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Research Experiences for Teachers in Simulation and Visualization for Innovative Industrial Solutions

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Abstract

An NSF Research Experiences for Teachers (RET) Site has been established at Purdue University Northwest to involved high school teachers and community college instructors in industrial research involving numeric simulation, such as computational fluid dynamics (CFD) and Finite Element Analysis (FEA), as well as interactive simulator development using the Unity 3D game engine. A cohort of 11 teachers participated during the summer of 2021 and included teachers and instructors from Indiana and Illinois high school teachers and community colleges. Research projects involved industrial collaborations with local steel industry partners.

The project kicked off with a 6-week in-person research experience hosted at the Center for Innovation through Visualization and Simulation (CIVS) at Purdue University Northwest. The teachers worked with faculty and research staff mentors and graduate students on research projects in the areas of blast furnace/environmental using computational fluid dynamics (CFD) simulation, reheat furnace efficiency using CFD, overhead crane stress using finite element analysis (FEA), and safety training using interactive visualization. Each research project included research mentor staff, graduate and undergraduate students, as well as collaboration with steel industry partners. In addition to the research outcomes, each teacher also developed a lesson plan and education module which will be hosted online for use by other educators. Lesson plans involved a variety of topics programming activities for computer science and related classes, chemistry and environmental activities, math and statistics analysis, and engineering. Each lesson plan also involved some form of activity involving computer simulation and/or interactive visualization.

Surveys measured teacher's self-efficacy in a number of areas including research literature review, design, data collection and analysis, communication of research results, ability to relate real world research problems to teaching, and use of simulation and visualization tools for research and teaching. There was a measured improvement between pre-summer experience and post-summer experience in all categories, with the largest improvements involving ability to discuss research ideas and ability to use simulation/visualization tools for research and teaching. Follow-up activities are ongoing during the teacher's academic school year, including assistance from the RET to carry out implementation of the lesson plans in the classroom, field trips, networking activities, presenting research career information to students, and surveying students on their interest in pursuing STEM activities and related careers.

Introduction

Over the past few decades, technological advances throughout nearly all industries have increased the need for education and occupations that emphasize science, technology, engineering, and mathematics (STEM) [1-3]. Unfortunately, only around 16% of high school seniors are both proficient in math and interested in STEM fields [4]. Only 17% of bachelor's degrees awarded to

U.S. citizens are in STEM fields [5], and roughly 30% of chemistry and physics teachers in U.S. public high schools did not major in these fields and have not earned a certificate to teach those subjects [6]. If the U.S. is to improve on its current competitive position in science and engineering, close the near-crisis workforce "skills gap" in steelmaking and other advanced manufacturing [1-3], and continue economic well-being, STEM education at the high school and postsecondary levels needs support—for its teachers as well as its students.

Despite its fundamental importance to the nation's economy, infrastructure, and national security [8], the steel industry, like many U.S. industries, is experiencing a large skills gap [1-3,9,10]. The growing shortage of skilled workers is fueled not only by loss through retirement, but by outdated perceptions of manufacturing jobs (e.g., "low-tech," "no glamor"), the changing nature of work that demands more skilled workers, and by students who are inadequately prepared for recognizing, investigating, and solving real-world problems [11,12].

Numerous reports draw a direct line between the nation's competitiveness and K-12 STEM education, which produces the next generation of scientists and innovators. To be effective, teachers need content knowledge and expertise in teaching that content, but research suggests that many STEM teachers are underprepared for these demands [12]. Compelling evidence indicates that using real-world engineering examples to translate concepts into practice significantly increases student success rates [11,13,14]. This project incorporates <u>authentic</u> steel-related research projects, thereby benefitting teachers and students, and connecting them directly with the region steel industry and diverse, associated economic partners.

Manufacturing sectors, including the steel industry, are actively transitioning to the use of modeling, simulation, and visualization and need both educated workers and a diverse range of problem-solving approaches and cultures. Schools and young people in particular are eager to be part of technology explorations and need only opportunity and encouragement. During their summer research experiences, teachers developed virtual teaching/learning modules that can connect theory to real-world problems and transfer knowledge and skills about research activities and innovative technology back to their students.

The Center for Innovation through Visualization and Simulation (CIVS) at Purdue University Northwest was established in 2009 and is globally recognized for its integrated and application-driven approaches to solving real-world problems with cutting-edge simulation and visualization technologies. CIVS works closely with industry, K-12 schools, colleges, and governmental branches to address critical issues in engineering, energy, productivity, quality, safety, education, and the environment. CIVS uses **computational models** to simulate real phenomena and predict their behavior under specified conditions, and **visualization technology** to create 3D images and virtual reality environments. Integrating simulation and visualization enables effective data analysis and presentation, communication of ideas, and problem solving, and promotes effective creation of virtual teaching/learning modules with real-world scenarios.

Through partnerships with over 110 external organizations, CIVS has completed over 230 virtual design and virtual education projects with steel-associated and other industries, saving collaborators over $40 million. A number of virtual teaching/learning modules have been implemented and evaluated for technical and engineering education, as well as for training in industry [17-25].

This project has established an RET in Engineering site at Purdue University Northwest, a regional Purdue campus in Northwest Indiana (NWI) where steel and other manufacturers face critical workforce needs. Each year for 3 years, the project will enroll 12 high school and community college teachers from region schools that are currently underserved in STEM education, located in economically depressed areas, and historically associated with "non-glamor," heavy industries such as steel and manufacturing. The first cohort completed their 6-week research experience during the summer of 2021 and is currently implementing their follow-up academic activities in the classroom during the academic year.

Goals and Objectives

With the overall goal of providing high school and community college STEM teachers with research experiences and development opportunities that will enhance their STEM understanding and in turn be adapted into class curricula, the project identifies these **three objectives**:

(1) To provide high school and community college teachers with authentic research experiences using advanced simulation and visualization technologies to solve real-world industrial problems. Through the research experiences, teachers will learn to use simulation and visualization for applied research in various engineering fields, which will be transferred back to their classrooms

(2) To translate teachers' research experiences and knowledge into curricular modules, utilizing existing real-world virtual industrial processes, that will be implemented in their STEM classes during the academic year

(3) To build a community of educators and engineers who will continue to collaborate, promote research and practical application of simulation and visualization technologies, advance STEM learning and career paths, and provide inspiration for students

Methodology

Technical Approach

Figure 1 illustrates the technical approach for using simulation and visualization as means for research and teaching module development at CIVS. In essence, the process uses computational techniques to model physical situations with real-world data, and applies visualization technologies to be able to "see" or visualize the most relevant data in forms useful to both people and "smart" machines. Finite element analysis (FEA), for instance, can be used to determine where areas of high stress or pressure may affect an object's functional capacity—whether that object is a small wrench (Figure 2) or a large, simply supported I-beam (see Figure 4, Project 3). Such visualized models are integral parts of investigational simulations: change the inputs (or situation parameters), and changing results can likewise be both calculated and seen.

Computer simulations and virtual reality are increasingly being used as educational tools, and there is a growing movement towards their use not only for knowledge transfer, but also to teach and assess broader competencies more rigorously [26]. Simulators that provide feedback for troubleshooting have been used in government service branches [27], and substantial research supports their use in the classroom to promote skill development, content area knowledge, and conceptual evolution [28]. Computer-based simulations also allow research experiences to be replicated in classrooms with limited resources. Thus, these technologies provide both a coherent research focus and a backbone for the program projects. Virtual simulators of various industrial processes developed at CIVS serve as the basis for this project.

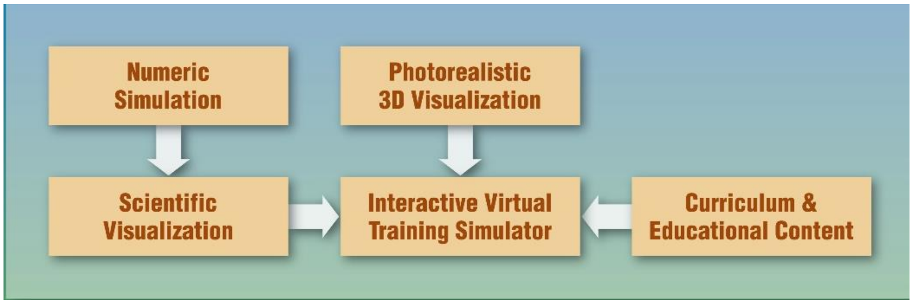

Figure 1. Technical approach for research

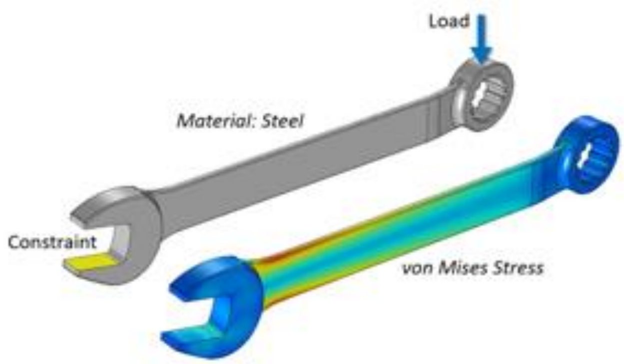

Figure 2. FEA depiction of von Mises teaching module development stress in wrench

Educational Philosophy

Within an **active learning** framework, this program embraces the concept of **project-based learning**, where knowledge and skills are gained by investigating a specific problem to be solved. This approach to learning is particularly effective, because in trying to solve a problem, students become acutely aware of the need to acquire knowledge, understand concepts, and apply skills; they become motivated to learn. Since the foundation of project-based learning lies in the authenticity of the project [29], students gain the competencies necessary to contribute to society. With this program, engineering-education institutions, manufacturing industries broadly, and steelmakers in particular will be direct beneficiaries. Project-based learning "refocuses education on the student … rewarding drive, passion, creativity, empathy, and resiliency" [30]; and research has demonstrated that students in project-based learning classrooms attain higher scores than students in traditional classrooms [31-34]. Active learning also results in greater gains in both learning efficiency and effectiveness, vs traditional lecturing, across STEM disciplines [13].

Schools in economically depressed areas often benefit most from project-based learning. When students take responsibility for, and ownership of, their learning, they increase their self-esteem. And when self-esteem rises, work habits and attitudes toward learning improve [30]. This project specifically targets school districts in such areas, and the research projects in the 6-week program are based on authentic problems in the steel industry, and participants produce results that matter. They pursue solutions to nontrivial problems by asking and refining questions, debating ideas, making predictions, designing plans and experiments, collecting and analyzing data, drawing conclusions, communicating their ideas and findings to others, asking new questions, and creating artifacts.

Results

The first cohort recruited 12 teachers. One teacher had last minute scheduling conflicts, resulting in a cohort of 11 teachers completing the summer research activities. The summer research followed a 6-week schedule as follows:

Summer Research Activities (6 Weeks)

The summer session research projects apply simulation and visualization to address issues in steel manufacturing. Each project produced research outcomes and a curricular module for academic-year classroom use. Faculty mentors responsible for the research projects were assisted by CIVS staff and graduate students in interacting with teachers to conduct the research projects. Virtual teaching/learning modules were created collaboratively by CIVS personnel and teachers, based on existing virtual industrial processes and simulations. The 6-week summer session included the following activities:

Week 1 – Orientation and Project Background

- Introduction to RET program, research facilities and methodology, security/safety issues, and industrial processes; discussion of regular meeting schedules (one-on-one, small- and large-group meetings), site visits, professional development lectures and activities, etc.
- Develop research plan, conduct literature reviews, become conversant with industry process
- Learn to modify existing virtual industry process simulation models for teachers' research projects

Week 2 to 5 – Conduct Research and Begin Curricular Module Development

- Conduct research and parametric studies to optimize and troubleshoot industry processes
- Interact regularly with faculty mentors, graduate students, and industry engineers
- Industrial site field trips, research colloquia, professional development seminars
- Weekly lunch presentations where all participant teachers meet together to discuss their progress
- Begin curricular module development, mid-program project assessment & refinement (as needed)
- Begin research report creation (short paper/manuscript, poster presentation, etc.)

Week 6 – Research Report, Curricular Module, Virtual Simulation, and Presentation

- Write a research report and develop a curricular module
- Direct CIVS students to create a custom version of existing simulation for their curricular module

Figure 3. Teachers worked in a simulation lab to carry out parts of their summer research activities

Teacher Research Projects and Outcomes

The 11 teachers were broken into 4 groups to work on different research projects according to alignment with the classes that they taught and their interests. Each project included a dedicate research faculty or staff, and graduate student researcher to mentor and guide the teachers. In addition to learning about general research practices, the teachers were also learning simulation software and were given dedicated space during the summer session to carry out their research activities (figure 3). The scope of the projects was also adjusted as the mentors became accustomed with each teacher's skills and capabilities to ensure they could achieve results within the summer timeline. A brief overview of the four research projects follows.

Investigate the Effects of Natural Gas (NG) Injection in a Blast Furnace

A blast furnace is a large vertical chemical reactor utilized in the conversion of iron ore to liquid iron during steelmaking. Operating a blast furnace is both energy- and cost-intensive. Since NG prices have decreased in recent years, it has become an attractive alternative fuel for increasing energy efficiency and productivity.

However, using NG greatly impacts several furnace operational parameters. Computational fluid dynamics (CFD) has been applied to simulate NG combustion in a blast furnace, but further research is needed to analyze NG performance. In collaboration with steelmaking industry partners, CIVS and SMSVC have already developed a detailed blast furnace geometry and CFD model which will be used by teachers in this research.

Investigate the Effects of Operating Conditions on the Energy Efficiency of a Slab Reheat Furnace

Reheat furnaces are commonly used in the steel rolling process, which is a critical part of the production of steel plates and coils. These furnaces impact both the quality and cost of the final steel product. During furnace operations, non-uniform temperature distributions create large stresses during the rolling process, which can result in an industrial accident.

CIVS has created a CFD model for the slab reheat furnace to examine furnace operations. The model will be able to predict the heating process in the slab and give details about the temperature distribution in a three dimensional space with the objective of optimizing the design to make it cost-effective.

Investigate the Effects of Operating Conditions on the Stress and Lifespan of an Overhead Crane

In the steel industry, the overhead crane is used in processes that require heavy lifting. An overhead crane consists of traveling bridge-like girders spanning two parallel runways. The lifting component of the crane, known as the hoist, travels along the bridge with a trolley.

As one of the most important components of the steel factory, large overhead cranes are capital Intensive units that typically remain in service for many decades. Currently, there are many cranes approaching the end of their design life, which is a time when there is a frequent need for repair and maintenance, increasing costs.

To ensure continued operations, many large-scale cranes undergo scheduled maintenance and repairs. The application of modern computational methods, such as finite element analysis (FEA), can enhance repair and maintenance by helping to identify structurally critical areas within an equipment assembly.

Working with steelmakers, CIVS has developed an overhead crane geometry and FEA simulation, and general methodology that can be applied to existing and/or proposed large-scale overhead cranes. The main objective of this project is to structurally analyze a large-scale overhead charging crane in a steel melt shop, using numerical simulation and visualization.

Investigate the Cause of Incidents in a Particular Safety Area in the Steel Industry and Determine Preventive Measures Through Safety Training

While modern steelmaking has advanced significantly, the industry still involves hazardous processes. Fall protection requires thorough understanding of the hazard and correct use of safety equipment. Selecting incorrect or damaged fall-protection equipment, or choosing incorrect anchor points, can result in fatality.

A web-based interactive 3D simulator was created to provide an engaging experience for trainees to accompany traditional training materials. The main objective of this project is to research the most important elements of a safety simulator for steel industry training and design a learning scenario in coordination with steel industry safety professionals.

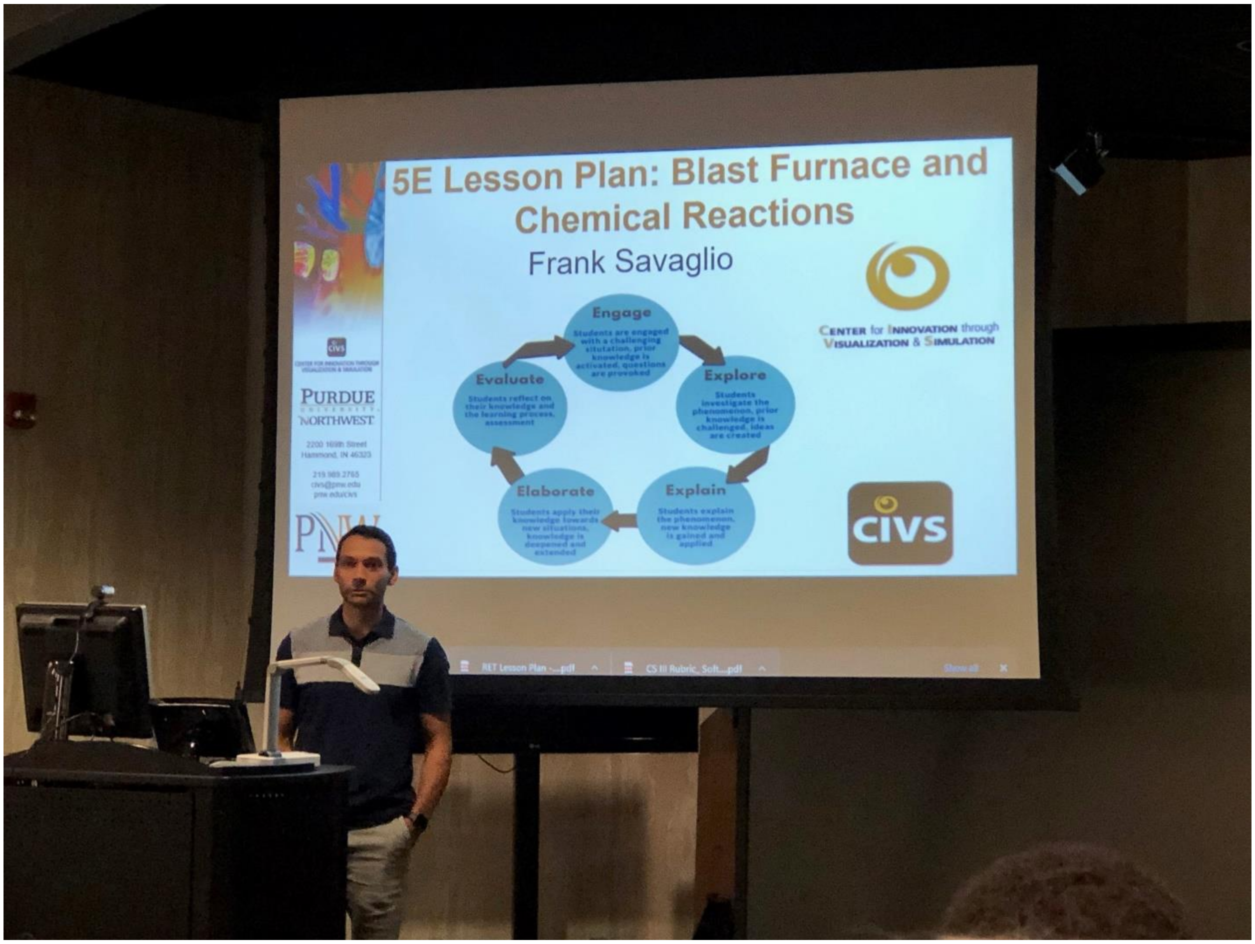

Figure 4. Teachers concluded the summer by presenting their research outcomes, lesson plans, and discussing plans for implementing their research experiences into their own classroom during the academic school year.

By the end of the 6-week summer research experience, teachers made a final presentation of their research results and had each generated three primary artifacts from their research (Figure 4).

Artifacts included:

1) Simulation Models used to conduct the research projects

2) A Lesson Plan or Education module including activities and discussion topics related to their summer research

3) A detailed plan for how they would integrate their research experience into their own classroom, which academic standards they would address, and what part of the academic year they would be included

Future Work

Teachers from the first cohort are currently still in their academic years and the project team is meeting with them individually to assist and ensure the plans from the summer are being implemented in the classrooms. Recruitment has begun for the second cohort of teachers which will run during Summer 2022.

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