Integrated STEM Learning in a Workplace Simulation

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Abstract

In this paper, we examined students' engagement in an implementation of a Workplace Simulation Project (WSP). Students in a high school in the rural Midwest worked alongside engineers from a unit of a government organization to solve a client-generated problem. Using a multiple methods study design, we analyzed disciplinary and interdisciplinary pre and posts test along with students' interviews to determine learning gains as well as students' interpretations of creative and critical thinking as experienced in the project and their knowledge of the engineering design process. Effect sizes showed that students in the WSP group had notable gains over the control group participants. Additionally, students' knowledge of core elements of the design process were identified in inductive analyses of the interviews. Findings from this study will provide usable knowledge about effective ways to support systems and design thinking and ways to support expert-novice collaboration to ensure success.

The *Next Generation Science Standards* (NGSS, 2013) and National Research Council's *A Framework for K-12 Science Education* (NRC, 2012) recommend the use of engineering design projects where students are expected to define problems, which included both new, complex situations and those for which people desire change; identify and describe the affordances and constraints of viable solutions; develop and evaluate multiple solutions; build and test prototypes; and optimize a solution that addresses the problem (NGSS Lead States, 2013). Interesting questions have been posed around how students can learn about science, technology and mathematics in the context of engineering, and conversely how can science, technology and mathematics be used to explore engineering concepts (Katehi, Pearson, & Feder, 2009). Such an approach for learning calls for an integration of science, technology, engineering and mathematics (STEM).

There are few documented integrated STEM programs that demonstrate how the engineering design process (EDP) is used to leverage the natural connections between STEM (English, 2016; Katehi et al., 2009; Pruitt, 2014). Pre-engineering programs developed for K-12 tend to place a greater emphases on the learning outcomes of the projects than on how students experience the processes of design (Rogers, Wendell & Foster, 2010). This is problematic as the engineering design process (EDP) is seen as the key skill that helps students apply foundational knowledge to ill-structured, real-world problems involving clients (Katehi et al, 2009; National Academy of Engineering, 2010). According to Dym, Agogino, Eris, Frey, and Leifer (2005), engineering design is "a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints" (p. 104). Engineering problems need to be framed before they can be solved and this framing can be done in multiple ways. As such, in addition to the learning of foundational mathematics and science, which is undoubtedly important to engineering, students must be able to think critically and creatively. For experts, such knowledge and thought processes are often tacit and is possibly best communicated through collaboration and active engagement in the design process. One area of innovation that has not been explored deeply is the effects of collaboration between expert engineers and novice students on students' development of design thinking (Fruchter & Lewis, 2003).

In this study, we created an integrated STEM project involving high school students enrolled in STEM classes, where they worked collaboratively with engineers to solve an industry-generated problem. We sought to answer the following research questions: (i) In what ways did engagement in an informal, pre-engineering curriculum support changes in high school students' disciplinary and interdisciplinary knowledge? (ii) How did participation in the WSP support students' engagement in the engineering design process?

The Workplace Simulation Project

The study was a part of a larger program called the *Workplace Simulation Project* (WSP). We focus on the first year implementation of the program that partnered a high school in the rural Midwest with an engineering unit of a government organization that provides support for the warfighter. The WSP was aligned with the state academic standards, school curricula and recommendations for K-12 engineering education (Katehi et al., 2009, NAE, 2010) and simulated the day-to-day business operations of the engineers. Students participating in WSP were co-enrolled in computer science, physics, algebra 1, junior reserve officer training core (JROTC) and Project Lead the Way's principles of engineering (POE). The project was crafted in collaboration with content area teachers, relevant university faculty and engineers. The project was an ill-structured problem comprising four subsystems (Fig 1). Each subsystem had specific sub-goal(s) that would be integrated to create the protection system. Each subsystem was assigned to one or two classes to develop over the course of the project. Subsystem 1 (build the electronic detection to detect the intruder) was assigned to the computer science and JROTC students; Subsystem 2 (intelligence center to analyze images/video of intruder entry and to calculate intercept drone angle and speed) was assigned to algebra 1 and physics students; and 3 (drone to intercept intruder) to the POE class. Students worked on these concepts in class for four days per week. On the fifth day, students worked in the WSP lab alongside the engineers.

Methods

Participants

Seventy-four 9th through 12th grade students from three high schools in a rural, Midwestern state participated in this study. Thirty-eight students from five classes – algebra 1, physics, computer science, PoE and Junior Reserve Officer Training Corps ROTC participated in the WSP. The remaining students were in the control group and did not participate in any WSP activities. There was no control group for computer science as we could not locate a comparable class in a school with similar demographics as the WSP school.

Data Sources

Pre and post tests. Two tests were administered to participants in a pre-post format. The first was discipline-specific (physics, math etc.) and aligned with the disciplinary content students explored through the WSP. The second test was designed to determine the participants' abilities to integrate and apply knowledge of disciplinary content in response to a scenario, similar but not identical to context of the WSP.

Interviews. WSP participants were interviewed at the beginning and end of the WSP. These interviews were conducted in focus groups of 2 -3 students within the same class. Interview questions were designed to probe participants' knowledge about engineering practices and the fundamentals of the EDP.

Analyses and Findings

All tests were scored using rubrics developed by a consultant with expertise in the content area. Interview transcripts were analyzed using grounded theory techniques (Corbin & Strauss, 1990; Glaser & Strauss, 1967). The analysis centered on responses of focus group participants (e.g., "algebra students") rather than individuals. Analysis began inductively, with an initial round of open coding. Using a process of constant comparison, codes were combined and sorted into emergent categories. Cycles of deductive and inductive analyses continued until categories were refined in relation to research questions. Analyses of focus groups afforded both general and course-specific analyses across categories.

Disciplinary Tests. In *algebra*, the differences in test score gains were not statistically significant. However, the effect size was 0.11 meaning the average WSP student made gains 0.11 standard deviations larger than students in the comparison group. *Physics* WSP students made substantively large gains (36.2 percentage points) compared to comparison students (9.7) with and effect size of 1.33. The two *ROTC* WSP students experienced gains (27.7 %) while the comparison student did not[1]. The average *PoE* WSP student scored 8.8 percentage points lower on the post-test than on the pre-test. The average comparison PoE student gained 2.2 percentage points on average. While differences were not statistically significant, the effect size is considered fairly large (-0.62) and negative. The average *computer science* student post-test score was 17.2 points higher than the pre-test, which was statistically significant. This translates into an average 1.67 standard deviation gain[2]. Comparisons of gain scores was made for the WSP and control students. Approximately 50% of students from the control group made gains on each test, with the exception of the single student in ROTC. At least 60% of WSP students experienced gains on each test, with the exception of PoE (n=2). 68% of WSP students had a higher post-test score than pre-test score (67% including computer science) compared to the comparison group which was 50%.

Interdisciplinary Test. For the *interdisciplinary tests*, ***i***ndependent sample t-tests did not reveal a statistically significant difference in gain scores between the two groups (t=1.37, p>0.10). The difference in changes was 1.7 points, corresponding to 0.34 standard deviation units on the pre-test. In the comparison group, 51% of students made gains while for the WSP students, 71% experienced gains. Although the design does not allow for causal inferences and the results did not achieve statistical significance, they do suggest benefits of involvement in the WSP as indicated by point estimates and some moderately large effect sizes.

. ***Engineering Design Process***. When asked about their knowledge of the engineering design process, an algebra student articulated the iterative nature of the process where one would move between planning, building, evaluating, and modification: "you have to write down the plans… then you might start to build it.. then you need to switch it up… so you can erase it and then make modifications…" A computer science student highlighted the significance of failure, troubleshooting, reflection, and redesign where they "tested it [electronic detection system] – it failed multiple times, started back and figured out our problem, came back to testing, got the solution." Testing was particularly important for the PoE students; one emphasized the process after building the chasis of the interceptor drone - "probably every day for the past week we were doing the speed tests." Some of the algebra students associated the procedure of calculations to obtain the speed of the interceptor drone or the sequence of steps. Examples of responses include: "look at what we had, the pictures... look at the coordinates… had to find the angle and the degree for our drone … testing calculations." A couple of students thought of the EDP as the solving of mathematical problems. Others associated it with complexity, invention, and a "diagram and a blueprint" – these are highly relevant to the EDP since design problems are ill-structured

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1 No statistical analysis conducted because there was only one comparison student.

2 There was no control group hence no comparison was made.

3 As described earlier, based on the subsystem each was assigned, the Algebra and Computer Science students were able to

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problems and design is often communicated through drawings. Although most students were able to describe the engineering process with respect to the WSP, they struggled to apply it to novel situations.

Comparing responses between algebra and computer science classes[3]. The task of determining the drone speed and angle by analyzing pictures of the intruder, determining coordinate points, and then applying systems of linear equations seemed deterministic for algebra students. One student explained, “we didn't get to customize anything. We didn't really get any say.” The tools for analysis were pre-determined for the algebra students. In contrast, computer science students experienced an open-ended project that enabled student choice within the design process. In their design of the electronic detection system, computer science students experimented with different sensors, tested its sensitivity to the intruder and in triggering picture-taking by a webcam, and considered constraints like time and budget. One student appreciated the freedom: “… we could do anything as long as we achieved that goal. Go wild. … we got to test out a lot of things. It wasn't just, ‘all right, you have to do exactly this…. We messed with multiple things. And we got to choose what we wanted.”

Discussion and Implications

In addressing the first research question, findings indicate that participation in the WSP supported most students in learning the scientific and mathematical ideas embedded in the project and improved their ability to integrate this knowledge to solve complex problems that drew from multiple disciplines. We considered this notable for two reasons – our model was designed to integrate the learning of content alongside engineering design in authentic contexts and the results of the tests showed marginal improvements in this regard. Second, engineering design necessitates drawing knowledge from a range of disciplines to generate viable and innovative solutions. The results show that students were better able to integrate knowledge after participating in the WSP. The lack of robustness of the gains along with the decline in scores of the POE students has implications for future implementations. The decline in scores for PoE could be due to: insufficient time for students to complete their subsystem and engineers were unfamiliar with the hardware/programming language used to construct the drone possibly affecting the quality of feedback to students.

Addressing the second research question, students seemed to have grasped, through experience, the iterative and non-linear feature of the EDP as articulated in the interviews. Their statements showed their developed appreciation for the role of failure, multiple approaches (idea generation), testing (idea evaluation) with the goal of finding a viable solution - key aspects of the design process (Hines, 2012). However, students struggled with the transfer of the EDP to new contexts. We know from research that knowledge transfer in challenging (Eraut, 2004). In this regard, it is important for engineering experiences to be better and more consistently woven into school curricula. Specific to our findings around the algebra and physics classes, connections can be drawn between the problem solving cycle used in mathematics and the scientific method applied in science (Mangold & Robinson, 2013). Of note was the experiences of the computer science versus algebra students. Specifically, the computer science students had more opportunities to design their own subsystem and were able to readily draw connections between the design process and their participation in the project. Conversely, the algebra students had less autonomy and agency in developing their subsystem and felt less engaged in the EDP. This underscores the need for a balanced focus on both analysis and design (Dym, 1999; Felder, Woods, Stice & Rugarcia, 2000).

One important observation was related to the way engineers (experts) were expected to collaborate with students in the WSP. Much of the expertise and the underlying knowledge that engineers draw on the design process is tacit (Schön, 1983). There is little need in their work life to make this knowledge explicit as they generally work with experts and not novices. As such, Like teachers, engineers need professional development to develop strategies to effectively work with novices (Kimmel, Carpinelli, & Rockland, 2007), and to have opportunities to reflect on how their knowledge can scaffold learning (Schön, 1983).

Engineering in the real world is collaborative and interdisciplinary (Brereton, Cannon, Mabogunje, Leifer 1996; Bucciarelli, 2003; Dym et al., 2005). However, opportunities for students in each class to interact with the other subject groups were limited. Students were only able to interact across subject groups twice. This proved to be significantly problematic in two key respects: (i) classes were not able to meet to consider how the subsystems work together or how their subsystem contributed to the overall project – lack of opportunities to

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[3] As described earlier, based on the subsystem each was assigned, the Algebra and Computer Science students were able to engage in the design process to varying degrees.

develop systems thinking, (ii) lack of opportunities to interact impeded continuity, diminished opportunities for learning from other subject groups, the strength of the ideas and overall the final product.

In sum, although this implementation of WSP had room for improvement, there was usable knowledge gained about how to better craft experiences for integrated STEM learning around the EDP. Specifically, student engagement in the problem defining and questioning phase of the process is critical; opportunities for collaboration within and across groups as a mechanism for idea generation and evaluation is important; knowledge of theory and design can occur simultaneously; professional development to support experts in meaningfully working with novices is necessary

Potential for Partnership with UW SOE Faculty

With greater global competitiveness in preparing students for STEM associated careers, there is a need for innovation in the design and implementation of integrated STEM projects. We believe that our Workplace Simulation Project model provides evidence-based guidelines that can be useful for UW SOE Faculty involved in STEM education. The WSP is currently being implemented in three other schools and will continue to generate knowledge to guide research and implementation efforts. The partnership will be symbiotic in nature as we are interested in how this model can work in Poland where the economic and social landscape is different from the United States. Our study shows gains in disciplinary and interdisciplinary knowledge as well as knowledge of the engineering design process. Considering these results, we would be interested in collaborating with faculty in mathematics, science, technology and engineering education to offer PD and expertise on the design and implementation of our WSP model; reciprocally, we are interested in learning from UW faculty what efforts they are making with integrating STEM teaching and learning for the purpose of further enhancing our model.

References available upon request