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Metrics for Efficacy in FIRST Robotics Programs: Aligning ABET Engineering Student Outcomes with K-12 STEM Educational Practices

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Abstract

Robotics programs for youth are critical to the nation's overall science, technology, engineering, and mathematics (STEM) development. However, little research has focused on broader impacts and efficacy of national robotics initiatives. Metrics for standardizing assessment have not been established. Currently, evaluation practices among K-12 STEM programs or FIRST® robotics impact reports have done little to align with national post-secondary educational practices. To understand their long-term impact, it is essential that K-12 STEM education programs, especially robotics, begin to utilize standard assessment and evaluation practices that align with college and career readiness outcomes. Since 2007, researchers in Arizona have been evaluating and assessing FIRST® robotics programs across the state. The purpose of evaluation was to indicate the 1) overall success and program impact on students, teachers and mentors; 2) the impact of hands-on learning to interest students in STEM subjects; 3) the impact of developing workplace skills that can be transferred to the classroom; and 4) impact on career choice. In addition to compiling data to understand increasing students' technical skills, research methods embedded ABET student outcomes in the assessment of AZ FIRST® programs. This paper will present an overview of FIRST programs and use excerpts from seven years of compiled research (2007–2013) to expose trends in previous assessment of AZ FIRST® robotics initiatives. Methods used to assess broader impacts of FIRST® robotics programs and their significance when mapped to ABET student outcomes will be discussed.

Introduction and Background

Reports from the National Science Foundation (NSF)[1], National Academy Engineering (NAE)[2], and National Research Council (NRC) Academies[3] have indicated a steep decline in the number of young students pursuing careers in STEM. Experts have concluded that the future economic well-being of our nation will largely depend upon the training of young students within these disciplines and will center upon their ability to be globally competitive with engineers from developing nations[4,5]. In addition, leaders of major U.S. technology firms have cited the state of K–12 education as a major barrier to filling jobs in the United States[5]. Despite current educational trends, it is clear that efforts must be increased to attract and retain students in critical subject areas.

FIRST® (For Inspiration and Recognition of Science and Technology), an international non-profit organization, has started robotics programs across the U.S. to address STEM educational needs and to open the pathway for young students. FIRST® aspires to transform the K-12 educational culture by making STEM exciting and enjoyable[6]. The platform has been utilized both in the classroom and as an extracurricular activity. Its purpose is to motivate students and provide an engaging framework for engineering design and innovation through hands-on application. By participating in the process, student team members develop necessary workplace skills through critical thinking, problem solving, teamwork, project management, fundraising and marketing. At multiple levels, FIRST® provides an opportunity for students, educators, industry and the community to interact while utilizing robotics as a mechanism for participants to grow their academic, professional and interpersonal skills.

Depending upon the grade level, the FIRST® framework usually includes a three-part combination of a robotic design and build challenge, a comprehensive project or technical report, and team core values. Within the team challenge areas, Jr. FIRST® LEGO® League (Jr. FLL); FIRST® LEGO® League (FLL); FIRST® Tech Challenge (FTC); or FIRST® Robotics Challenge (FRC); the robot mission is the initial area that includes a specified theme or "game" with mission components. Participants have specified materials (parts or kits) to work with to custom design and build a robot capable of meeting the challenge and scoring points. Mission challenge components range from easy to difficult to ensure a level playing field between veteran (established) and rookie (new) teams. For the robotics challenge, participants engage in active learning, use engineering computer-aided tools, work through the engineering design process while testing and analyzing their robots. At the high school level (FTC, FRC), students are given a "game" scenario and are requested to build alliances with other teams to be successful. In all three cases (FLL, FTC, FRC), teams are provided with instructions to build scale versions of the challenge field to test their robots and hone their skills.

The second area is a comprehensive project or technical report. General themes are announced at the Jr. FLL and FLL levels annually to incite teams to solve a global engineering problem. Each team provides documentation and supporting research, while enlisting the engineering design process to create a prototype, process or idea. FTC and FRC teams engage in technical report writing to support their ideas and provide documentation on testing and improvement. The third area involves team identity. Many of the teams create unique personas, costumes, and participate in the culture of FIRST®, which is more about the social interactions surrounding working teams and the environment. In all three areas, it is essential that students understand and participate in written and oral communication to convey their ideas. Regional, statewide, national and international events are offered within the FIRST® community to showcase ideas and provide opportunities for learning based on a culture of Gracious Professionalism and Coopertition™[7].

According to FIRST® impact evaluation data (ten years of national research through FIRST), students that participate in FRC are two times as likely to major in engineering or science; 41% major in engineering and 33% of females that participated in FRC enter engineering[8]. FIRST® research has also shown that engagement in school increases for participants with 84% of FTC participants and 90% of FRC participants indicating they plan to take more challenging math or science courses in high school[9]. FIRST® also assists participants in attaining 21st Century work-life skills by improving their problem solving (98%), increased conflict resolution skills (93%) and strengthening communication skills (76%). Finally, research shows that FIRST® has an impact on STEM and engineering professions with 89.6% of alumni entering STEM career fields[9].

FIRST® has been meeting or exceeding its objectives and is positively impacting STEM education in Arizona. From 2007 to 2013, researchers have evaluated FIRST® robotics programs (FLL, FTC, FRC) across the state. As Jr. FLL was not implemented in AZ with a significant number of teams, researchers did not include Jr. FLL in the assessment measures. The purpose of evaluation was to indicate the 1) overall success and program impact on students, teachers and mentors; 2) the impact of hands-on learning to interest students in STEM subjects; 3) the impact of developing workplace skills that can be transferred to the classroom; and 4) impact on career choice.

In addition to compiling data to understand increasing students' technical skills and self-efficacy, researchers embedded outcomes that are aligned to the Accreditation Board for Engineering and Technology (ABET) accreditation outcomes for undergraduates in engineering and technology. After careful examination, many FIRST® outcomes were already aligned with ABET Criterion 3: Engineering Student Outcomes[10] in university engineering programs. One researcher directed and participated in ABET accreditation at the university level for over ten years and noted, the link between ABET and FIRST® was apparent. A finding of this study suggested that participation in FIRST®, due to similarity in core outcomes, has the potential to facilitate the success of students choosing to enter undergraduate engineering and technology programs. Integrating ABET accreditation outcomes into FIRST® assessment assists researchers to understand elements that prepare students for post-secondary education.

Methods and Research Design

To address evaluation questions, researchers employed a mixed-methods approach to accumulate qualitative and quantitative data from a variety of sources. Researchers determined that the use of multiple approaches, in combination, provides greater understanding of the research problem to be addressed[11,12]. Data samples included teams that received funding through an AZ-funded grant as well as comparison teams that participated in regional and state-wide events in FLL, FTC and FRC competitions. Though instruments and methods were refined over the course of the grant-funded period, data was gathered via the following approaches:

- Pre and Post inventory questionnaires, including Middle School STEM BAS[13] (Barriers and Supports) and High School STEM BAS[14] national instruments, with youth surveys administered to participants in grades 4 – 12.
- Coach and parent surveys administered during regional qualifier events
- Phone interviews and email correspondence with coaches
- Focus groups with coaches and mentors during regional and statewide events
- Personal interviews with FIRST® AZ grant-funded teams
- Informal observations to record team dynamics and adult-student interactions during regional events

Primary data sources were instruments that were administered to students, coaches, and parents before the season and during regional events. Due to time constraints, pre-interest inventories were utilized in 2007 to assess teams. A Middle School STEM BAS pre-interest inventory was administered to FLL students to assess their interest in career fields, self-efficacy, and academic performance. Pre and post-surveys instruments were designed in conjunction with FIRST® evaluation staff at the national office as well as with the PI of a five-year AZ-funded grant. IRB was obtained for the study through the use of portions of the STEM BAS survey instrument, previously developed and validated through a national research project[15]. The Middle School STEM BAS instrument was given in its entirety to compare AZ students with data obtained from comparable students in other states. Based on recommendations from the FIRST® national office, the coach survey, parent survey, and student survey instruments developed by Brandeis University[7] were modified and used to collect additional information.

Data Analysis

The Wilcoxon signed-ranks test[16] was used to examine differences within the groups when pre-post- surveys (STEM-BAS surveys) were collected. The Wilcoxon signed-rank test is a non-

parametric statistical hypothesis test used when comparing two related samples (i.e., two paired groups) to assess whether their population mean ranks differ. As the Wilcoxon signed-rank test does not assume normality in the data, it can be used when this assumption has been violated and the use of the dependent *t*-test is inappropriate. It is used to compare two sets of scores that come from the same participants. This can occur when we want to investigate any change in scores from one time point to another. In this study, we used ordinal variables that included Likert scales and we had "related groups" (matched pairs) indicating that the same subjects were present in both groups.

Qualitative data analysis included the Grounded Theory Method[17]. As researchers reviewed responses; repeated ideas, concepts or elements became apparent and were tagged with *codes*, when extracted. As more data were collected and re-reviewed, codes were groups into concepts. Utilizing Grounded Theory involved basic steps: coding text and theorizing; memoing and theorizing; integrating, refining, and writing up theories. Initial steps included open *coding* (breaking data into conceptual components), which involved theorizing (coding while examples are pulled out). This involved the *constant comparative method*; ongoing throughout the process. Memoing was used as an intermediate step between coding and the first draft of the completed analysis. Integrating and writing up theories become the final step. Data subjects' excerpts formed the basis for identifying themes, assertions, and supporting survey data.

Program Evaluation Alignment to ABET Accreditation Standards

The study provided an assessment of the overall success and impact of FIRST® on participating students, parents, and coaches/mentors. Integrating ABET accreditation outcomes into FIRST® assessment allowed researchers to map participation in robotics activities and interest in STEM directly to college outcomes. FIRST® is linked to ABET standards and outcomes in terms in following areas: engineering design skills, problem-solving, use of technology, communication skills including oral presentation (team sharing), and 21st century learning.

The following section contains qualitative results as well as excerpts from open-ended responses from individual data sets to illustrate ways FIRST® research findings are mapped to ABET student outcomes. The following research is not comprehensive due to differences in data collection and metrics used to evaluate teams (FLL, FTC, FRC). However, comprehensively, 1423 individual participants, 450 team coaches and mentors, and 60 parents from FLL, FTC and FRC participated in the study from 2007 – 2013. Excerpts are used to illustrate trends across programs and four-years to reflect key ABET student outcomes.

Finding 1: FIRST® Positively Impacts Student Interest, Skills and Abilities in STEM ABET Student Outcomes: (a) an ability to apply knowledge of mathematics, science, and engineering; (k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

From the team leaders' perspective, FIRST® had an impact in areas such as team members' interest in computers and technology, interest in jobs or careers in science and technology, and interest in or awareness of how math and science are used in the real world. Overall, coach responses suggested that FIRST® participants' skills, interests, and abilities increased "a lot" during the program. As a result, findings indicate FIRST® participants use techniques and

modern tools and apply principles, procedures and methodologies. Thus, FIRST® facilitates important *learning* experiences both inside and outside the classroom.

Table 1: Team Leader View: FIRST® impacts student interest, skills and abilities

N=450	**X**	**σ_X**
a. Team members' interest in/awareness of how math or science used in real world	3.36	.67
b. Team members' interest in computers and technology	3.64	.51
c. Team members' interest in jobs or careers in science/ technology	3.55	.69
d. Team members' interest in succeeding in school	3.09	.54
e. Team members' understanding of basic science principles (force momentum)	3.25	.45
f. Team members' basic computer programming skills	3.50	.52
g. Team members' basic math skills (computation)	2.58	.67

Range: 4=increased a lot; 3=increased a little; 2=no change; 1=decreased

Finding 2: FIRST® Positively Impacts Students' Ability to Solve Problems through Design and Experimental Testing

ABET Student Outcomes: b) an ability to design and conduct experiments, as well as to analyze and interpret data; (c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability; (e) an ability to identify, formulate, and solve engineering problems

FIRST® strategically promotes problem solving and critical thinking through broadly defined, open-ended scenarios. Participants are engaged in designing systems, components and processes to develop their robots. In addition, team members conduct tests and measurements to analyze and interpret results (especially through programming). In reading technical reports and oral presentations, it is apparent that teams (especially FRC teams) are able to apply experimental results to improve processes. Though many of the younger students (FLL) participate in trial and error, coaches and mentors assist teams in analysis of why their robot failed or their programming may have been inaccurate. In these instances, team members were more likely to have conversations about identifying a "problem" and subsequent problems, and brainstorming why something wasn't working and moving to the next level of using acquired information to improve their robot.

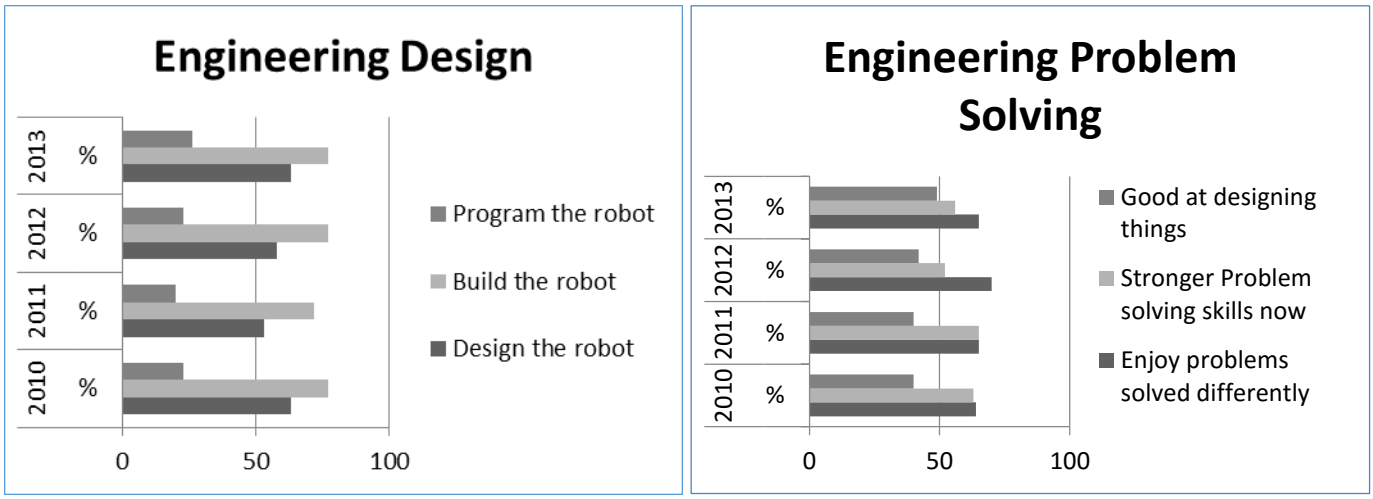
Coach/mentor focus groups and survey responses across all sample years (FLL, FTC, FRC) were positive regarding problem solving skills and agreed that students were engaged in engineering problem solving. Average participant responses (FRC four year data trends in Figure 1) echoed coach/mentor responses, indicating participants liked designing (59% strongly agree) and building the robot (75% strongly agree), but have less experience in programming the robot (23% strongly agree). Students also "strongly agreed" that they understand engineering design (63%), and many indicated they were "good at designing things" (43%).

Table 2: FIRST® impact on problem solving through design and experimental testing

N=1423	**X**	**σ_X**
a Problem-solving strategies (steps in thinking a problem through)	3.58	.90

Range: 4=increased a lot, 3=increased a little, 2=no change, 1=decreased

Figure 1: FIRST® impact on FRC participant interest in design and problem solving (4-year trends)



When examining the STEM BAS survey results, data revealed significant pre- post- differences in areas of problem solving (<.05). Participant scores increased over the course of the FIRST® program (participation for at least one season).

Table 3: High School STEM BAS pre- post- comparison: FIRST® FRC participants

N=1423	**X**	**σ_X**	*P-value < 0.050*
A. I am good at thinking about different solutions	4.00	1.00	
post_C	4.04	0.85	.030
B. I enjoy working on projects that may have more than one right answer	3.72	1.17	
post_D	4.15	1.03	.001

Range: strongly agree=5, agree=4, neutral=3, disagree=2, strongly disagree=1

Finding 3: FIRST® Positively Impacts Students' Ability to Participate on Technical Teams
ABET Student Outcome: (d) an ability to function on multidisciplinary teams

Completing requirements in FIRST® (robots, research projects) allows participants to engage and function as leaders or members on a technical team. Many of the students and coaches indicate that their experience in FIRST® does "more to develop teaming skills" than classroom projects or academic activities alone. Team coaches perceived that FIRST® facilitated a "sense of team identity or belonging" and described teamwork skills as "negotiating roles, compromise, and giving feedback." The majority of coaches (89% strongly agreed) that "teaming skills increased a lot" and that "teaming skills are outcomes of FIRST®."

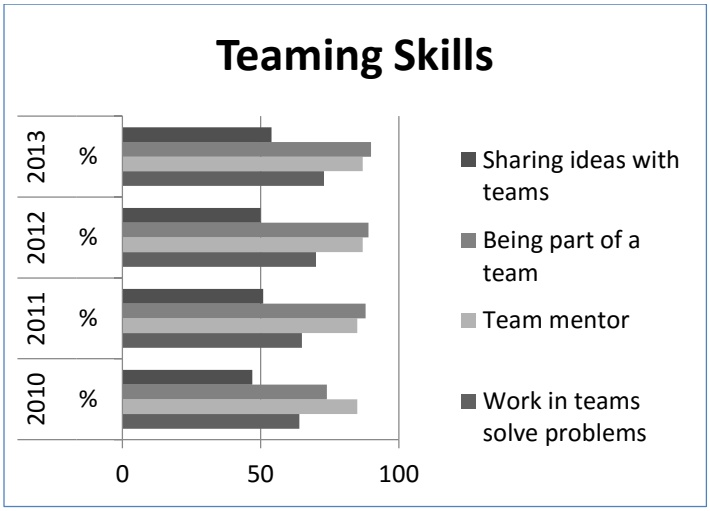
Table 4: Coach View: FIRST® impacts student leadership and teaming

N=450	**X**	**σ_X**
a. Teamwork skills (negotiating roles, compromise, giving feedback)	3.50	.67
b. Leadership skills (working with a group, running a meeting, assigning tasks, solving conflicts)	3.50	.80
c. Belief in the importance of helping others	3.42	.79

Range: 4=increased a lot; 3=increased a little; 2=no change; 1=decreased

Throughout the study, data captured the depth and breadth of experience that FIRST® participants gained in working on projects as leaders and team members to hone their teaming skills. Data indicated that the majority strongly agreed (73%) with, "I like working with other teams at the regional event" and they collaborated and shared ideas with other peers. Four-year trends revealed that they liked "being part of a team" (85% strongly agreed) and recognized that "working in a team helped solve problems" (68% strongly agreed).

Figure 2: Participant 4-year trends teaming



Finding 4: FIRST® Positively Impacts Students' Ability to Perform Research and Communicate Ideas through Writing and Oral Presentations
ABET Student Outcome: (g) an ability to communicate effectively

From a participant perspective, interest in research, writing, and presentation skills improved. Though the majority of students indicate they "didn't enjoy writing", they viewed it as a "necessary part of participating in FIRST®". Table 5 includes seven year data trends from FLL, FTC and FRC on the development of writing, research, and presentation skills.

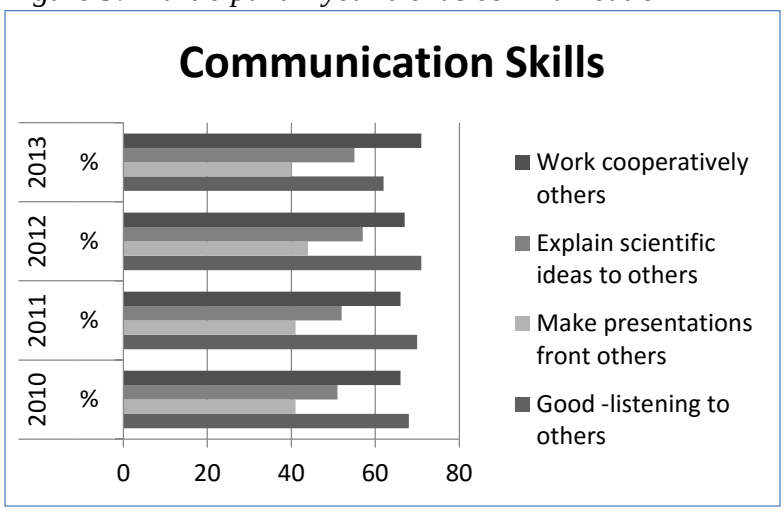
Table 5: Student Outcomes: FIRST® builds research and communication skills

N=1423	**X**	**σ_X**
l. Writing skills (writing brochures)	2.67	.89
m. Presentation skills (talking to groups, presenting)	3.42	.52
n. Research skills (using the library, Internet)	3.17	.84

Range: 4=increased a lot, 3=increased a little, 2=no change, 1=decreased

The majority of participants enjoyed communicating and sharing ideas with others. Coaches indicated participants transferred knowledge learned in their group to teams outside the group. Participants indicated they liked working cooperatively with peers they did not know, highlighted in their communication, teaming, sharing, and collaboration skills. Participants demonstrated they were good at "explaining scientific ideas to others" (54%) and effective at "making presentations in front of others" (41%).

Figure 3: Participant 4-year trends communication



Finding 5: FIRST® Participants Engage in Self-Directed Learning, Professional Development and Continuous Improvement
ABET Student Outcome: (i) recognition of need for and ability to engage in life-long learning

FIRST® allows young students and their adult mentors to participate in self-directed study. For rookie coaches, the learning curve is steep however, since FIRST® is *student directed and coach guided*, it allows for learning and professional development on multiple levels. For coaches, responses showed that the primary reason coaches chose to become involved with FIRST® lies in their personal belief they could help with getting children interested in science and technology (75% strongly agreed) and that it was a way to contribute to their community (42%).

After the experience, coaches were more likely to indicate that FIRST® had a significant impact on their own learning and professional development as they were more likely to incorporate FIRST® framework into educational activities. If coaches were educators, they were more likely to "emphasize the application of science and technology in real-world settings", "employ computers and robotics in their own classrooms", and "use student-led projects". Coaches stated that students were "building their skill set" and had an increased "competence in science, technology, and engineering" during focus groups and follow-up interviews. Coaches revealed additional respect for students' capacity to work as a team independent of adults to complete their projects.

Table 6: FIRST® impact on coaches' learning and professional development

N=450	**X**	σ_X
a. My emphasis on the application of science and technology in real world settings	3.25	.71
b. My use of computers and robotics in my classroom	3.25	.89
c. My use of student-led projects in my teaching	3.25	.46
d. My own knowledge of current science and technology	2.88	.64
e. My sense of connection to my students	3.88	.35
f. My understanding of what young people can accomplish	3.50	.93
g. My respect for students' capacity to work as a team independently	3.25	1.04
j. My own enjoyment or satisfaction in teaching	3.00	.93

Range: 4=increased a lot, 3=increased a little, 2=no change, 1=decreased

For continuous improvement, FIRST® facilitated project management skills to strengthen participants' reasoning abilities associated with planning and development of projects. Participant responses revealed a growth over time regarding getting projects done in a timely fashion, considering options, determining the best answer, and planning steps of a project ahead of time. Although students felt that they typically started their projects early, this process significantly improved throughout the FIRST® experience. Similarly, participants that considered themselves as planners when the program began, became more proficient and improved their organizational skills. When examining STEM BAS FRC surveys, individual years showed differences between pre- and post- tests and significant impact in areas of project management, time management and planning, skills that encompass teaming practices. Participants showed they improved on these areas after participating in FIRST® for at least one season.

Table 7: High School STEM BAS pre- post- comparison: FIRST® FRC participants

N=1423	**X**	**σ_X**	*P-value < 0.050*
A. I usually start my homework or projects early to get them done on time	3.61	1.22	
post_A	3.65	1.18	.001
B. I like to plan what has to be done ahead of time	3.85	1.17	
post_B	4.00	0.92	.000

Range: strongly agree=5, agree=4, neutral=3, disagree=2, strongly disagree=1

Table 8: Student Outcomes: FIRST® impacts planning skills

N=1423	**X**	**σ_X**
b. Planning skills (developing action plans, budgeting)	3.17	.72

Range: 4=increased a lot; 3=increased a little; 2=no change; 1=decreased

Coaches listed a variety of responses about team organization. The following are unedited responses and comments from coach surveys:

- Understanding that adults don't always have the answer.
- As a first year, they are learning that it takes dedication and determination. Because they are all in a gifted program they are used to things being done their way. It is not enough to be "smart", you have to put the effort in.
- Students learn from one another and start to actively listen. They attempt to do difficult, challenging things but they can attempt them together, as a team member.

Finding 6: FIRST® Positively Impacts Students' Ability to Professionally and Ethically Understand Global Issues

ABET Student Outcomes: (f) an understanding of professional and ethical responsibility; (h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context; (j) a knowledge of contemporary issues

Participants were asked about their future directions before and after FIRST®. It was evident that students became significantly more interested in solving environmental problems like global warming (FLL *Climate Connections* 2008). It is noteworthy that responses revealed that middle school students were already aware of some of the negative impacts of energy use in the world and that trend increased during participation in the FLL program. In addition, students participated in themes that encompassed "global engineering grand challenges". Each year,

FIRST® changes the mission themes and challenge to incite students to study, research, write, and present solutions to real-world issues, thereby increasing their understanding of issues in societal and global contexts.

Table 9: Student Outcomes: FIRST® impact on understanding global issues

N=1423	**X**	σ_X	*P-value < 0.050*
A. I would like to design an alternative fuel vehicle	3.46	1.43	
post_A	3.22	1.47	.002
B. I would like to help solve global warming	4.00	1.10	
post_B	4.02	1.18	.014
C. I have taken an energy audit of my school or home	2.93	1.29	
post_C	3.13	1.44	
D. I am aware of some negative impacts of energy use in the world	4.07	1.10	
post_D	4.28	0.91	

Range: strongly agree=5, agree=4, neutral=3, disagree=2, and strongly disagree=1

Discussion

FIRST® robotics offers an opportunity for students to be engaged in self-directed study and actively participate in their own learning. Providing interesting themes and technical scenarios, participants are better able to understand engineering concepts and use critical thinking strategies to solve problems. In the classroom, and highly structured environments, students are unable to fully take responsibility for their learning outcomes and decisions they make to select activities, find information and self-assess their work. Through FIRST®, the majority of teams that were researched found that learning and improvement occurred at multiple levels (students, parents, mentors, coaches). Teaming through a technical challenge empowers students and coaches to be responsive an assess information and skills that are needed for improvement.

FIRST® employs small group learning, a key strategy found in the literature for pre-college and undergraduate STEM education. Students who learn in small groups demonstrate greater academic performance, express more positive attitudes toward learning, and persist in STEM courses more than their counterparts[18]. Small group learning rather than lecture-based instruction impacts academic achievement for members of underrepresented groups and the learning-related attitudes of females[18,19]. Small group learning is facilitated by mentors but driven by peer groups in FIRST®. In addition, national engineering programs reveal that these types of mentoring activities provide positive impact through role models in applied learning projects that aid in student retention[20].

In addition to teaming skills, leaders perceived that FIRST® facilitated the "sense of team identity or belonging", an important strategy in building a sense of community for participants. Research shows that fostering a strong "learning community" aids in retention and also assists with a positive learning climate. It appears that FIRST® facilitates learning climate and social integration for participants. Literature indicates that the more integrated a student is in the academic environment, the more likely the student is to persist in STEM courses and programs. Though FIRST® is usually utilized as an after school program, several AZ teams were able to

integrate FLL, FTC and FRC into their classroom curriculum. Thereby using the framework of FIRST® to enhance classroom experiences.

Conclusion

Through seven years of data, we have shown that elements of FIRST® robotics programs mirror skills required by post-secondary institutions to maintain accreditation. Therefore, FIRST® can be used by K-12 STEM educators to prepare students for admissions and success in engineering programs. Metrics to assess these programs are necessary and can ensure alignment of critical program elements. Embedding engineering student outcomes into the assessment is necessary to ensure K-12 programs map to university engineering curricula. The researchers understand that ABET engineering student outcomes are constantly changing and voted upon by the engineering community. In 2017 it is expected that the 11 student outcomes (a – k) will be condensed into seven. With or without the changes, participation in FIRST robotics efforts clearly is aligned with ABET engineering student outcomes.

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