Project-Based Learning in Modeling and Simulation Education: Positive Trends over Three Cohorts

Stephanie G. Fussell, Maria Chaparro Osman, William Stalker, Summer Rebensky, Samantha K. B. Perry

Aptima, Inc.

Fairborn, OH

sfussell@aptima.com, mosman@aptima.com, lstalker@aptima.com, srebensky@aptima.com, sperry@aptima.com

Stephen McGee

USAF AFMC 711 HPW/RHWOW

Dayton, OH

stephen.mcgee.3@us.af.mil

ABSTRACT

The demand for a robust workforce skilled in Science, Technology, Engineering, and Mathematics (STEM), as well as Modeling and Simulation (M&S), is projected to grow, underpinning the success and stability of nations. The COVID-19 pandemic negatively impacted student performance in mathematics and science national assessments, highlighting the need for impactful and engaging learning opportunities that promote project-based learning. Addressing this educational gap, the Gaming Research Integration for Learning Laboratory® (GRILL®), an initiative of the Air Force Research Lab in Dayton, OH, collaborates with emerging M&S engineers through the Wright Scholar Research Assistant Program. Participants engage in real-world challenges, honing skills in modeling, simulation, problem-solving, troubleshooting, and task management.

Since 2022, the GRILL team has implemented surveys to monitor the students' self-assessed confidence and proficiency across 11 critical areas. This longitudinal study spans 8 weeks for each cohort, with evaluations from both students and their mentors. The survey methodology has been continuously improved to increase validity and reliability, ensuring comprehensive data collection and insightful identification of both strengths and areas for improvement. Skills critical for M&S, including idea deconstruction, rapid prototyping, development of M&S software, and game engine proficiency, have shown clear growth with each cohort. This presentation will explore the impact and benefits of project-based learning to prepare students for an M&S career, best practices to mentor students interested in this field, and areas of opportunity for future research.

ABOUT THE AUTHORS

Stephanie G. Fussell, PhD, is a Scientist with Aptima, working closely with the Air Force Research Laboratory's (AFRL) Gaming Research Integration for Learning Laboratory® (GRILL®). Her research focuses on extended reality (XR) training competency, efficiency, and effectiveness; meeting user experience requirements; and demonstrating transfer of training.

Maria Chaparro Osman, PhD, is a Scientist with Aptima Inc. Her research focuses on decision making under novel conditions, training and instructional design, performer/learner engagement during complex monitoring tasks in operational and training contexts, as well as usability of mobile applications.

William (Liam) Stalker, MS, an Associate Scientist at Aptima, Inc., specializes in neuroergonomics and human factors to enhance adaptive training and survey methods in the Training, Learning, and Readiness Division. His graduate research investigates the effects of visual environments on performance and the integration of physiological measures with adaptive learning systems to improve outcomes.

Summer Rebensky, PhD, is a Senior Scientist at Aptima, Inc., leading AFRL work focused on training solutions for the modeling and simulation environment, managing a portfolio of work focused on evaluating simulation training capabilities and informing readiness through virtual training data. She leads efforts to develop, test, and implement modern training solutions to improve and measure human performance.

Samantha K. B. Perry, PhD, is a Division Director and Principal Scientist at Aptima, Inc. She has supported dozens of projects primarily associated with the AFRL and Army Research Institute (ARI). In these efforts, Dr. Perry is implementing cutting-edge methods of developing, delivering, and evaluating the training of individuals and teams, integrating multiple relevant scientific fields including cognitive science, artificial intelligence, and advanced analytics to provide real-time, adaptive solutions focused on maximizing human performance.

Stephen McGee, AFRL, is a Research Scientist and Team Lead of the GRILL, where he spearheads innovative research projects and advancements and leads the Just-in-Time Multi Mission Airmen/Warfighters (JITMMA/W) Program. His work focuses on integrating technology and innovation to ensure that warfighters receive the most effective and efficient training possible.

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INTRODUCTION

Creating an innovative workforce necessitates an important, interdisciplinary component of education: Science, Technology, Engineering, and Mathematics (STEM) learning (National Science and Technology Council, 2013). STEM competencies are not only pivotal in driving technological advancements but also impact economic growth, contributing to global competitiveness and national stability (Shernoff et al., 2017; Taylor & Arbeit, 2024). The U.S. National Science Foundation (NSF) projects a 34% increase in STEM occupations by 2032 (Taylor & Arbeit, 2024). To meet this challenge, educators and trainers are tasked with integrating STEM curricula into K-12 programs, a strategy that has been shown to increase student engagement and motivation (Nugent et al., 2010; Rogers & Portsmore, 2004). Furthermore, STEM education fosters critical thinking and problem-solving skills, equipping students to apply classroom learning to real-world problems (Chamberlin & Pereira, 2017; Morrison, 2006). This approach not only prepares a workforce capable of positively impacting the nation's economic prosperity but also accelerates the rate of innovation (Marginson et al., 2013; National Academy of Engineering & National Research Council, 2014).

Project-based learning stands out as an effective method for delivering STEM curricula. This student-centered approach emphasizes a "learn by doing" method, fostering collaboration, communication, and investigation (Kokotsaki et al., 2016). It encourages students to set their own goals, employ critical thinking, and immerse themselves in real-world practices. Moore et al. (2014) outline a comprehensive K-12 STEM education as one that integrates (1) math and science content, (2) student-driven pedagogy, (3) lessons rooted in engaging contexts that motivate, (4) challenges involving engineering design or redesign, (5) opportunities for learning through mistakes, and (6) a focus on teamwork. A strength of project-based learning is it can be designed to include all six aspects to create a robust and impactful learning experience. These aspects are particularly impactful in developing modeling and simulation (M&S) interested and skills in students. Involving STEM professionals in educational projects can further enhance student engagement and foster a mutually beneficial environment where professionals gain new perspectives through the shift from *doing* to *teaching*. Although STEM education has many documented benefits, the integration of STEM curricula into K-12 programs comes with challenges, including a lack of specific resources (e.g., advanced technology, financial resources; Stohlmann et al., 2012), a higher level of knowledge as well as confidence from the educators (Asghar et al., 2012; Stohlmann et al., 2012), and support from engineering and science subject matter experts (SMEs; Ejiwale, 2013).

RESEARCH BACKGROUND

The U.S. Air Force Research Lab (AFRL) Gaming Research Integration for Learning Laboratory® (GRILL®) is helping educators meet this challenge by introducing high school juniors and seniors to various disciplines of engineering and science. As a Department of Defense (DoD) facility, the GRILL is developing the next generation of training and is fostering the future workforce through STEM outreach initiatives that extend to primary and secondary schools, as well as universities nationwide. The GRILL, as a part of the AFRL, specializes in researching, evaluating, and utilizing commercial off-the-shelf technologies—both hardware and software. The aim is to rapidly produce prototypes, testbeds, and virtual environments that not only facilitate personalized training applications and research but also enhance the capabilities of airmen and reduce the time required for their readiness. The rapid pace of technology evolution requires adaptation, and effective adaptation is most readily achieved with a deep understanding

of these complex, evolving systems. The GRILL works with industry to compile and continually update a comprehensive knowledge base of current and emerging game-based technologies, best practices, and other relevant STEM information to benefit both the DoD and the academic community. This knowledge is disseminated through technical evaluations, rapid prototypes, testbeds, and virtual environments, ensuring that the latest insights and innovations are accessible to those shaping the future of defense and education. Building on this commitment to fostering a knowledgeable and adaptable future workforce, the GRILL extends its educational outreach through various summer programs. The GRILL participates in assistantship and internship opportunities in collaboration with the Strategic Ohio Council for Higher Education (SOCHE), as well as the AFRL's Wright Scholar Research Assistant Program (WSRAP) and LEGACY Program. Additionally, the GRILL welcomes interns from local high schools and colleges, impacting over 200 students using project-based learning experiences since 2012.

Research Purpose

This research focuses on the trends of 11 skills documented in three student cohorts from 2022 to 2024. Each cohort completed an 8-week assistantship at the AFRL's GRILL. The tracking of progress is important to ensure that the challenge problems and structure of the project-based learning initiatives is not only meeting the customer's needs but also helping to create workforce with strong STEM and M&S skills. Furthermore, by analyzing this growth, the GRILL can refine its educational strategies to better prepare students for the demands of the evolving tech landscape, ensuring that they are not only job-ready but also primed to innovate in their future careers. The goal of the paper is to present a robust evaluation methodology and insights from a longitudinal study, demonstrating the value of project-based learning in M&S education. Best practices and lessons learned are presented.

METHODS

Setting

During the summer programs, students work with GRILL Computer Science Engineers to develop their M&S skills to create real-world technical projects over the course of eight weeks. All students have a demonstrated interest in a STEM career, are U.S. citizens, are juniors or seniors in high school at the time of application to join a summer program, and have a GPA of 3.5 or higher on a 4.0 scale. Students who come to the GRILL tend to have a background or interest in computer programming, technology, and mathematics.

The projects, called *challenge problems*, are designed to hone skills in technology, engineering, and mathematics. The challenge problems are submitted by customers from government and industry and require the students to utilize game engines and extended reality technologies to meet the needs of the customer and successfully complete the challenge problem. Over the course of the program, the students engage directly with customers, responding to their needs, and ultimately deliver a functional final product. Mentorship is provided by the GRILL personnel as the students create the project in a game engine. Since 2022, researchers at the GRILL have monitored the development of skills in areas such as program design, modeling and simulation, communication and collaboration, problem-solving, and proficiency with game engine technologies. The GRILL summer programs require students to work in groups of three to four on a challenge problem in which they design a computer simulation program based on guidelines from the customer. The students receive mentorship and guidance from the GRILL SMEs, online and local resources, and training on technical skills including 3D modeling, computer programming, and working with game engines (e.g., Unreal Engine®, Unity®). Aside from training, resources available to the students also include virtual reality headsets, high-end game development computers, and other technology and equipment needed to meet the challenge problem. The experience naturally requires the students to develop many critical skills for a strong STEM workforce, including troubleshooting, rapid prototyping, communication, collaboration, goal setting, and task management. Throughout the program, the students discuss the project with the customer, further honing professional communication abilities. The experience culminates with an End of Summer Showcase, in which the project groups present their problem and solution to the customer as well as other stakeholders.

Study Design and Procedure

Each cohort followed a similar data collection process. During week 1, the students were asked to participate in regular questionnaires to assess skill change over the course of the assistantship. The timing of these questionnaires occurred

during weeks 1, 4, and 8. The questionnaires included items related to both proficiency and confidence across 11 and then 13 skill areas, as well as skills utilized, roadblocks faced, and solutions used. The week 1 questionnaire also included items related to demographics, Big Five Personality Traits, STEM interests, and extracurricular activities. Only the trends related to skill proficiency relevant to modeling and simulation are discussed in this paper (see also Stalker et al., in review). Mentors completed similar surveys during weeks 2, 4 or 5, and 8. The mentor surveys did not begin until week 2 to give the mentors time to assess the skills of each student, and questionnaire delivery cadence changed based on feedback. The questionnaires were administered using Qualtrics®. At the end of the eight weeks, the participants were also asked about their feelings toward STEM education, and feedback on the experience. Approval from an Institutional Review Board (IRB) was not required as the research qualifies as organizational continuous process improvement.

The skills were based upon a review of US Air Force Academy (USAFA) and STEM school competencies, discussions with the mentors on the skills needed to be successful within the computer/software engineering career, and an assessment of STEM measures. In 2022 and 2023, participants were asked to rate their proficiency in the first 11 skills, detailed in Table 1 (see also, Stalker et al., in review). In 2024, the skills of Adapting and Novel Solutions were added based on discussions with the SMEs to simplify previous constructs. The skills and items were iterated prior to each program start to ensure the skills reflected the needs of the STEM and M&S communities. Table 1 reflects the 2024 iteration of the survey with some details on changes that occurred, if applicable. The iterative review by multiple SMEs helped to ensure the face validity of the item verbiage as they related to the skills.

Students rated their proficiency using a 7-point scale from “Unfamiliar” (1) to “Highly Proficient” (7), with 7 reflecting the level of proficiency expected from a first-year college computer science intern. These scales remained the same for each cohort. The mentors assessed each student along the same skills, starting in week 2 to give them time to assess student capability. The mentors rated the students on a 7-point scale from “No Proficiency – Cannot complete task independently” (1) to “High Proficiency – Can do all parts of the task independently” (7) during week 2. This scale was used again for weeks 5 and 8 in 2022, and weeks 4 and 8 in 2023. In 2024, weeks 4 and 8, the mentors rated the extent of improvement of the students on a 7-point scale from “Much Worse” (1) to “Much Better” (7). The change occurred based on feedback from the mentors on results that could help them gauge rate of progress.

Table 1. Skills Rated for Proficiency by Each Cohort and Mentor

Skill Name	Questionnaire Item	Changes Made
Program Design	Implement clear logic in program design (algorithmic thinking)	n/a
Troubleshooting	Troubleshooting coding problems and bugs	Referenced “unexpected” problems in 2022 and 2023
Rapid Prototyping	Perform rapid prototyping tasks (quickly developing prototypes and testing their efficacy)	n/a
Applying Mathematics	Find and apply the correct mathematical formulas for realistic physics and modeling	n/a
Developing Modeling and Simulation Software	Transform conceptual designs into models, interactable simulations, or VR technology	n/a
Team Project Coordination	Coordinate work with other members of a team on a long-term project	Added emphasis on "Project" in 2023
External Communication & Customer Briefs	Communicate topics, progress, and goals effectively with the customer and others outside of the project team	Added explaining project to customer. Name evolved from “External Communication.”
Independent Problem Solving	Utilize online resources to solve problems at hand without relying on others	Added emphasis on “Independence” in 2023. Previously called “Investigative Problem-Solving.”
Task Management	Identify, divvy up, and complete priority objectives in a timely manner across a long duration team project	Added emphasis to the long duration team component in 2023

Proficiency with Game Engines	Utilize available tools / features of a game engine	n/a
Idea Deconstruction	Break ideas and problems down into step-by-step processes	Simplified the wording in 2023
Adapting	Adapting to unexpected problems and situations	New for 2024 to remove the "unexpected" aspect from the Troubleshooting item
Novel Solutions	Creating or coming up with new ideas and solutions	New for 2024

RESULTS

Student Assessment of Skill Proficiency

A total of 50 high school students participated in the eight-week summer challenge problems during 2022 (n = 17), 2023 (n = 18), and 2024 (n = 15). Because of the changes between years, especially 2023 and 2024, the team chose to only assess the data for trends rather than statistical differences. A statistical analysis will be executed following the completion of the 2025 cohort. Figure 1 shows the change in average proficiency ratings for each year, as reported by the students, for each skill as measured by the difference in average ratings between weeks 1 and 8. Figure 2 depicts the change in proficiency for the three cohorts in terms of the difference in ratings between weeks 1, 4, and 8 for each year. Figure 2 shows the consistent growth in each skill over the course of the eight weeks for each cohort. Two exceptions are Independent Problem Solving in 2024, which decreased from 5.7 in week 1 to 5.5 in week 8, and Adapting, which decreased from 5.6 to 5.3. Developing Modeling and Simulation Software consistently increased the most for each cohort, ranging from an increase in average rating from 2.7 to 5.2 in 2022, 3.6 to 5.7 in 2023, and 2.9 to 5.1 in 2024. The highest proficiency skills, as rated by the students during week 8, are shown in Table 2. All three cohorts rated their skill iteration of External Communication and Team Coordination in the top three highest proficiency skills in week eight, and Task Management was rated highly for the 2023 and 2024 cohorts.

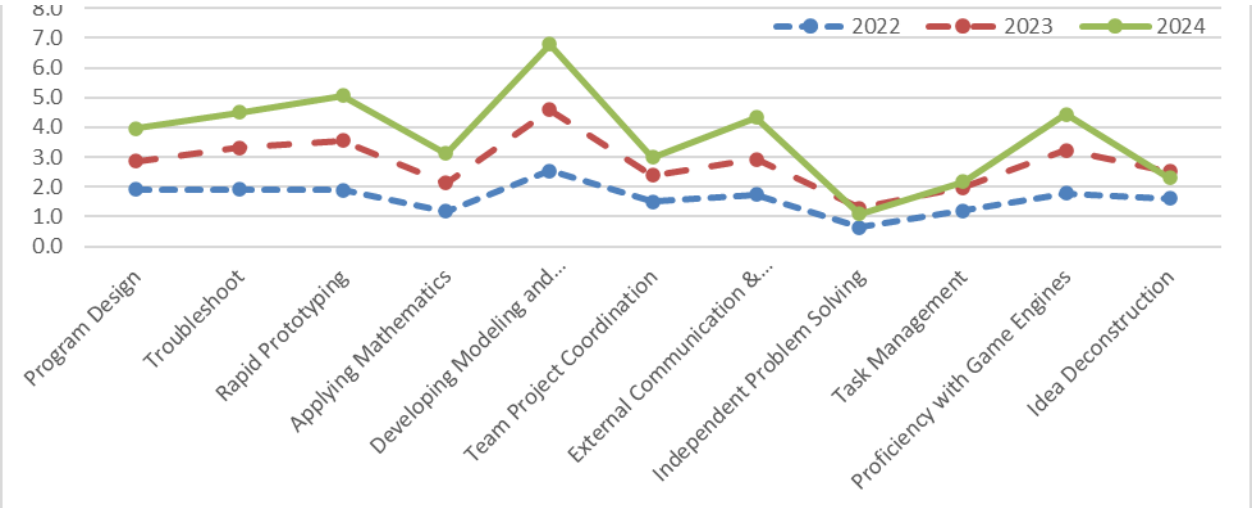

Figure 1. Average Proficiency Rating Changes, Student Ratings

Note. The skills of Adapting and Novel Solutions are not shown because these were only measured in 2024.

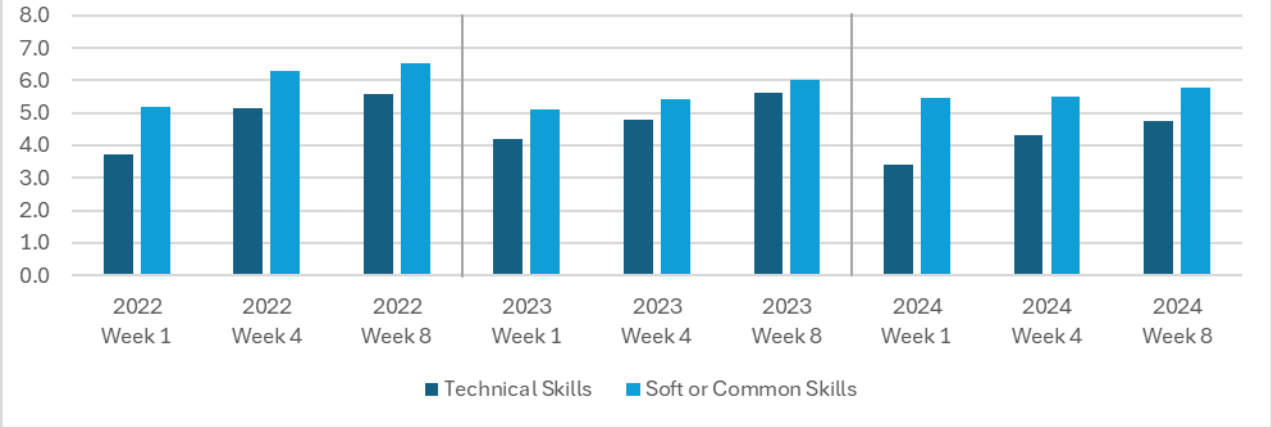

Figure 2. Per-Skill Proficiency Rating Changes, Student Ratings

Note. Technical Skills are Program Design, Troubleshoot, Rapid Prototyping, Applying Mathematics, Developing Modeling and Simulation Software, Proficiency with Game Engines. Soft or Common Skills are Team Project Coordination, External Communication & Customer Briefs, Independent Problem Solving, Task Management, Idea Deconstruction, Adapting, Novel Solutions

Table 2. Students' Top 3 Proficiency Skill Ratings, per Cohort

Year	Skill	Week 8 Score
2022	Team Coordination	6.67
	Idea Deconstruction	6.67
	External Communication	6.50
2023	External Communication & Customer Briefing	6.11
	Task Management	6.06
	Team Project Coordination	6.0
2024	External Communication & Customer Briefs	6.47
	Team Project Coordination	6.40
	Task Management	5.67

Mentor Assessment of Skill Proficiency

The mentors rated baseline proficiency for all three cohorts during week 2. In 2022 and 2023, the same rating scales were used in weeks 4 or 5 and week 8. The 2024 ratings of proficiency changed in weeks 4 and 8 to focus on improvement. The mentor ratings rose consistently from week 2 to week 8 for all cohorts, as seen in Figure 3. Figure 4 shows the change in average proficiency ratings, as reported by the mentors, for each skill as measured by the difference in average ratings between weeks 2 and 8. Figure 4 shows a proficiency increase for each cohort. The highest proficiency skills, as rated by the mentors during week 8, are shown in Table 3. Skills in 2023 and 2024 had multiple skills tied for the highest and second highest rating, as seen in Table 3.

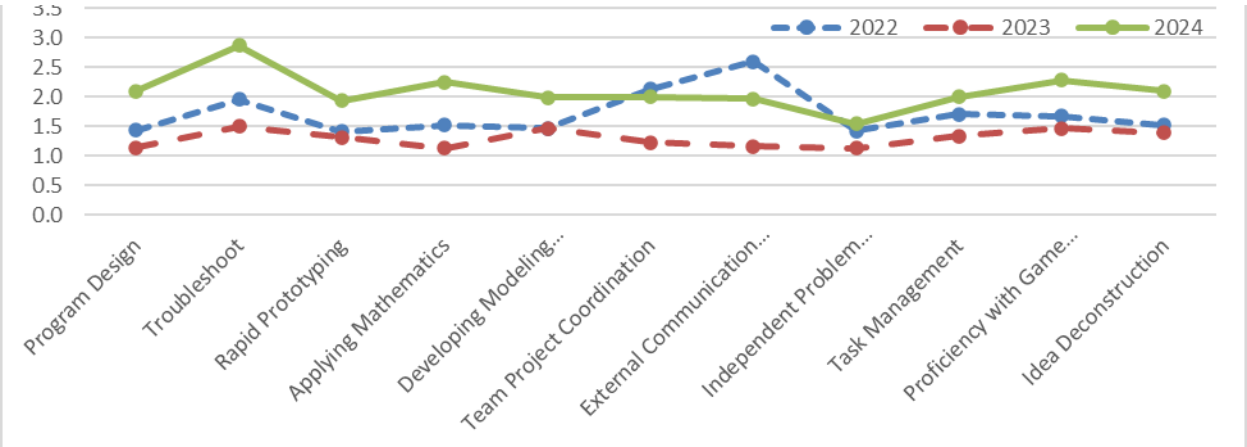

Figure 3. Average Proficiency Rating Changes, Mentor Ratings

Note. The skills of Adapting and Novel Solutions are not shown because these were only measured in 2024.

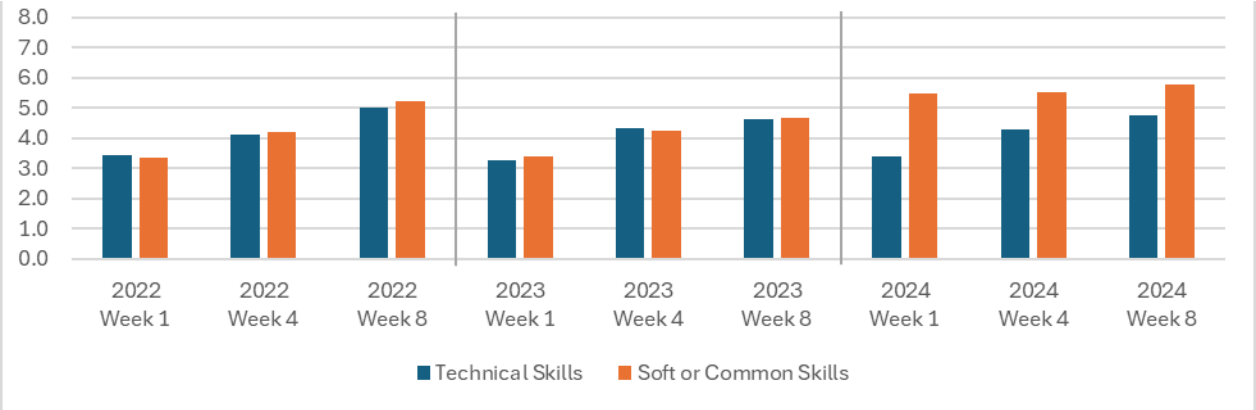

Figure 4. Per-Skill Proficiency Rating Changes, Mentor Ratings

Note. Technical Skills are Program Design, Troubleshoot, Rapid Prototyping, Applying Mathematics, Developing Modeling and Simulation Software, Proficiency with Game Engines. Soft or Common Skills are Team Project Coordination, External Communication & Customer Briefs, Independent Problem Solving, Task Management, Idea Deconstruction, Adapting, Novel Solutions

Table 3. Mentors' Top 3 Proficiency Skill Ratings, per Cohort

Year	Skill	Week 8 Score
2022	External Communication	5.65
	Team Coordination	5.53
	Task Management	5.33
2023	Independent Problem Solving, Proficiency with Game Engines	4.80
	Troubleshooting, Team Project Coordination, Idea Deconstruction	4.67
2024	External Com & Customer Briefs	6.2
	Proficiency with Game Engines, Adapting, Troubleshooting	6.1

Student Feedback

During week eight, the students were asked to give feedback on the summer program via a survey about what went well, and what could be improved. Many of the qualitative comments were positive and constructive, consistently aligning to technical skills as well as soft skills.

Skill Development and Learning

Many students highlighted the value of learning new technical skills, such as 3D modeling, mathematical modeling, coding logic, Unreal Engine 5, and technical aspects of game development. Some students requested to learn about additional programming languages and software, the technical side of game systems, and incorporating other aspects of engineering related to hardware.

Teamwork and Collaboration
Several students mentioned the positive experience of working with others, communicating effectively with teammates, and coming to a consensus without direct supervision. A few students mentioned that increased interaction between teams could be a beneficial way to learn from each other.

Independence and Responsibility
Many students reflected on a growing sense of independence, expressed satisfaction in working on their own components of the project, and taking responsibility for their work. The ability to work independently while still having support when needed was a recurring positive theme.

Customer Interaction and Feedback
Engaging with customers and receiving feedback was noted as a valuable experience, particularly in terms of learning how to prepare and present professionally. The process of working with customers to meet their needs and incorporating feedback into the project was seen as an essential part of the GRILL learning experience.

Mentorship
Students also gave feedback on working with a mentor. Overall, the guidance and advice from mentors was appreciated and contributed to their learning and development. A few students noted that more technical instruction would be beneficial.

DISCUSSION

Over the course of eight summer weeks, students at the GRILL participate in project-based learning to solve a challenge problem for a customer. The experience necessitates collaborative teamwork to produce a final product, as well as individual effort to research issues and manage tasks. The students enter the summer programs with a baseline interest in computer engineering and software development, if not a foundation through coursework and extracurricular activities. Over the program's duration, students demonstrate significant skill development, particularly in technical areas and in customer-related skills. Developing Modeling and Simulation Software consistently saw the highest rate of change for each cohort, as rated by the students. Other technical skills, like Rapid Prototyping and Troubleshooting, also see consistent increases as the students use them in their daily work. Through practical application, they gain a deeper understanding of their abilities and recognize areas for improvement. This realization, coupled with their aspiration to pursue STEM careers, drives them to refine their skills further.

While the students generally have a realistic perception of their technical and engineering skills, they tend to overestimate their proficiency in Idea Deconstruction and Adapting to problems they encounter. The mentors can observe growth from a more realistic standpoint. However, mentors provide a more objective perspective, noting tangible skill advancement despite discrepancies between student self-assessment and mentor observation. The consistent improvement in technical skills, such as Troubleshooting and Proficiency with Game Engines, suggests that project-based learning is an effective method for preparing the future STEM and M&S workforce through hands-on, realistic applications (e.g., challenge problems from customers) that foster independent yet structured work. Additionally, skills in Team Project Coordination and External Communication & Customer Briefs show marked improvement for each cohort. These skills become more pronounced as students gain confidence in managing projects and interacting with customers. The honing of soft-skills is particularly relevant, as many students suffered from a lack of personal interaction when education shifted to remote learning during the COVID-19 Pandemic.

Areas of Opportunity

The open-ended feedback indicated a desire for more opportunities for different project groups to interact and test each other's projects. There was a sense that current interactions were limited unless individuals actively sought out other groups. Future iterations of the program can include encouraging the students to test each other’s projects. This

may provide an opportunity to learn from each other and give peer-to-peer feedback. To foster this environment of rapport, structured activities (e.g., icebreakers) could be used for team building and to promote social interaction throughout the program.

Another area of opportunity is that of more formal instruction and structured mentorship. Some students mentioned the need for more explanations, particularly regarding the game engine they work with, aimed at those less familiar with such technologies. Linking the learning to real-world applications was also requested, to enhance the understanding of how the challenge problem—and the skills associated with meeting the customer's needs and creating a product—align with the environment in which the product is used. This feedback indicates a desire for educational opportunities and knowledge sharing within the program and within the working environment (i.e., with the customer), which can further support the GRILL's goal of developing the next generation of training the future workforce through STEM programming and outreach (GRILL, 2025).

BEST PRACTICES

Aligning with five Moore et al.'s (2014) six aspects of a robust K-12 STEM education and considering the goals of project-based learning for M&S under SME mentorship, the following best practices are recommended. The themes combine into a balanced approach to project-based learning that values individual growth, mentorship, autonomy, collaboration, goal orientation, real-world application, communication skills, and engagement.

Mentorship and Guidance

- Ensure regular check-ins by mentors to monitor progress and provide resources or redirection as needed.
- Mentors should be approachable, friendly, and honest, providing a balance between support and direct feedback.
- Bring levity to coding and other challenging tasks to help students relax and succeed, remembering that the students have different levels of experience.
- Establish feedback (questionnaire) buy-in by ensuring that everyone understands the purpose of the questionnaires as a tool to measure quality information, every step of the way. Design questionnaire items with the audience in mind.

Student-Centered Pedagogy

- Recognize that each student learns differently and avoid a one-size-fits-all method.
- Learn students' strengths and weaknesses to guide them into suitable roles.
- Engage with students individually to reduce social pressure and encourage participation.
- Start with bite-sized tasks to assess confidence and gradually increase complexity based on performance.

Situated, Motivating, and Engaging Learning Contexts

- Engage students with real-world problems and active customer/user involvement for meaningful learning experiences.
- Highlight the relevance of skills learned to students' future careers and personal development.
- Provide opportunities for students to face real customers to enhance their practical experience.
- Ensure that students understand the importance of their work and feel that their contributions are meaningful.

Engineering Design/Redesign Challenge

- Encourage students to create SMART (Specific, Measurable, Achievable, Relevant, Time-bound) goals.
- Support student autonomy, independent learning, and leadership.
- Encourage students to take initiative in breaking down projects into manageable tasks and choosing their areas of interest.
- Offer feedback from various perspectives to improve the students' ability to convey project background, purpose, need, and results.
- Prepare students for final presentations from the beginning of the program.
- Provide resources and practice opportunities to refine presentation skills.
- Break down projects into smaller, more manageable tasks and assigning them based on interest and experience.

- Work with SMEs to identify core competencies and skills early, establish how the skills should be measured, and iterate to ensure items are valid and reliable.

Learning From Mistakes

- Let students take charge of the project, with mentors serving as guardrails.
- Allow students to struggle with problems to enhance learning, with the mentor acting as a guide rather than a leader.
- Encourage students with experience in a certain area to try new challenges and support their peers.

Focused Teamwork

- Promote teamwork by forming teams with a mix of experience levels and diversity.
- Encourage students to contribute regularly to collaborative platforms and repository management tools like GitLab® to minimize conflicts and enhance visibility of their impact.
- Practice soft skills by having students form leadership roles naturally, present to non-technical audiences, and engage in briefings.

CONCLUSION

The use of project-based learning to complete a challenge problem in a structured settings has many benefits and can positively impact the skills needed to succeed in a STEM career. The value of being part of a competent and supportive team is evident, as is the benefit of learning from experienced mentors. Project-based highlights the importance of learning how to figure things out independently, which can result in an increased sense of self-reliance and problem-solving ability, yet emphasizes the importance of team coordination, communication, and other inter-personal skills. A learning environment that is fosters growth and development and includes mentorship with experienced SMEs can yield a conducive atmosphere for learning and collaboration. The best practices presented can be used to implement project-based learning that will benefit the STEM workforce through the application of M&S skills. Future research with the data will include statistical analysis to better understand differences between annual cohorts, mentor and student ratings, and between student groups (e.g., new vs. returning students, high school vs. collegiate students).

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