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# Cross-Case Analysis of Engineering Education Experiences in Inclusive STEM-Focused High Schools in the United States

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**Abstract**

In an attempt to broaden participation in STEM, a new type of high school is emerging, high schools which include a focus on engineering, have few or no academic admission criteria, and actively involve students of all levels of ability, known as Inclusive STEM High Schools (ISHSs). One aspect of successful ISHSs includes the intentional and explicit integration of engineering learning opportunities into coursework. The purpose of this paper is to report results of a systematic cross-case analysis exploring the extent of engineering learning opportunities in five exemplar ISHSs. The results are framed by the *Engineering in K-12 Education* report from which seven different topics were derived to appropriately represent the field of engineering in schools: design, identifying constraints, modeling and analysis, engineering habits of mind, systems thinking, modeling, identifying constraints, communication, and optimization,. The cross-case analysis was conducted by aggregating the information gathered through surveys, interviews, focus groups, classroom observations, and document analysis, noting similarities and differences across schools and mechanisms for the course foci. It was found in the participating ISHSs that engineering is not merely an elective; all students must take at least one engineering course to graduate, although the states in which the schools are located did not require engineering for a diploma. The most prominent topics from the recommended list found at the schools were design, engineering habits of mind, and communication, while the least prominent were modeling, analysis, and identifying constraints. Based on the results of this study, the engineering education community is encouraged to continue making engineering concepts and skills accessible to K-12 educators, who may not have prior formal training in the field of engineering or engineering education.

## Introduction

More STEM-educated professionals prepared to fill jobs in science, technology, engineering, and mathematics (STEM) will be needed around the world in the next 10 years. In 2012, there were 3,814,700 jobs in the U.S. in the computer and mathematical occupations, and these occupations were projected to have an 18% growth rate in the next ten years with approximately 1.3 million openings (U.S. Bureau of Labor Statistics, 2013). Similarly, Cedefop, the European Centre for the Development of Vocational Training (2012), predicts there will be a shortage of up to 700,000 STEM workers in Europe. This is not a new development, and reports have called for increased attention to STEM education to fill the gap (Committee on Prospering in the Global Economy of the 21st Century, 2007). One solution to the need for a greater number of well-prepared STEM professionals is to provide access to STEM education to a more diverse pool of students. By focusing efforts on increasing STEM learning opportunities for students from traditionally underrepresented groups STEM education can heed the call of the National Research Council's (2011) report entitled *Expanding Underrepresented Minority Participation: America's Science and Technology Talent at the Crossroads* in which the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine identified the development of a "strong, talented, and innovative science and technology workforce" (p. 1) as critical to our nation's future.

One solution is the diversification of the workforce. In fact, the need to be more inclusive in STEM education is seen in a report entitled *Expanding Underrepresented Minority Participation: America's Science and Technology Talent at the Crossroads* (National Research Council, 2011), the National Academy of Sciences, the

National Academy of Engineering, and the Institute of Medicine have identified the development of a "strong, talented, and innovative science and technology workforce" (p. 1) as critical to our nation's future.

Shifts in demographics show that minorities are the most rapidly growing segment in the U.S. but are greatly underrepresented when it comes to employment in STEM jobs (U.S. Bureau of Labor Statistics, 2010). However, the number of underrepresented minorities enrolling in undergraduate programs in colleges and universities in the United States is increasing at a rate that exceeds enrollment trends for white students. According to Hussar and Bailey's (2013) *NCES* report, *Projections of Education Statistics to 2021*, enrollment in postsecondary degree-granting institutions for white students is expected to increase 4% from 2010 to 2021, while enrollment of black students is expected to increase by 25%, and enrollment of Hispanic students is expected to increase by 42%. The enrollment of males in postsecondary degree-granting institutions is projected to increase 10% between 2010 and 2021, while enrollment of females in the same time span is projected to increase 18% (Hussar & Bailey, 2013). Therefore, any effort to strengthen the pool of potential STEM professionals in the United States must include a strategy for channeling talented students from underrepresented groups into the STEM pipeline.

## Engaging Students in STEM in High School

In an attempt to broaden participation in STEM education in the United States, a new type of public high school is emerging, high schools which have few or no academic admission criteria and actively involve students of all levels of ability, known as Inclusive STEM High Schools (ISHSs; National Research Council, 2011). ISHSs represent an important alternative to both traditional public schools and selective STEM high schools. The goal of ISHSs is to immerse students who may otherwise "leak out" of the STEM pipeline into a rigorous STEM education environment, while providing them the support needed to exit high school prepared to enroll in STEM college majors, and ultimately to enter STEM careers (LaForce, et al., 2016; Means, Confrey, House, & Bhanot, 2008; Peters-Burton, Behrend, Lynch, & Means, 2014; Scott, 2009). ISHSs enroll students from a variety of backgrounds, and these students may not initially be ready to embark on rigorous STEM coursework in ninth grade. For example, students who enroll in ISHSs may have below-grade level experiences in mathematics or may be below grade level in their reading performance. Therefore, ISHSs must provide supports for students who may not be as prepared as the students traditionally found enrolling in selective schools. If the U.S. is truly interested in rebuilding the STEM pipeline, then increased enrollment in these subject areas is needed, particularly before the undergraduate experience. More K-12 schools will need to bolster their STEM curricula, and knowledge of the types of supports that transform struggling students into successful students is imperative for creating schools that will be equipped with informed goals.

Data from the 2011 *Trends in International Mathematics and Science Study* (TIMSS) report indicates that, at grade 4, Black and Hispanic students in the United States scored below the national average in mathematics, and that the average score for females in mathematics was 9 points below that for males. While a gap in mathematics performance was not evident between males and females in grade 8, the underperformance of Black and Hispanic students in mathematics persisted. The TIMMS 2011 data also indicated that students attending higher-poverty schools often displayed lower mathematics achievement. Based on the need to increase participation of students from traditionally underrepresented groups in STEM education, and the academic challenges that some of these students face, increased attention to STEM instruction and activities provided in ISHSs is timely.

As a response to the need to repair the STEM pipeline at the K-12 levels, the National Academies in the United States (National Research Council, 2011) identified five "ingredients for success in STEM" (p. 240), including:

- acquisition of [STEM] knowledge, skills, and habits of mind
- opportunities to put [STEM knowledge, skills, and habits of mind] into practice
- a developing sense of competence and progress
- motivation to be in, a sense of belonging to, or self-identification with, the [STEM] field
- information about stages, requirements, and opportunities [in STEM education].

The nature of this list highlights the importance of providing students with exposure to a rigorous and supportive STEM curriculum at the high school level. Evidence suggests that students who participate in rigorous STEM coursework, taught by experienced and demanding teachers, are more likely to be prepared for success in STEM fields, and that this trend holds regardless of the race/ethnicity or socioeconomic status of the student (Lleras, 2008). Therefore, researchers should carefully consider the state of teacher education and STEM curriculum and how that curriculum is implemented by teachers in schools that serve groups typically underrepresented in STEM such as ISHSs. Further, there is a need to closely examine the approaches for implementation of engineering in high school classrooms, since it is the least emphasized and has the least representation of expertise of the STEM subjects at this level. The ways in which the subject of engineering is offered in an already crowded curriculum, either in an integrated or stand-alone method, has vast implications for the effective inclusion of all STEM subjects at the high school level.

## Examining Engineering Education at the High Schools

Engineering education has been introduced into K-12 classrooms in a piecemeal fashion, and the role of engineering in elementary and secondary education across the United States remains somewhat unclear. Even with the adoption of *Next Generation Science Standards,* which includes engineering practices and engineering disciplinary concepts woven into the science standards, there is still argument among educators about the role of engineering within science (Bybee, 2010). The movement towards integrated STEM education proposes a position for the topic of engineering in the core subjects; however the "E" in STEM does not share the same prominence as the other topics (Bybee, 2010; Carr, Lynch, & Strobel, 2012).

With regards to the design and implementation of STEM curricula, it is not clear that engineering is being addressed consistently and effectively (Bybee, 2010; Carr, Bennett, & Strobel, 2012). Some challenges to implementing effective engineering education include insufficient engineering content knowledge of teachers, lack of access to professional development, lack of consensus on how best to assess engineering learning, and difficulty faced by teachers in selecting appropriate engineering design challenges for students to engage in (Bailey & Szabo, 2007; Brophy, Klein, Portsmore, & Rogers, 2008; Davis, Gentili, Trevisan, & Calkins, 2002; Denson & Lammi, 2014; Householder, 2011). More guidance on the effective integration of engineering in STEM curricula and instruction is needed.

Past research has provided some evidence on how to address challenges involved in implementing effective engineering education, specifically the challenges of selecting appropriate engineering design challenges and assessing the design process. Householder and Hailey (2012) used ill-structured problems, which are "problems with vague goals and unclear problem-solving paths" as effective engineering design challenges (Byun, Lee, & Cerreto, 2014; p. 230). Hynes et al. (2011) suggest that high school students should be presented with open-ended problems that require students to identify the constraints, conduct a needs analysis, and identify goals in the face of multiple solution options. In addition to being ill-structured or open-ended, many researchers agree that engineering design challenges should be connected to real-world problems (Apedoe, Reynolds, Ellefson, & Schunn 2008; Schunn, 2011). Some evidence also suggests that allowing students to choose their own challenges, and perhaps include aspects of cultural relevancy in design projects, may increase the efficacy of the learning experiences (Eisenkraft, 2011; Schunn, 2011). Based on the increased attention to the development of engineering skills and knowledge in high school STEM education and the need for rigorous engineering concepts in the curriculum, the documentation of the design and implementation of engineering curriculum in ISHSs that already productively engage in integrated STEM education and that are serving underrepresented students in STEM is necessary for a cohesive effort to improve engineering education (Valtorta & Berland, 2015).

## Conceptual Framework for the Present Study

Given that there is a need for STEM professionals in the future and the lack of diversity reflected in the upcoming STEM workforce, a close examination of the STEM pipeline is needed. This examination is crucial for the "E" in STEM, as engineering education has not been fully established at the secondary education level. The conceptual framework for this study focuses on the high school portion of the STEM pipeline by examining critical components of STEM schools that serve a diverse student population and that are successfully supporting all students.

One framework that could be used to evaluate the state of engineering education in ISHSs is proposed in the 2009 *Engineering in K-12 Education: Understanding the Status and Improving the Prospects* report by the National Academy of Engineering and National Research Council. The purpose of the NAE and NRC report was to determine the scope and nature of efforts to teach engineering to students from kindergarten to twelfth grade. The *Engineering in K-12 Education* report has promise as a guide to clarify and prioritize the teaching of engineering topics in a systematic and rigorous way. In doing so, the report made three recommendations:

1. K–12 engineering education should emphasize engineering design.
2. K–12 engineering education should incorporate important and developmentally appropriate mathematics, science, and technology knowledge and skills.
3. K–12 engineering education should promote engineering habits of mind.

The critical components found in STEM high schools can be examined at two levels: design and implementation of engineering curricula. These two levels act within the environment of the school system and the context of the community. The design level of the framework sought to find program goals, missions, visions, governance, academic structure, curriculum, and intentions for outside partnerships. The implementation level of the framework included the enactment of administrative policy, instruction, student relations, and external partnership activities. Through the design and implementation lenses, we sought to explain the strategic planning of the schools as well as how they were enacted.

The engineering learning opportunities afforded students in five exemplar ISHSs were examined regarding two broad topics (knowledge and skills; habits of mind) which were extracted from the National Research Council's (2011) first two "ingredients for success in STEM" (p. 240): the acquisition and application of STEM knowledge, skills, and habits of mind. Principle 1 from The *Engineering in K-12 Education* report (NAE & NRC, 2009) identified design as the preeminent skill that should be emphasized in engineering education, and that knowledge of the design process works as a stimulus for gaining knowledge of systems thinking, modeling, and analysis. It should also be noted that the *Engineering in K-12 Education* report emphasized constraints as a defining characteristic of engineering, describing engineering as "design under constraint" (NAE & NRC, 2009, p. 17). Several specific constraints, including the laws of nature, time, money, available materials, ergonomics, regulations, manufacturability, and repairability, were identified as important factors impacting the engineering problem solving process. Principle 3 from The *Engineering in K-12 Education* report highlighted the need to promote engineering habits of mind, including: systems thinking, creativity, optimism, collaboration, communication, and attention to ethical considerations.

In alignment with the recommendations of the NRC (2011) and the Engineering in K-12 Education report (NAE & NRC, 2009), the current study examines data collected as part of a larger, multiple case study of exemplar ISHSs across seven engineering topics that were specifically observable at the classroom level, and that represent recommended topics for engineering education in K-12 schools:

- Design (Engineering Skills and Knowledge)
    - Identifying constraints
    - Modeling & Analysis
- Engineering Habits of Mind
    - Systems thinking
    - Communication
    - Optimization

## Design

Although design is a common word that has many different contexts in everyday life, in engineering it is one of the most agreed-upon topics, encompassing the iterative processes of design and redesign. Of course, this does not refer to tinkering without a conceptual foundation, but refers to the cyclical process of identifying the problem; specifying requirements of the solution; decomposing the system; generating a solution; testing the solution; sketching and visualizing the solution; modeling and analyzing the solution; evaluating alternative solutions, as necessary; and optimizing the final design (NAE & NRC, 2009).

### *Identifying Constraints*

Constraints help to frame problems in engineering by identifying the limitations in the design process. Within the design process, engineering not only addresses human needs and the goals of the project, but must consider constraints or limiting factors in order to have a viable solution. Students who are learning to become engineers or who are learning to think like engineers must understand the process of identifying constraints. However, this is a difficult task because although some constraints are concrete, others are more abstract and may not be in the immediate purview of student experience. The NAE report found that in most curricular efforts in engineering education at K-12, constraints were identified to students as mainly resources such as time, money, and materials.

### *Modeling and Analysis*

Modeling and analysis is useful to the engineering design process because it is a way to understand what may happen during a process to a product. Models can exist as representational models, such as drawings or physical three dimensional depictions. From representational models, mathematical models can be derived based on potential solutions. Mathematical models add a factor of precision in predictive analysis of the outcome of the product or process.

## Engineering Habits of Mind

According to the NAE and NRC report, engineering habits of mind include "(1) systems thinking, (2) creativity, (3) optimism, (4) collaboration, (5) communication, and (6) attention to ethical considerations" (2009, p. 152).

### *Systems Thinking*

The NAE report defined systems as any organized and interdependent collection of parts, processes, and people designed to fulfill one or more functions. The concept of the sum being more than its parts describes the foundation of systems thinking. Students who can use systems thinking can recognized interconnections that may not be tangible, and also appreciate that systems connections may cause unanticipated results.

### *Optimization*

The NAE report defines optimization as finding the best solution to a problem that is technical in nature by balancing specifications and constraints, which are often competing factors. (2009, p. 43). Typically there is not one solution for optimization of a technical problem. Rather, there may be decisions that are better in different ways, such as choosing an expensive material for its strength. Optimization is a negotiation among the components of a solution, leading to a solution that best fits the specifications and constraints while maintaining the most number of desirable components.

### *Communication*

The NAE report reminds educators that successful engineers need not only analytical skills, but communication and skills as well. Engineers must be able to collaborate, understand the needs of a client, and explain design solutions to others. With these seven topics in mind, we employ our conceptual framework to examine the design and implementation of engineering learning at STEM schools that serve diverse student populations and support these students successfully. We sought to find any design components related to engineering teaching and learning, as well as observing the implementation of engineering teaching and learning at the inclusive STEM high schools. The list of topics in our conceptual framework does not include all of the recommendations from the *Engineering in K-12 Education*. It excludes some of the habits of mind such as creativity and attention to ethical consideration as well as a deep look at engineering content. This study was derived from a larger study that developed cases and logic models at the school level. Because the overall study was examining the design and structural components of a school as a whole, we were unable to obtain student level data addressing some of the habits of mind in engineering. However, we were able to capture engineering curricular and instructional components that addressed in these new types of schools, which can inform schools attempting to become ISHSs.

The purpose of this paper is to report results of a cross-case analysis exploring the extent of engineering learning opportunities in five exemplar Inclusive STEM High Schools found in the United States; schools that include all students regardless of academic background. Unlike the selective STEM schools, inclusive STEM schools actively seek diversity in their school population by recruiting and supporting students from groups typically underrepresented in STEM. Additionally, the *Engineering in K-12 Education* report calls for features of engineering education in schools that excite and interest students from typically underrepresented groups in STEM. The results of this study will inform the engineering education community about how exemplary schools, particularly those who serve diverse populations, are responding to the calls for reform by the National Academy of Engineering. This study will attempt to describe topics that are productive for students typically underrepresented in STEM can give insight into the ways these schools are creating successful experiences for all students in the field of engineering. This study will also attempt to identify areas of concern so that the engineering education community may support these efforts as new STEM schools continue to surface.

For this purpose, the research questions that drove this study were

> (a) In what ways are engineering learning opportunities present across inclusive STEM high schools serving students that are equally or more diverse than their community?
>
> (b) How do the distinguishing features of engineering education found in the schools compare with engineering topics identified based on the recommendations made in the 2009 *Engineering in K-12 Education* report?

## Method

This article is derived from a larger study titled, *Multiple Instrumental Case Study of Inclusive STEM-focused High Schools: Opportunity Structures for Preparation and Inspiration* (Lynch et al., 2017). The purpose of this section was to describe the procedures for the larger study in order to validate and make transparent the data that was drawn for the engineering education study. The larger study, a multiple instrumental case study research design (Yin, 2008), sought to document the design, implementation, and context in school-level case studies of eight expert-recommended ISHSs, driven by a conceptual framework of ten Critical Components with consideration of other emerging Components from the empirical work:

1. STEM-focused curriculum
2. Reform-based instruction
3. Integrated, innovative technology use
4. Blended formal/informal learning beyond the typical school day, week, or year
5. Real-world stem partnerships
6. Early college-level coursework
7. Well-prepared stem teaching staff
8. Inclusive STEM mission
9. Administrative structure
10. Supports for underrepresented students

### Participants

Each school was selected as an exemplary case of a school that was considered successful by a range of stakeholders, regardless of the background of the students. The criteria for inclusion were that schools needed to have a STEM-oriented mission, the school should have no academic barriers for admission, and that the students at the school outperform peer schools on state content tests. These case studies are not meant to be generalizable; however, they can be used as models from which to transfer understanding of exemplary practices (Yin, 2008). All schools involved in this study had no academic admissions standards, and accept all students using weighted lottery systems, such as separate lotteries for location or for sibling priority. The schools admitted students representing a wide range of academic readiness, and thus were good examples from which to build engineering education for all students. Because the schools did not have prior academic performance as an entry criteria, they had student demographic distributions that were more diverse than the surrounding community. The schools were selected because they actively sought out students who were from groups traditionally underrepresented in STEM fields.

The following section summarizes the demographics and school characteristics of each of the five ISHSs (see Table 1) that offered stand-alone engineering courses and explains how they offered the engineering opportunities in the school context (see Table 2). Permission was obtained for each of the five ISHSs to use actual school names in publications. The five schools are Manor New Technology High School, Wayne School of Engineering, Gary and Jerri-Ann Jacobs High Tech High, Denver School of Science and Technology:

Stapleton, and Metro Early College High School. Because this study was interested in the engineering classrooms of schools that served students from groups traditionally underrepresented in STEM, we include their demographic distributions as evidence of their diverse student populations.

Table 1. Profiles of inclusive STEM high school

| School | Affiliations | Diversity |
|---|---|---|
| Manor New Technology High School (MNTH)<br>Austin, TX<br>approx. 350 students<br>Grades: 9-12<br>First year opened: 2007 | T-STEM network of academies | 19% African American<br>2% Asian/Pacific Islander/American Indian<br>44% Hispanic<br>32% White<br>2% Two or more races<br>52% Economically disadvantaged |
| Wayne School of Engineering (WSE)<br>Goldsboro, NC<br>approx. 325 students<br>Grades: 9-12<br>First year opened: 2007 | North Carolina New Schools Project<br>Wayne Community College (Mechanical Engineering Department) | 31% African American<br>7% Hispanic<br>47% White<br>15% Two or more races<br>44% Economically disadvantaged |
| Gary and Jerri-Ann Jacobs High Tech High (HTH)<br>San Diego, CA<br>approx. 575 students<br>Grades: 9-12<br>First year opened: 1998 | High Tech High Network | 11% African American<br>41% Hispanic<br>33% White<br>15% Asian/Pacific Islander/American Indian<br><1% Two or more races<br>44% Economically disadvantaged |
| Denver School of Science and Technology: Stapleton (DSST)<br>Denver, CO<br>approx. 500 students<br>Grades: 9-12<br>First year opened: 2004 | Denver School of Science and Technology Network | 26% African American<br>4% Asian/Pacific Islander/American Indian<br>35% Hispanic<br>28% White<br>8% Two or more races<br>45% Economically disadvantaged |
| Metro Early College High School (Metro)<br>Columbus, OH<br>approx. 400 students<br>Grades: 9-12<br>First year opened: 2006 | The Ohio State University<br>Battelle Memorial Institute<br>Coalition of Essential Schools | 28% African American<br>8% Asian/Pacific Islander/American Indian<br>4% Hispanic<br>54% White<br>6% Two or more races<br>29% Economically disadvantaged |

## Methods for School-Level Case Study

### Data Collection for the Overall School-level Study

The design of the larger study focused on the collection of a variety of data so that conjectures about the schools could be triangulated and confirmed through multiple sources (Maxwell, 2005). Data were collected before and during a site visit to each school by a six-person research team. Data collected before the school visit included a search of website information and requests for materials available to students and parents such as admission materials, school handbooks, curriculum guides, scope, and sequence documents. Approximately three hours of interviews with the principal or a designated site coordinator were conducted prior to the visit in order to focus the observational data collected during the site visit. Data collected for the overall study during the site visit included interviews informed by the prior principal interview with industry partners, administrators, counselors, teachers, parents, students, and alumni. Observational data were collected with classroom observations using the Lesson Flow (Lynch, Szesze, Pyke, & Kuipers, 2007), a tool to capture classroom characteristics and freely written field notes of classroom activities during observation.

### Data Analysis

Figure 1 illustrates the process of analysis for the qualitative case studies. Interviews were transcribed and all data sources were coded with the ten Critical Components as a priori codes, with allowances for emerging codes. At least two researchers independently coded each unit of data and compared codes until consensus was reached. Codes were input into NVivo 10 (Richards, 2012), and reports for each Critical Component and emerging code were run. Across the eight schools, four additional Critical Components emerged:

1. Dynamic assessment systems for continuous improvement
2. Innovative and responsive leadership
3. Positive School Community and Culture of High Expectations for All
4. Agency and Choice

Each researcher wrote at least one of the Critical Component sections of the case study and the lead writer then composed the entire case study for coherence. All researchers edited the case study and the final draft was sent to the participating school for member checking (Maxwell, 2005). The finalized case studies can be found at this website *https://ospri.research.gwu.edu/*

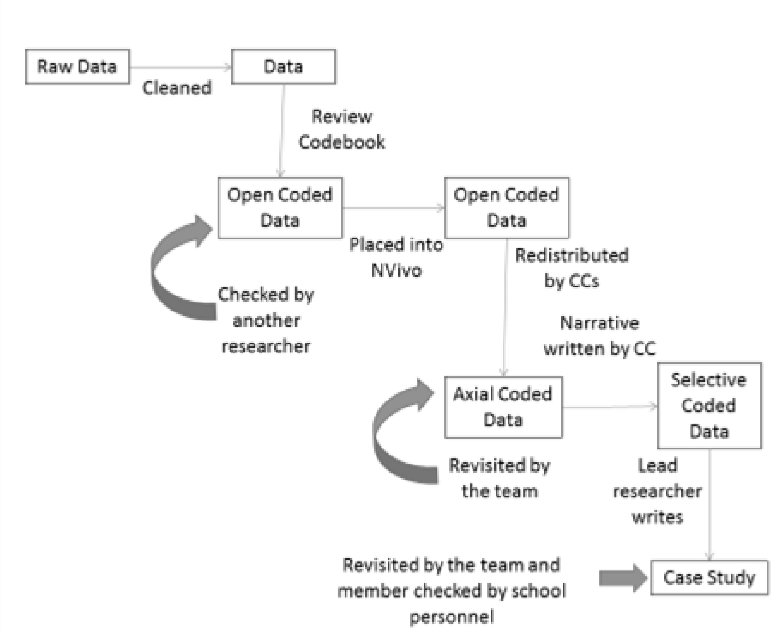


Figure 1. Process of analysis for each case study

## Methodology for Cross-Case Analysis of Engineering Education Experiences

After the single case studies of the schools were completed, the research team considered variables that were of interest across the ISHSs. The team considered smaller variables that would inform STEM education literature through cross-case analysis. The cross-case variables included curriculum and instruction, leadership, teacher preparation, and engineering education. The following describes the methodology for the engineering education cross-case analysis.

**Data Sources**

Data sources for this study included the finalized case studies which were approximately 80 pages of single spaced text detailing the context of the school and the design and implementation of all of the critical components found at the ISHS. The finalized case studies were considered data because they were an overall interpretation of the schools that matched school personnel's perceptions. However this study takes a deeper look at engineering education at the school level, so additional data sources were used from the raw data including interview transcripts from teachers of engineering, and Lesson Flow field notes from the engineering courses that were observed.

**Data Analysis**

To answer the research questions posed for this study, researchers created a matrix of the seven different topics that were derived from the recommendations by the National Academies of Engineering (NAE) report: design, systems thinking, modeling, identifying constraints and optimization, analysis, communication, and engineering habits of mind. Of the eight schools in the larger study, only five had stand-alone engineering courses in their curriculum, and these schools were entered into the matrix. Researchers then independently coded the interviews, and Lesson Flow field notes for each of the seven engineering topics derived from the NAE report. The codes were compared and had 93% overlap of agreement. The remaining 7% of different codes were discussed until consensus was reached.

Once the matrix was populated for all five schools, the cross-case analysis was conducted by following recommendations for a Type-1 cross-case analysis by Stake (2005), as illustrated in Figure 2. This process is accomplished in five stages: (a) developing themes across cases by aggregating the information across instructional topics, (b) summarizing cases including key contexts, situational constraints, and uniqueness among other cases, (c) rating expected utility of each case for each theme, (d) rating theme-based assertions per case for importance, and (e) refining assertions, and noting similarities and differences, across schools and mechanisms for the course foci. School demographics and characteristics from the larger case studies have been included to provide a context for the results.

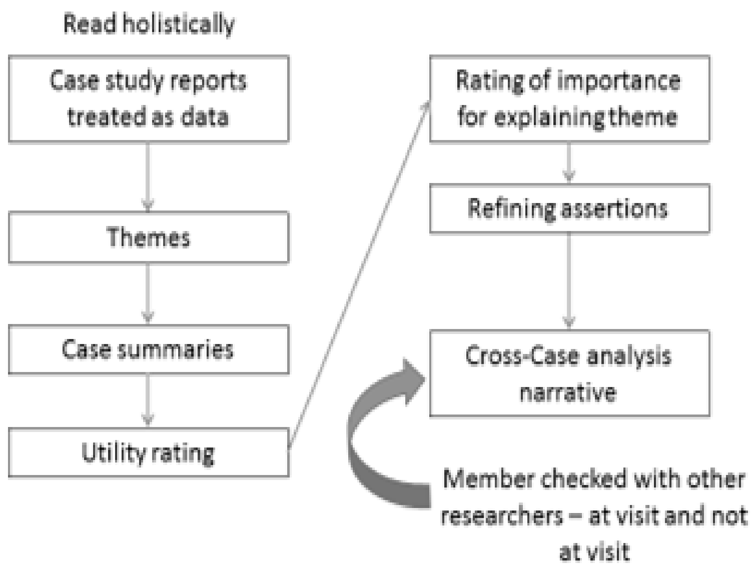


Figure 2. Process of analysis for cross-case narrative

## Results and Discussion

In this section, background from each of the Inclusive STEM High Schools will be presented to answer research question one, how each school situated engineering education opportunities. Then research question two, how the exemplar schools addressed each recommendation from the NAE report, will be answered via cross-case analysis organized by topic recommended from the NAE report.

### School Engineering Education Opportunities

To answer the first research question, "In what ways were engineering learning opportunities present across inclusive STEM high schools serving students that are equally or more diverse than their community?," we examined the curriculum in each school, specifically selected for their diversity of school population, noting what engineering courses were required and which engineering electives might be offered. We also examined the source of curriculum for the coursework. Note that acronyms for the schools are consistent with the acronyms used in the larger OSPrI study (https://ospri.research.gwu.edu/).

Manor New Technology High School (MNTH) is a public school serving roughly 350 students in grades 9 through 12 near Austin, Texas. Student demographic makeup is 19% African American, 44% Hispanic, 32% White, 2% Asian/Pacific Islander/American Indian, and 2% two or more races. Fifty-two percent of the students are considered economically disadvantaged. MNTH opened in 2007 and is part of the T-STEM network of academies. MNTH has been in the national spotlight as an Inclusive STEM High School for at least five years. They have been featured as a successful model school in National Research Council Reports (National Research Council, 2011; 2014), and President Obama selected the school to present his speech launching initiatives for new STEM schools (The White House, 2013). MNTH offers three engineering courses, two are required and one is an elective. The required courses are a sequence of Introduction to Engineering followed by Principles of Engineering and the elective is Digital Electronics. The engineering courses are structured from the Project Lead the Way (PLTW) curriculum, but are modified to fit the Problem-Based Learning pedagogy that is pervasive in the school. The teachers all have PLTW professional development experience. The school also has a thriving Robotics Club, and is considering offering another elective to support the activities of this club (Lynch et al., 2013).

Wayne School of Engineering (WSE) is a public high school serving approximately 325 students in grades 9 through 12 in a rural school district in eastern North Carolina. Student demographic makeup is 47% White, 31% African American, 7% Hispanic, and 15% two or more races, with 44% classified as economically disadvantaged. WSE started with a ninth grade class in 2007 and has expanded one class per year, graduating its first senior class in 2012. WSE is one of the networked STEM schools connected to industry and institutions of higher education in the North Carolina New Schools Project. WSE has limited resources but has capitalized on its relationship with the Mechanical Engineering Department at Wayne Community College, from which instructors come to the high school to teach age-appropriate AutoCAD and other elective courses. At WSE there are five required courses, Engineering the Future, Applications of Science, Drafting Engineering I, Drafting Engineering II, and Drafting Engineering III which lead to a variety of electives that WSE students can take at Wayne Community College, including Computer-Aided Manufacturing and AutoCAD III. The two introductory courses were designed by WSE faculty. All three Drafting Engineering courses are taught at WSE by Wayne Community College instructors and students earn both high school and college credit for successful course completion. The intention of having Community College instructors come to the school is to forge a mentoring relationship so that students will consider pursing an engineering diploma at Wayne Community College (Peters-Burton et al., 2013).

Gary and Jerri-Ann Jacobs High Tech High (HTH) is a public charter high school, located in San Diego, California, and is part of the High Tech High Network, founded in 1998 by Larry Rosenstock and colleagues. The HTH Network services at total of about 4,500 elementary, middle, and high school students in its eleven charter schools, and HTH itself enrolls approximately 575 students in grades 9 through 12.The demographic makeup of HTH is 41% Hispanic, 33% White, 15% Asian/Pacific Islander/Native American, and 11% African American, with 44% being socioeconomically disadvantaged. The pervasive school premise was "production not consumption" and all courses except for mathematics were integrated across content areas. HTH requires one year of engineering to graduate, and this course is typically integrated with biology or chemistry, depending on the team of teachers. The engineering teacher has PLTW training and has training through the EPICS program at Purdue University. Like MNTH, HTH is focused on Project Based Learning throughout the curriculum (Spillane et al., 2013).

Denver School of Science and Technology: Stapleton (DSST) was the first high school established by the Denver School of Science and Technology Network under a public charter to Denver Public Schools in Colorado in 2004. The DSST Network includes seven different middle and high schools, and each school in the network has a different focus; DSST: Stapleton's focus was engineering. DSST: Stapleton services approximately 500 students from in and around the Stapleton neighborhood of Denver in grades 9 through 12. Student demographic makeup at DSST was 35% Hispanic, 28% White, 26% African American, 8% other or multiple races, and 4% Asian/Pacific Islander/Native American. Forty-five percent of students were eligible for the Free and Reduced Lunch Program. DSST had one required 9$^{th}$ grade Creative Engineering course and one Advanced Creative Engineering elective offered in conjunction with Advanced Physics during twelfth grade. DSST also had one Computer Science elective offered at the 9$^{th}$ grade. The personnel at DSST felt that the best place to create engineers was in four-year institutions of higher education, and that their role as high school teachers was to ensure students were academically prepared to flourish in these types of programs by expecting academic rigor (Spillane et al., 2013).

Metro Early College High School (Metro) is a public high school serving approximately 400 students in grades 9 through 12 and is located on the campus of The Ohio State University's (OSU) in Columbus, Ohio. Metro, a product of the partnership between OSU, Battelle Memorial Institute, and the Coalition of Essential Schools, opened in 2006 and graduated its first senior class in 2010. Metro's demographic makeup consists of 54% White, 28% African American, 8% Asian, 6% two or more races, and 4% Hispanic, with 29% of the student body being classified as economically disadvantaged. Metro had one required engineering class, a choice of either Introduction to Engineering Design or Principles of Engineering, which could also be taken as an elective. Both courses were taught using the PLTW curriculum and Metro teachers received PLTW training and certification. Students at Metro also had the opportunity to take college-level engineering classes through its partnership at OSU. Additionally, engineering was experienced in the junior and senior years, when the students participated in Learning Centers that offered integrated STEM themes such as Biomedical Engineering and Design (Han, Lynch, Ross, & House, 2014).

Table 2. Engineering course offerings

| Abbreviated School Name | School Name | Engineering course offerings |
|---|---|---|
| MNTH | Manor New Technology High School | Introduction to Engineering (1st in sequence; required) |
| | | Principles of Engineering (2nd in sequence; required) |
| | | Digital Electronics (elective) |
| WSE | Wayne School of Engineering | Engineering the Future (required) |
| | | Applications of Science (required) |
| | | Drafting Engineering I (required) |
| | | Drafting Engineering II (required) |
| | | Drafting Engineering III (required) |
| | | Computer-Aided Manufacturing (elective) |
| | | AutoCAD III (elective) |
| | | Variety of other electives |
| HTH | Gary and Jerri-Ann Jacobs High Tech High | One year of engineering typically integrated with biology or chemistry (required) |
| DSST | Denver School of Science and Technology: Stapleton | Creative Engineering (required; 9th grade) |
| | | Advanced Creative Engineering (elective) |
| Metro | Metro Early College High School | Introduction to Engineering Design (required or elective) |
| | | Principles of Engineering (required or elective) |
| | | college-level engineering classes at OSU (elective) |

All of the schools studied had at least one engineering course required for all students. This was typically offered at the freshman level, with more advanced engineering courses offered in later grades as electives. The curriculum for the schools was taught from the PLTW curriculum or created by PLTW-trained teachers who wrote engineering curriculum.

The following section includes a pair of classroom vignettes, presented to paint a more detailed picture of classroom experiences. The vignettes reflect data from the field notes taken on the Lesson Flow tool. Vignettes from an integrated Engineering/Biology course at HTH and an Introduction to Engineering and Design course at Metro are presented. Because the overall study was a school level study, the research design did not target all of the engineering courses that were offered at the five schools. Although WSE was an engineering-centric school, the engineering courses that were observed at WSE were isometric drawing courses and were not suitable for a vignette.

*Gary and Jerri-Ann Jacobs High Tech High (*HTH): *Integrated Engineering and Biology Class*

As soon as students entered the classroom, they all got in their groups and went to work on their projects. The classroom had a very large "garage door" that could open so that students could work on constructing their projects outside. There were several computers placed throughout the classroom, with about one computer for every two students. The classroom was also used to store the students' projects.

As students worked on constructing their exhibits for the showcase the following week, the teacher walked around and assisted students as they needed help. Some of the students needed extra materials, which the teacher planned on obtaining from a wood supply store later in the day. Work on the exhibition project was being done in conjunction with the students' biology class.

Students first began this project in their biology class where they picked a topic they wanted to explore (e.g., genetic engineering). Once the students picked their topics, they were put into groups with other students with similar topics. In biology class they learned about the science of their topic, while in their engineering class they created a physical representation of their topic. It seemed that the students knew what they needed to complete for their upcoming showcase, and the teacher assisted students as they had questions.

Student displays were mostly complete and resembled the high quality caliber of what you might see at a public museum. One student created a display with black and white light to show bioluminescent bacteria. Two students walked to their Biology teacher's classroom to get a brighter black light that would allow their bacteria to glow more brightly. The students initiated a discussion with their teacher about some specific materials they needed for their project. They had already researched the needed materials ahead of time online, but were worried about the cost. Their teacher said she was willing to purchase the materials for the students, but she also said she was afraid the materials wouldn't arrive in time for the showcase the following week. The students decided to order the equipment with the help of a teacher from another classroom and returned to the engineering class to continue with the display construction of their luminescent bacteria. The class ended with a student discussion of what had been accomplished and what still needed to be done to complete the projects.

*Metro: Introduction to Engineering and Design*

The class started at 12:55 pm, and the 30 students had taken their seats throughout the classroom, many talking quietly with a classmate before the teacher began class. The teacher got everyone's attention from the front of the class and passed out a packet of AutoCAD diagrams. The diagrams were sample engineering schematics for three-dimensional figures made of varying numbers of cubic components; the students' task was to examine each schematic and determine any errors in how the dimensions of each one were marked off for production purposes. The students were currently working on a project where they were designing their own wooden cubic puzzles, and this opening activity was meant to help them avoid these types of errors when drafting their own schematics. The teacher split the classroom down the middle and directed each student to pair up with someone from the opposite side of the room to work on these problems together – this way, the students were collaborating with a classmate that they perhaps had not worked with often. There was some good-natured grumbling as the students moved and paired up with their new partners, but everyone found a partner quickly and active conversations began comfortably and without delay.

While the students worked through the packet, the teacher walked from group to group, listening to their conversations and noting their comments. After several minutes, the teacher asked those students who were done to raise their hands. Most of the class did so. The teacher then directed the students to pair up with a different classmate to compare and discuss their answers. While the new pairs were sharing their work, the teacher turned on his computer and projector and put the first problem up on the screen. The class as a whole then went through the problems, with the teacher asking students to volunteer their thoughts on where the errors were on the schematics and why those errors would be problematic during the production of the actual figure. When a student gave an answer that actually was not an error, the teacher followed up with that student with questions that helped him or her see why it was not wrong. Throughout the activity, students were using technical terminology to explain and describe the engineering issues captured in the schematics.

After they reviewed the schematics, the teacher directed the students' attention to the assignment board to review the work that was due later that week: students were responsible for turning in their schematics and drawings produced using the Autodesk Inventor software (3D computer-aided design and mechanical design software) that each had on their laptop. He also pointed out the resources that were available to them online through the school's learning management system. Additionally, the teacher called attention to one of the students in the class who was an expert with the Inventor application; this student had been using the software on his own to design a violin, and the teacher encouraged students to ask him questions when needed.

The remaining time left in the class period was given for the students to work on their projects – designing and building a model of the wooden puzzle using small cubes. Before they broke into working groups, the teacher directed the students to sit on one side of the room if they were comfortable with their plans and next steps. Those who wanted extra guidance were to sit on the opposite side of the room. Eight students took him up on his offer and received an extra workshop session as he walked them through the Autodesk Inventor program interface and the design process. The other students broke off individually or in small groups to work on their projects. With the time remaining in class, the teacher talked with various groups of students, including those who needed extra help with the Autodesk software and those who had individual questions on their design process. The work continued until 2:30 pm when the class ended.

## Alignment of Engineering Education Opportunities with the NAE Report

In addition to examining the depth and breadth of engineering education courses in exemplary ISHSs, it is of interest to see in what ways these engineering learning opportunities address the recommendations of the 2009 NAE and NRC report, *Engineering in K-12 Education.* All of the schools were operating during the time of the release of this report, and it was assumed that being cutting-edge schools involved in the early stages of K-12 engineering education, they would adapt coursework to align with the recommendations. The following results (summarized in Table 3 and Table 4) report the ways the ISHSs incorporated each of the curriculum recommendations from the NAE and NRC report. Table 3 summarizes the overall categories found with each recommendation.

### *Design*

To accomplish the engineering design process, it is necessary to know basic science and mathematics concepts, domain-specific concepts, and engineering concepts. The required engineering courses at each of the schools studied centered on the principle of design. Design was so central to instruction at the ISHSs that the teachers used this approach to plan lessons and to troubleshoot student issues. At each school, we observed teachers peer reviewing each other's instructional design during faculty meetings, department meetings, and in one-on-one settings. Students were given a challenge and time to accomplish the goal, as opposed to the approach in traditional schools where teachers explain information step-by-step.

At the schools embracing problem-based learning, such as MNTH, HTH, and DSST, in the junior and senior years, design was central to student learning because students needed to work collaboratively to design models, prototypes, or solutions around the problem scenarios they were given bi-weekly. For example, at MNTH a chemistry teacher taught Gay-Lussac and Boyles' Gas Laws with a dome project requiring students to design a canister that can carry a gas to the moon or a planet that they imagine they will inhabit (Lynch et al., 2013). Because the idea of design was pervasive throughout MNTH, the principal saw engineering as an opportunity to give students opportunities to apply mathematics and science concepts:

> We score low on testing in math … so the question is what do I need to teach in order to improve science and math understanding … there is a joint effort to cover the content…Geometry, for example, is used in the roller coaster project in determining the shapes of the coaster, and engineering would work with the structures needed to support these shapes.… Engineering represents the application of math and science. All are interconnected. Previous math and science content is reinforced with engineering content whenever possible.

Table 3. Evidence of engineering topics in ISHSs

| Engineering topic | How topic was addressed in ISHSs |
|---|---|
| Design | • Required engineering courses centered on design<br>• Teachers used design to plan lessons and troubleshoot student issues<br>• Students worked collaboratively to design models, prototypes, or solutions around the problem scenarios they were given<br>• Internships provided real-world experiences with design<br>• Extra-curricular activities (ex. Robotics club) revolved around concept of design |
| Identifying Constraints | • Coursework went beyond narrow conceptualization of constraints (time, money and materials) to help students identify less tangible constraints (laws of nature, repairability)<br>• Teachers did not provide students detailed information on what limitations might be; students needed to identify and deal with abstract notions of constraints<br>• Few instances of coding for constraints in the data, possibly because constraints were only sometimes identified by teachers in the entry documents or directions to a project |
| Modeling & Analysis | • Modeling almost entirely consisted of representational modeling.<br>• Representational models were rarely used to build mathematical models.<br>• Representational models were tested physically and adjusted due to physical constraints.<br>• The representations were not run through mathematical models before being tested physically.<br>• Students participated in active analysis of outcomes, which included prototyping and representational modeling. |
| Engineering Habits of Mind | • Coursework nurtured engineering habits of mind through open-ended, often interdisciplinary, group project challenges in which students were expected to be creative, collaborate, consider opportunities in every challenge, attend to ethical considerations, and communicate effectively about their project.<br>• Extra-curricular activities (ex. planning and implementing student assemblies and fundraisers) provided opportunities for students to develop engineering habits of mind. |
| Systems Thinking | • Systems thinking was an introductory topic taught explicitly in the required engineering courses and adopted in a larger way by connecting subject matter to the world of work<br>• Teachers were explicit about showing how different ways of thinking could be incorporated to better address human needs rather than using one singular way of thinking |
| Optimization | • Demonstrated value of optimization by giving additional time to students to proceed through multiple cycles of the engineering design process<br>• Demonstrated value of optimization by fostering culture of not being afraid of making mistakes, but to use data to inform the next design<br>• Teachers changed their curriculum often so students could try other variables in considering trade-offs for the purpose of optimizing their products<br>Students worked toward optimization through iterative data collection |
| Communication | • The need for articulate and thoughtful communication was emphasized along with the need to back up claims with evidence<br>• Internships provided opportunities for students to become effective communicators in authentic settings by presenting their process and products in briefings to professional engineers from the community for critical review |

Internships offered at all schools gave students a real-life experience with the design process as well. At HTH, a student reported that in his internship at Solar Turbines, he worked on projects involving CAD software, as well as Pro-Engineer software to design components that may be used in future turbine projects (Behrend et al., 2014). These ISHSs even allowed extra time for the classes involving design, such as at DSST where the Creative Engineering class met two to three times longer than other classes during the week so students could work collaboratively on designing their projects (Spillane et al., 2013).

Often the concept of design was a theme throughout classes, such as at WSE where the Applications of Science teacher teamed with the World History teacher during the Roman unit and taught about the design of arches and other structures during that era (Peters-Burton et al., 2013). As the principal of WSE explained how design is incorporated in their instructional design and implementation process,

> We also take the engineering design principles… no one should just be satisfied doing something one time and turning it in. It's always … making it better. That's kind of what we want to teach our kids…. A lot of times they'll do something, turn it in, get a grade and be happy with it. We want them to look beyond that.

Extracurricular activities, such as the Robotics Club offered in three of the schools (HTH, WSE, and Manor), revolved around the concept of design by teaching its members to design and build a robot, including electrical work and programming. Of all seven engineering education topics derived from recommendations from the NAE report, design was overwhelmingly present at all ISHSs that offered engineering in this study.

### *Identifying Constraints*

In the practice of engineering, constraints can be less tangible things such as political, legal, social, ethical, and aesthetic limitations. In some ways, constraints were dealt with in the same way at ISHSs as seen in the curricula in the NAE report, but often the ISHSs went beyond the narrow conceptualization of constraints to help students to become more proficient at identifying less tangible constraints.

In the classroom activities at the ISHSs, typically constraints were conceptualized as limits of the laws of nature, time, money, materials, and repairability. Although the ISHSs had a slightly more complex implementation of the idea of constraints in their classrooms, there were very few observations of this idea at play in the classrooms. At MNTH, teachers launched projects by providing students entry documents, often in the form of white papers, detailing the goals and constraints of a project. The teachers provided the outcome goals for the projects in the entry documents, but did not provide detailed information on what limitations might be so that students needed to identify and deal with the abstract notions of constraints. For example, at MNTH, students were given an entry document for each PBL they attempted. This entry document explained the specifications of the final project, but did not explain the factors that might limit the production of their final product. Based on this type of curriculum design that gave students a great deal of freedom to make choices, fail, and try again, students needed to be adept at identifying constraints to successfully complete the projects. During a remote control car design project at MNTH, one student group had to redesign their prototype on the fly because of the difference in surfaces in the final test. During a classroom observation at DSST, the engineering teacher asked students to identify constraints by explaining, "I'd say there is no right or wrong way to do this. The only constraints are what?" The students responded "It has to fit through the door, move, and hold the art work," which demonstrated concrete constraints as found in the NAE report. Although identifying constraints are an important component to the design process, there were far fewer instances of coding for constraints in the data, possibly because the constraints were only sometimes identified by teachers in the entry documents or directions to a project. Typically students managed constraints when they emerged unexpectedly during the project design. Students at ISHSs did not directly anticipate or identify constraints. Instead they reacted to the constraints as failure occurred in prototypes and trials.

### *Modeling and Analysis*

When modeling was mentioned in the interviews or observed in the classes it almost entirely consisted of examples of representational modeling. For example, DSST and HTH students were both building interactive prototype museum exhibits (one portable and one permanent) to demonstrate subject matter concepts from science topics. All of the five schools in the studies had some version of a fabrications lab, ranging from

AutoCAD to 3D printers to laser saws and Computer Numerical Control machines. The subject of mathematics was integrated by using scale drawings and measurement, but rarely were the representational models used to build mathematical models. That is, the representational models, once drawn to scale, were never modeled mathematically. Instead the testing of the representation was done physically and adjusted due to physical constraints. The representations were not run through mathematical models before being tested physically, which could be due to the phenomena reported at each ISHS visit that mathematics knowledge tended to be the limiting factor to the advancement of student academic progress. The educators at ISHSs understood that because there were no academic criteria for admission to the school students would come to them with various levels of mathematics achievement (see case studies at *https://ospri.research.gwu.edu/*). The schools addressed this barrier by having those students who needed more time to engage in mathematics take two mathematics classes per year, or take mathematics courses over the summer or winter intersession. Therefore, there were few students who had the background to be able to build a mathematical model to predict physical responses in their prototypes. Limitations of mathematics achievement by students also limited the ways that students developmentally understood engineering. This conjecture is corroborated in the ways that the schools used engineering as additional time to provide mathematics instruction, which in this case was measurement and scaling.

### *Engineering Habits of Mind*

Habits of mind observed at the ISHSs included connecting ideas across disciplines, perseverance, responsibility for learning, collaboration, creativity, and application of troubleshooting and problem solving. Because the curriculum at the ISHSs consisted of collaborative projects and direct instruction to prepare for collaborative project challenges, these schools nurtured engineering habits of mind in all of the engineering courses. The teachers in the schools sought to create an environment where students were not afraid to fail and instead learned from their mistakes. The open-ended, often interdisciplinary projects encouraged students to be creative, collaborate, consider opportunities in every challenge, and communicate to members within their group to external factions about their project. Even ethical considerations were observed by the research team in the design projects. At HTH one group of biology students could have chosen a local project to educate museum-goers about bacteria. However, they took initiative to undergo a more ambitious project to design a user-friendly DNA identification kit to test meat in South Africa to determine if the meat was from a poached animal such as a rhinoceros. Although this project may seem beyond the capability of a 9$^{th}$ grade team, they were able to create the DNA testing kit so that it was affordable and, through the connections of the faculty at HTH, were able to send it to South African residents to use. The kit actually identified a vendor of poached meat who was turned over to the authorities (Behrend et al., 2014). Other schools such as WSE may not have had such global connections, but were able to integrate ethical considerations into design projects by challenging students to consider accessibility issues for physically disabled users. Throughout this project, the teacher reminded students to consider the perspective of the user in the design so that students were making ethical choices to respect the humanity of the user while optimizing the design.

Additionally, the ISHSs fostered engineering habits of mind in academics through design projects in formal classrooms, but also encouraged strong habits of mind in student extracurricular activities such as in planning and implementing student assemblies and fundraisers. At HTH, teachers encouraged students to consider the optimization and trade-offs when dealing with limited resources during the planning for a student assembly talent show. At MNTH, teachers used a peer review system to help robotics design teams consider trade-offs in the robotics tasks for a competition.

### *Systems Thinking*

Often in a K-12 engineering curriculum, systems thinking is an undercurrent and may not be explicitly used to help students analyze how two or more elements work together (NAE & NRC, 2009). This was not the case for the ISHSs. Systems thinking was an introductory topic taught in the required engineering courses and it was adopted in a larger way by connecting subject matter to the world of work. That is, teachers were explicit about showing how different ways of thinking were incorporated to better address human needs rather than using one singular way of thinking. For example, in WSE students read novels in their humanities courses and analyzed the designed environments to see the underlying interacting pieces, such as reverse engineering aqueduct systems when reading about Roman culture and explaining how the construction of aqueducts affected daily life. At HTH students read about socio-cultural theory and were given the project to create a working, interactive gear-driven art installation that represented a culture of their choice. This represented systems thinking because the art installation needed to be as interconnected as the members of society in their chosen socio-cultural theory.

*Optimization*

Three ways the ISHSs demonstrated that they valued the concept of optimization were the additional time they gave their students to proceed through multiple cycles of the engineering design process, the culture they fostered to not be afraid of making mistakes and to use data to inform the next design.

First, teachers at all five schools consistently reported that they changed their curriculum often so that students could try other variables in considering trade-offs for the purpose of optimizing their products. At MNTH, all teachers, counselors, and staff met to improve the delivery and support of their problem based learning projects and consulted each other so that students learn to communicate through a variety of media, choose valid resources for a project, use evidence in making claims, take in feedback and use it to improve the project, and, most important, to not fear making mistakes (Lynch et al., 2013). Sometimes during these staff planning meetings, a suggestion was made to explain the constraints so that the students could be more efficient with their time. When these suggestions were made, the teachers presenting their curriculum pushed back and promoted more student responsibility to identify trade-offs.

Second, at HTH the research team observed a student creating a prototype museum display with black and white light to show bioluminescent bacteria. After the students went to a different teacher's classroom to get a more intense black light to make their bacteria glow brighter, they initiated a discussion with their teacher about some specific bacteria needed for their project. They had already researched these materials ahead of time online, but were worried about the cost. Their teacher helped the students to isolate the variables they were trying to optimize by encouraging them to use only one type of bacteria and led the students to understand that they only needed a portion of the materials to address the problem they were trying to solve. In this example, the teacher did not immediately offer constraints (cost and availability) and the students worked toward optimization through the iterative collection of data.

Third, at DSST, where persistence and grit were valued, the idea of optimizing was infused into students' individual learning strategies. In the Creative Engineering class, students learned that the first prototype they designed probably wasn't going to be a perfect product and they would have to revise and rework until it fit the goals of the project. According to the teacher, this was a class where the students could learn to "handle frustration and be comfortable with failure" (Spillane et al., 2013). Although the concept of design was most prominent across all schools, the concept of optimization was present in all of the case studies as well, and was aligned to the definition of the NAE report that emphasized optimization based on data and not on brainstorming alone.

*Communication*

The ISHSs embraced communication skills and were effective in teaching them to students. MNTH teachers excitedly explained that before each of their students graduate, they must perform more than 50 public presentations, many of which can be found on YouTube. When interviewing students at these schools, it was apparent that being articulate and thoughtful about communicating was emphasized along with backing up their claims with evidence. All of the ISHSs underscored the need for students to be effective communicators, particularly in the required internships. During interviews at the ISHSs, students often mentioned that they understood they were representing the school and made every effort to be as professional as possible. For example, at WSE one student collaborated with local businesses and governmental agencies to hold a one-time charity 5K running race whose proceeds helped the homeless in his community.

This student used his communication and other STEM skills to submit a successful proposal that resulted in USA Track and Field race certification, which has exacting standards. Other effective communication strategies at ISHSs were fostered by having students present their process and products in briefings to professional engineers from the community for critical review. Industry partners at the ISHSs all indicated that they had preferential hiring for graduates of these schools because they already witnessed the professionalism displayed by students even before they attended college. Engagement in communicating professionally was fostered at the ISHSs because the students worked in authentic settings so that they were communicating to a larger community, not only the teacher.

**Engineering Opportunities across ISHSs**

Looking across the ISHSs in the larger OSPrI study, it is notable that three of the eight exemplary schools chosen for the larger study did not offer engineering education although they were recognized as highly performing STEM schools (two were Career Technical Education schools that offered a series of career-related courses in agriculture and health professions that used some of these engineering principles). This is evidence that engineering has still not achieved the profile of the other STEM subjects, and further efforts at infusing or mapping engineering throughout the curriculum as recommended by the NAE report is needed (Stohlmann, Moore, & Roehrig, 2012). However, in the remaining five schools as seen in Table 4, engineering is thriving and is as important a component as science, mathematics, and technology. At these schools, engineering is not merely an elective, and all students must take at least one engineering course to graduate, although the states where the schools are located do not require this for a diploma. Where engineering was offered, there was always an opportunity to pursue a higher-level engineering course, and several of the schools offered college credit for the advanced courses, which simultaneously encouraged students to understand that they can be successful in college-level engineering.

Table 4. Cross-case analysis

| Engineering topic | MNTH | WSE | HTH | DSST | Metro |
|---|---|---|---|---|---|
| Design | + | + | + | + | + |
| Identifying Constraints and Optimization | + | √ | √ | + | √ |
| Modeling & Analysis | √ | √ | √ | √ | √ |
| Engineering Habits of Mind | √ | √ | + | √ | √ |
| Systems Thinking | + | + | + | + | + |
| Optimization | + | √ | + | + | √ |
| Communication | + | + | √ | √ | √ |

+ = *topic addressed effectively*

√ = *topic could be addressed more effectively*

The National Academy of Engineering made recommendations for knowledge and skills that are appropriate for the K-12 engineering learning environment. From this report we derived seven topics to be taught in K-12 schools: design, systems thinking, optimization, modeling, identifying constraints, analysis, communication, and engineering habits of mind. By examining the prominence of the key areas of knowledge and skills for engineering across ISHSs, we have identified which can establish which components are being well-addressed and which need more support by the engineering education community. Ranked from most prominent to least prominent these components are:

1. **Design**. The concept of design was found to be pervasive through the engineering curriculum as well as being a foundational concept that was taught to all students, as it was the first concept learned in all required engineering education courses offered at the ISHSs. Design thinking has been found to be essential to meaningful learning activities (Cantrell, Pekcan, Itani, & Velasquez-Bryant, 2006; Carroll, 2014), which were embraced by the ISHSs in the study.

2. **Engineering habits of mind**. Learning experiences at the ISHSs deliberately build in the explicit explanation of the types of thinking embraced by the field of engineering as well as the skills that must be developed.

3. **Communication**. The ISHSs are particularly adept at providing experiences for students to learn how to work within teams and how to express the findings of their work to the public.

4. **Systems**. Systems thinking was taught to the students in all ISHSs because it was a concept in the required engineering course. Students were consistently taught that they should consider how parts work together. However, emphasis was not always placed on planning for emergent changes in a system.

5. **Modeling and analysis**. Representational modeling was demonstrated across the ISHS courses and all schools had some type of equipment to carry out physical modeling with technology. However, mathematical modeling was rarely observed and should be considered an area for improvement.

6. **Identifying constraints and optimization**. These two categories were the least prominent component of the NAE recommendations because the constraints in the projects tended to be built into the instructions or otherwise identified by teachers. Curriculum that has student-developed constraints as a goal would improve the rigor of this component across schools. Students working on design projects at the ISHSs were engaged somewhat in optimization through constantly being encouraged to redesign and to learn from their mistakes.

The NAE report synthesized three positive outcomes to the inclusion of engineering education into K-12 learning through either mapping or infusion that were found in the literature. The benefits of K-12 engineering education included improved learning and achievement in science and mathematics, increased awareness of engineering and the work of engineers, and interest in pursuing engineering as a career. All of these benefits were apparent in the ISHSs that required introductory stand-alone engineering courses and offered advanced engineering courses.

## Conclusion

This study examined the extent of engineering learning opportunities in five exemplar Inclusive STEM High Schools (ISHSs) found in the United States; schools that include all students regardless of academic background. These schools used engineering as an opportunity for students to apply mathematics skills to real world settings. Additionally, when the schools used the engineering design process, students had extra time-on-task with science because they needed to know how the principles of scientific phenomena interacted with their design. This is similar to findings that students who took “Project Lead the Way” courses scored significantly higher on science and mathematics on standardized tests than students in comparison groups (Bottoms & Anthony, 2005; Bottoms & Uhn, 2007; Hotaling et al., 2007). Schools, both STEM-focused and comprehensive alike, could improve the engineering education they offer by infusing project-based learning and experiential learning that use the engineering design process. Not only does the engineering design process reinforce the process of making evidence-based decisions that reinforce concepts in science and mathematics, but it also generates a culture where reflection and re-design of work are viewed as necessary for improvement.

Students at the five ISHSs studied inevitably developed an awareness of engineering because they were required to take stand-alone courses that were carefully designed to scaffold students’ understanding of ways of knowing in engineering. Students reported their tendency to see engineering design as a way of thinking about the world and ways to problem solve. The schools educated students to understand the variety of career options in engineering through these courses, but the students did not overwhelmingly report engineering as a career option. Even students who studied at WSE did not report an overwhelming interest in pursuing an engineering career. Instead, they reported that they went to WSE because the school had a good reputation and that they wanted to study using projects rather than lecture. This runs counter to other studies that have found experiences in engineering-related activities may boost interest in pursuing careers in engineering (Anderson & Northwood, 2002; Anderson et al., 2005), although these studies reported engagement in summer camp activities and had no comparison group. The findings of the current study do align with findings that other educational interventions have had a lesser impact on groups underrepresented in STEM (Anderson & Gilbride, 2003). Since the students at ISHSs were from a variety of backgrounds, many of them were from groups underrepresented in STEM, which may explain this result. The ISHSs developed a well-informed appreciation for engineering but not necessarily a drive to pursue engineering as a career.

## Recommendations

Inclusive STEM High Schools enroll students from a variety of backgrounds, who are typically underrepresented in STEM fields. The ISHSs in this study were as or more diverse than their surrounding communities and provided evidence that all students can learn the key components of the field of engineering, and "engineering for all students" can be achieved. However, some of the key features of engineering as a discipline were missing at these exemplary schools, such as the tension between optimization and constraints, systems thinking, and modeling that goes beyond representation to include mathematical modeling. Engineering educators can take the initiative to bridge the gap between the field of engineering and K-12 educators by offering professional development in the concepts recommended by the NAE, particularly in the topics that are more nuanced to someone not involved in the engineering field.

Policymakers should take note of the ways that these ISHSs are creating learning environments for STEM that not only engage all students, but also sustainably support students who are from groups underrepresented in STEM. The schools actively sought out a diverse group of students through their recruitment efforts. The schools also made STEM engaging to students through problem-based learning and through authentic learning environments. If students struggled to learn, the schools responded by having tutoring sessions, bridge programs, and extra time on academic work for students. Policymakers can look to the 14 critical component of ISHSs to provide legislation to build networks supporting these structural components of schools.

Based on the results of this study, the engineering education community is encouraged to continue making engineering concepts and skills accessible to K-12 educators, who may not be trained in the field of engineering. Engineering educators should consider designing different tiers of educational experiences based on the knowledge level of the learners. Concepts that are the most accessible to K-12 educators based on this study are engineering habits of mind, communication, and design. Therefore, when engineering educators design professional development experiences for teachers or informal educational experiences for students, they may want to focus on the most manageable concepts for novice learners. If teachers or students have a basic understanding of engineering, including habits of mind, communication, and design, then engineering educators should consider designing learning experiences focused on one or more of the following: systems thinking, modeling and analysis, and identifying constraints. Experiences with systems thinking should include scenarios involving implications for a whole system when one part changes, which tends not to be addressed in the K-12 environment. Another area of focus for engineering educators to improve K-12 engineering education is mathematical modeling. Although these exemplary schools are adept at representational modeling, mathematical modeling was not observed as frequently, suggesting that most high school engineering teachers could use support in this area. Lastly, as the ISHSs focused mainly on constraints of the natural world, lesson design emphasizing other areas of constraint would help to improve the landscape of K-12 engineering.

This examination of what exemplary ISHSs offer in engineering education and how the practices of these courses align with the key components of engineering education as recommended by the 2009 NAE and NRCreport helps to provide a foundation of the status of engineering education in high schools. It is necessary from time to time to "take stock" of what is currently happening in schools to help design the next iteration of professional development experiences for teachers. Findings from the current study provide tangible evidence from which engineering educators can create effective professional development for teachers and informal educational settings for students informed by current high school practices.

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