first clear call for the integration of sustainability education into the K-12 curriculum occurred in 1996 with the release of the U.S. President's Council on Sustainable Development's *Education for Sustainability: An Agenda for Action* [9]. Since then, sustainability has become an increasingly important topic in K-12 education; however, many times teachers find it difficult to incorporate these concepts into their classrooms and end up only providing examples as add-on material [9]. The *Building Education RET* program provides an experience and framework for teachers to learn about sustainability through the context of building engineering. The combination of authentic research experience and supportive professional development leads teachers to design and implement classroom research projects that engage students in relevant, place-based engineering projects for sustainability education. With the integration of engineering in precollege science classrooms, RET programs can play a critical role in helping secondary science teachers to better understand the field of engineering and develop engineering CLRPs that mirror or closely approximate the work of expert engineers.

References

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[8] Data loggers. Onset Computer Corporation. https://www.onsetcomp.com/products/data-loggers/mx1100-family (accessed March 16, 2022).
[9] W. Church, W and L. Skelton, "Sustainability education in K-12 classrooms," *Journal of Sustainability Education,* vol. 1, pp. 1-13, 2010.

Appendix

Concept map and MASTER model diagrams of exemplar project

CLRP Template

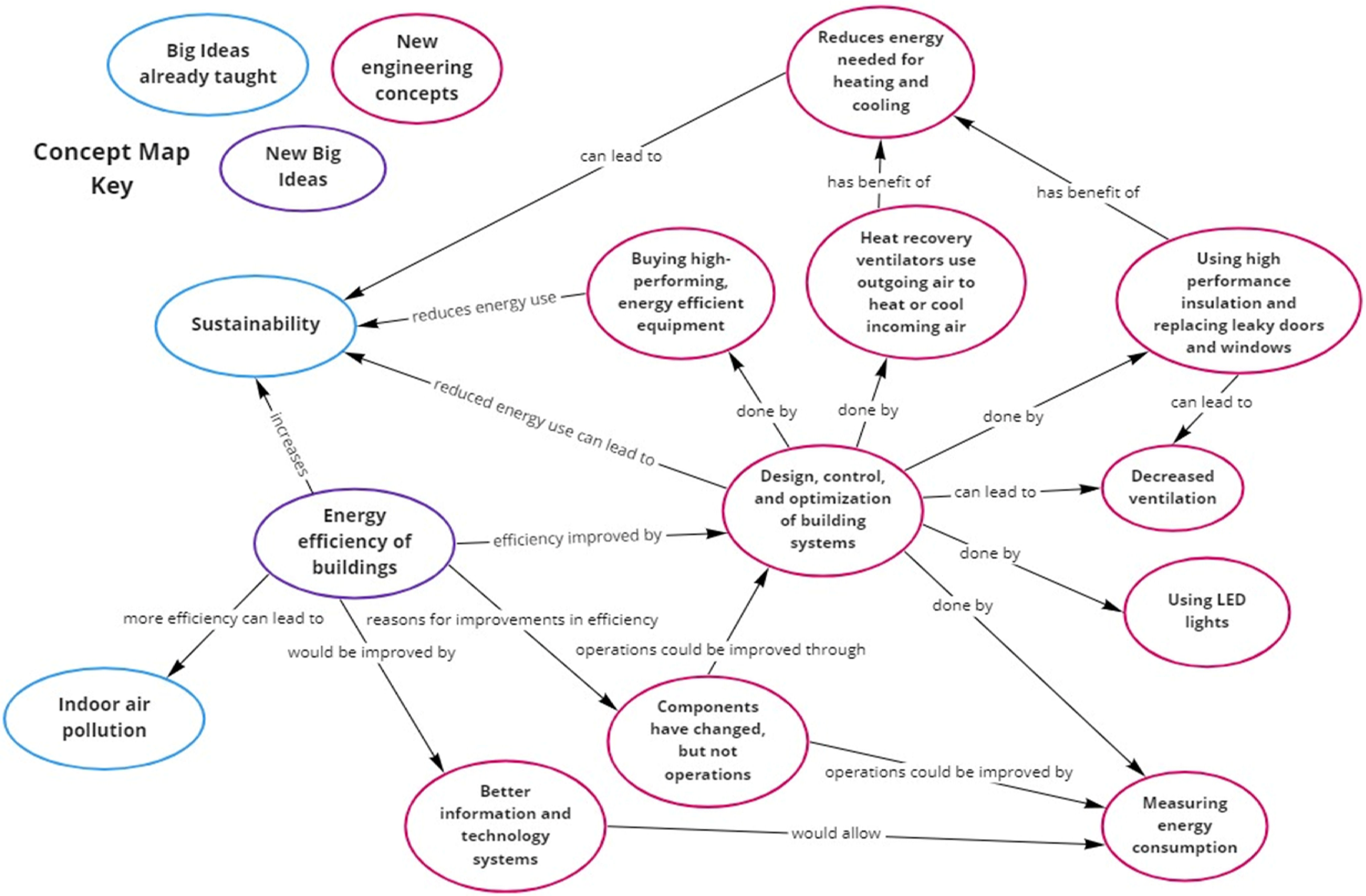

Figure A.
John's CLRP Concept Map highlighting the integration of engineering concepts into his already existing sustainability and indoor air pollution curriculum.

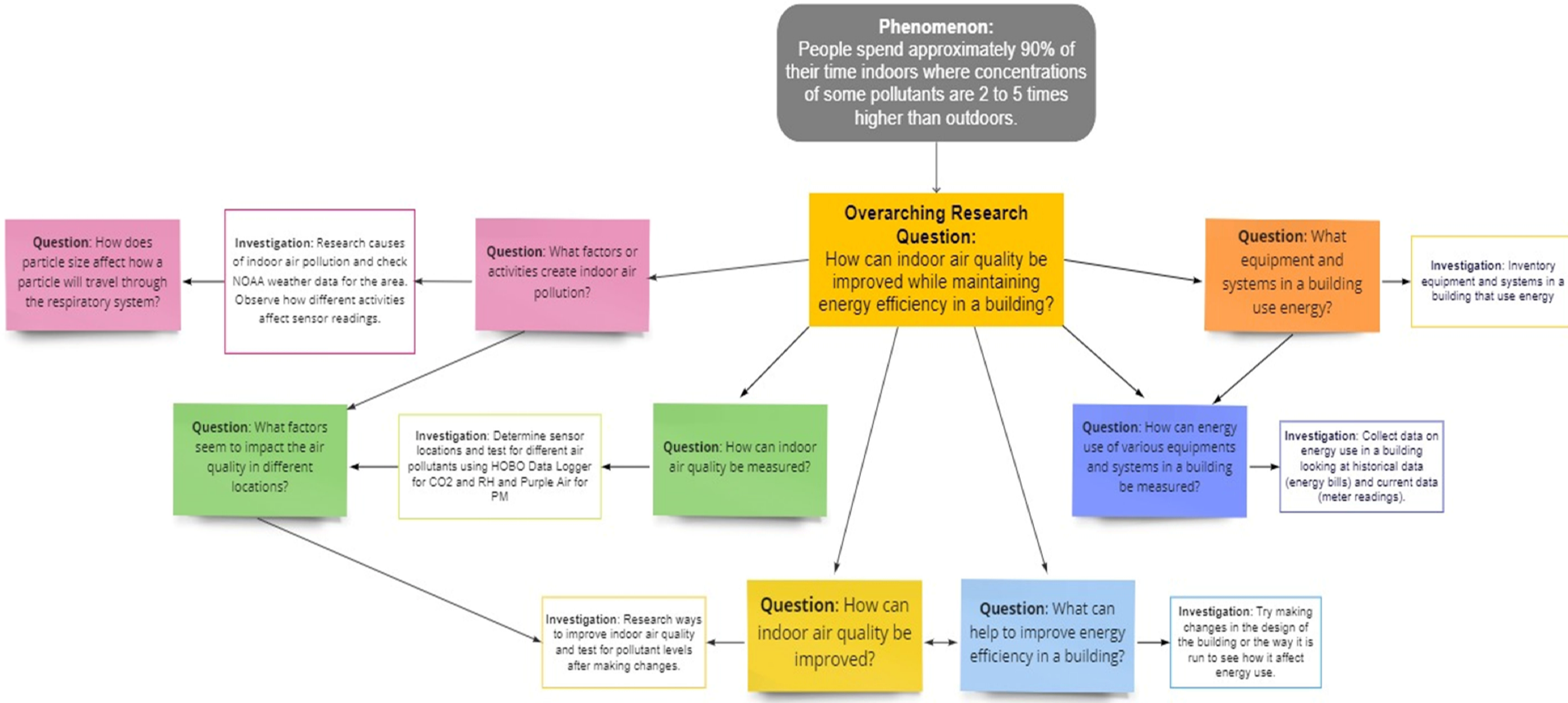

Figure B

John's MASTER Model diagram depicts the research questions and the investigations the students will carry out during the 2022 CLRP implementation.

2021 Summer Research Experiences for STEM Teachers
Pennsylvania State University
Center for Science and the Schools

Classroom Research Project Template

Name:	**School:**
Grade/ Grade Band:	**Topic:**
Anchoring Event - Description of the context and conditions of phenomenon or engineering problem:	
Explanatory or Solution Model - Develop a scientifically accurate explanation of a phenomenon or an engineering solution to a problem with sufficient detail that it represents the most sophisticated level of understanding, including targeted science/engineering concepts, appropriate for your students:	

Overarching Goal of the CLRP - Making sense of a phenomenon or designing solutions to a problem:
Narrative/Background Information
Disciplinary Core Ideas and PA Standards - May include multiple disciplines):
Classroom Research Project Concept Map: Click the box to indicate that you have uploaded your final CLRP concept map on Canvas ☐
MASTER Model of the Classroom Research Project: Click the box to indicate that you have uploaded your final CLRP MASTER Model on Canvas ☐
Description of CLRP Implementation in terms of Student/Class Organization:

CLRP Lesson Plan		
Opening Activity Description - Opening Activity – Access Prior Learning / Stimulate Interest / Generate Questions: How will you introduce the phenomenon or problem to your students?		
CLRP Investigation 1 Explanation - summarize the goal of this investigation and how it connects to the anchoring event (overarching phenomenon or problem):		
Research Question 1.1 -		
Approach 1.1.1 -	**Approach 1.1.2 -**	**Approach 1.1.3 -**
Materials:	**Materials:**	**Materials:**
Practices[1] **– List and describe:**	Practices[1] **– List and describe:**	Practices[1] **– List and describe:**
Assessment Strategies: Describe the ways in which students will express, clarify, justify, interpret, and represent (text, drawing, diagrams, presentations, etc…) their ideas and respond to peer and teacher feedback.		

Research Question 1.2 -		
Approach 1.2.1 -	**Approach 1.2.2 -**	**Approach 1.2.3 -**
Materials:	**Materials:**	**Materials:**
Practices[1] **– List and describe:**	Practices[1] **– List and describe:**	Practices[1]**– List and describe:**
Assessment Strategies: Describe the ways in which students will express, clarify, justify, interpret, and represent (text, drawing, diagrams, presentations, etc…) their ideas and respond to peer and teacher feedback.		

CLRP Investigation 2 Explanation – summarize the goal of this investigation and how it connects to the anchoring event (overarching phenomenon or problem):		
Research Question 2.1 -		
Approach 2.1.1 -	**Approach 2.1.2 -**	**Approach 2.1.3 -**
Materials:	**Materials:**	**Materials:**
Practices[1] **– List and describe:**	Practices[1] **– List and describe:**	Practices[1] **– List and describe:**
Assessment Strategies: Describe the ways in which students will express, clarify, justify, interpret, and represent (text, drawing, diagrams, presentations, etc…) their ideas and respond to peer and teacher feedback.		

Research Question 2.2 –		
Approach 2.2.1 -	**Approach 2.2.2 -**	**Approach 2.2.3 -**
Materials:	**Materials:**	**Materials:**
Practices[1] – List and describe:	**Practices[1] – List and describe:**	**Practices[1] – List and describe:**
Assessment Strategies: Describe the ways in which students will express, clarify, justify, interpret, and represent (text, drawing, diagrams, presentations, etc…) their ideas and respond to peer and teacher feedback.		

CLRP Investigation 3 Explanation – summarize the goal of this investigation and how it connects to the anchoring event (overarching phenomenon or problem):		
Research Question 3.1 -		
Approach 3.1.1 -	**Approach 3.1.2 -**	**Approach 3.1.3 -**
Materials:	**Materials:**	**Materials:**
Practices[1] – List and describe:	**Practices[1] – List and describe:**	**Practices[1] – List and describe:**
Assessment Strategies: Describe the ways in which students will express, clarify, justify, interpret, and represent (text, drawing, diagrams, presentations, etc…) their ideas and respond to peer and teacher feedback.		

Research Question 3.2 –		
Approach 3.2.1 -	**Approach 3.2.2 -**	**Approach 3.2.3 -**
Materials:	**Materials:**	**Materials:**
Practices[1] – List and describe:	**Practices[1] – List and describe:**	**Practices[1] – List and describe:**
Assessment Strategies: Describe the ways in which students will express, clarify, justify, interpret, and represent (text, drawing, diagrams, presentations, etc…) their ideas and respond to peer and teacher feedback.		

<table>
<tr><td colspan="3">CLRP Investigation 4 Explanation – summarize the goal of this investigation and how it connects to the anchoring event (overarching phenomenon or problem):</td></tr>
<tr><td colspan="3">Research Question 4.1 -</td></tr>
<tr><td>Approach 4.1.1 -</td><td>Approach 4.1.2 -</td><td>Approach 4.1.3 -</td></tr>
<tr><td>Materials:</td><td>Materials:</td><td>Materials:</td></tr>
<tr><td>Practices[1] – List and describe:</td><td>Practices[1] – List and describe:</td><td>Practices[1] – List and describe:</td></tr>
<tr><td colspan="3">Assessment Strategies: Describe the ways in which students will express, clarify, justify, interpret, and represent (text, drawing, diagrams, presentations, etc…) their ideas and respond to peer and teacher feedback.</td></tr>
</table>

Research Question 4.2 –		
Approach 4.2.1 -	**Approach 4.2.2 -**	**Approach 4.2.3 -**
Materials:	**Materials:**	**Materials:**
Practices[1] **– List and describe:**	Practices[1] **– List and describe:**	Practices[1] **– List and describe:**
Assessment Strategies: Describe the ways in which students will express, clarify, justify, interpret, and represent (text, drawing, diagrams, presentations, etc…) their ideas and respond to peer and teacher feedback.		
Summative Assessment (Test / Project / Report): Describe the ways in which there will be documented evidence of student learning. How could this relate back to your action research (for example, will you have the students write a final explanatory model)?		

<table>
<tr><td colspan="2"></td></tr>
<tr><td colspan="2">[1]In identifying the practices, you can either identify the 8 NGSS Science and Engineering (National Research Council, 2013) or the 16 Epistemic Practices of Engineering (Cunningham & Kelly, 2017):</td></tr>
<tr><td>NGSS Science and Engineering Practices
1. Asking Questions and Defining Problems
2. Developing and Using Models
3. Planning and Carrying Out Investigations
4. Analyzing and Interpreting Data
5. Using Mathematics and Computational Thinking
6. Constructing Explanations and Designing Solutions
7. Engaging in Argument from Evidence
8. Obtaining, Evaluating, and Communicating Information</td><td>16 Epistemic Practices of Engineering
Developing processes to solve problems
Considering problems in context
Envisioning multiple solutions
Innovating processes, methods, and designs
Making trade-offs between criteria and constraints
Using systems thinking
Applying math knowledge to problem-solving
Applying science knowledge to problem-solving
Investigating properties and uses of materials
Constructing models and prototypes
Making evidence-based decisions
Persisting and learn from failure
Assessing implications of solutions
Working effectively in teams
Communicating effectively
Seeing themselves as engineers</td></tr>
</table>

References:

Cunningham, C. M. & Kelly, G. J. (2017). Epistemic practices of engineering for education. *Science Education*, 101(3), 486-505.

National Research Council. (2013). *Next Generation Science Standards: For States, By States.* The National Academies Press.

Materials Required for This Lesson/Activity				
Item Title	**Description**	**Potential Supplier (with Item #) and link to product**	**Quantity**	**Total Estimated Price**