Critical Components of STEM-Focused Elementary Schools

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This study described the components key to the designs of five exemplar STEM-focused elementary schools. The 17 critical components common to the exemplar elementary schools grouped into three themes. First were those that were foundational for the STEM school design, the second set of components described the key participants and resources that provided the means for STEM program implementation, and the third set of components describe the implementation of the school STEM design. These components provide a blueprint from which elementary schools can increase their quality STEM offerings for students.

Keywords: STEM school, school model, curriculum and instruction, elementary school

INTRODUCTION

Expanding quality STEM learning opportunities is a challenge that many schools and districts have addressed by creating schools with STEM education integral to their mission and design. The first STEM-focused schools were high schools. Studies in recent years (e.g., Lynch et al., 2017; Lynch et al., 2015; LaForce et al., 2016) provide an understanding of the components critical to the design of STEM-focused high schools (Lynch et al., 2015). With the success of STEM high school initiatives and the emphasis on STEM education generally (NRC, 2013; PCAST, 2010), STEM-focused elementary schools have begun to emerge across the country. But how are STEM-focused school designs implemented at the elementary level? To address this question, this paper reports on a study that identified and described the key design components of exemplar elementary STEM-focused schools (eSTEM). This study was driven by the following questions: What are the critical components shared by well-established eSTEM schools? How do these critical components combine to provide a design framework of eSTEM schools?

To explore these questions, this study sought to develop a framework describing eSTEM school design based on case study findings from five exemplary eSTEM schools. Informed by previous research on the design components of successful STEM high schools (Lynch et al, 2016, Peters-Burton, et al., 2014, the study implemented a case study replication design (Yin, 2003) to examine the designs and implementation of these exemplar schools in their varied contexts. Using an iterative process, the findings from each case study contributed to a final common framework that describes the design components that were critical to the success of these schools. The case study schools in this study enrolled students based on residence and interest and not on test admission scores or demonstrated prior achievement in STEM. Given the inclusive focus the study provides actionable finding that other elementary schools can use to develop or expand a school-wide STEM focus.

Literature Review

United States policy documents such as Rising Above the Gathering Storm (National Academies, 2005) and Prepare and Inspire (PCAST, 2010) underscore the importance of science, technology, engineering, and mathematics (STEM) jobs for economic growth and global competitiveness in science and technological innovation. The U.S. science and engineering workforce is expected to be the fastest growing sector of the economy in the years ahead (National Academies, 2011) and policymakers argue that these workforce needs will be met only if there is greater interest in pursuing a STEM-related career among a broader demographic population.

The report *Successful K-12 STEM Education* from the National Research Council (2011) pointed to the importance of providing all students with a coherent STEM education, starting in kindergarten or earlier. A second report, *Monitoring Progress Toward Successful K-12 STEM Education* (NRC, 2013) addressed the need for research and data that can be used to monitor progress in the K-12 STEM education system and to make decisions for its improvement. The indicators provide a framework for Congress and relevant federal agencies to create and implement a national-level monitoring and reporting system that could support progress toward the NRC's goals for U.S. K-12 education in the STEM disciplines. Three of these indicators target the elementary grades, including the need for more information about the types of elementary STEM schools and programs that are available.

The number and quality of eSTEM schools in the United States is unknown. A special analysis of the 2012 National Survey of Science and Mathematics Education (NSSME) by Horizon Research (Fulkerson & Banilower, 2014), revealed that 4% of U.S. public elementary schools reported having a STEM focus. State-level efforts to create STEM-focused schools at scale have been concentrated at the high school level, with ongoing initiatives in Texas, Ohio, North Carolina, Arkansas, Tennessee, Arizona, and Washington State. Several school networks now include eSTEM schools, including High Tech High (Rosenstock, 2008), Harmony Public Schools in Texas, and the New Tech High Foundation (2015), yet these numbers remain modest in contrast to the scale up of STEM-focused high schools.

Science and Mathematics in Elementary Schools

Providing all students with quality science-related learning opportunities in elementary school is critical because of the potential long-term impact. Research by Tai and colleagues, for example, has found that "life experiences before 8th grade and in elementary school may have an important impact on future career plans" (2006, p. 1144). Subsequent research further underscores the importance of the early years for establishing students' interest in science. For example, Maltese and Tai (2010) examined reports from scientists and science graduate students about how they became engaged in science. Their analysis revealed that for the majority of participants, their interest in science began in elementary school. This was particularly the case for women scientists. More females in the study reported that their interest was sparked by a school-related science activity, whereas males recounted self-initiated science activities as being an early motivator for pursuing science. This finding highlights the critical need for quality science learning opportunities—both in class and extra-curricular—for developing students' interest and identity work in science, especially for girls (Carlone, Scott, & Lowder, 2014; Fortus & Vedder-Weiss, 2014).

Despite the research base on the importance of elementary science, national U.S. datasets reveal that students are not receiving the early science learning opportunities they need for developing a sustained interest in science. In their review of the 2012 NSSME dataset, Horizon researchers found that science instruction is not frequently scheduled in grades K-5, and when it is scheduled, the amount of instructional time is minimal. Only 19% of grades K-2 classes and 30% of grades 3-5 classes receive science instruction on all or most days every week of the school year. Among the K-5 public schools that responded to the survey, it was reported that approximately half of all elementary classes (40%) provide science instruction only a few days a week or during certain weeks of the year. Moreover, when science is taught in grades K-5, less than 25 minutes per day is devoted to it—averaging 18 minutes per day in grades K-2 and 30 minutes per day in grades 3-5 (Fulkerson & Banilower, 2014). Unlike reading and mathematics, which are assessed by federal accountability systems, elementary school science instruction receives less focus and attention than is required for helping students to become successful STEM learners (National Research Council, 2007; Dorph, Schunn, Crowley, & Shields, 2011).

Beyond problems of quantity, research on the quality of science in public elementary education has also raised concerns. To provide more rigorous science and mathematics instruction for students, in 1994 the National Science Foundation began the Urban Systemic Initiatives (later replaced by the Urban Systemic Programs, or USPs). The funding, which lasted up to a decade in some districts, was intended to improve the academic performance of all students with a particular focus on those from minority groups. During this period, while many school districts in the U.S. reduced science instruction, the USPs did the opposite by creating and implementing research-based science curriculum taught by well-trained teachers starting in kindergarten and continuing through high school. While the USP programs improved math and science education on a number of levels, the impact of the program on minority student groups was barely discernible. Subsequent large-scale studies of public elementary schools have found that teachers routinely underperform and thus deprive students—especially those from economically disadvantaged families—with the opportunity to learn (Pianta, Belsky, Houts, & Morrison, 2007). In other research, charter elementary schools have similarly underperformed, with schools reporting highly variable and inconsistent measures of school effectiveness (Dobbie & Fryer, 2011).

On balance, reform efforts have shown that substantial improvements to public schooling are not only possible, but also predictable. In a large-scale longitudinal study of high-needs public elementary schools, researchers from the Consortium on Chicago School Research studied the school design and organizational features that are critical for optimizing school and student success (see Byrk, Sebring, Allensworth, Luppescu, & Easton, 2010). The researchers identified five interconnected "essential supports" that were all shared among effective schools: school leadership, parent and community ties, professional capacity of staff, school learning climate, and instructional guidance. Studies of these schools showed that schools that were strong in all five essential supports were 10 times more likely to show increased student achievement in reading and math than schools that were strong in only one or two supports. Moreover, schools that were weak in just one of these areas were significantly compromised in their efforts to improve student learning. When schools attend to all of the essential supports, improvements in student achievement can be met and sustained at scale.

A key lesson from the Chicago research is the importance of an organizational and school-wide perspective. The Chicago researchers found that improvements to individual school features, such as teacher professional development or a new curriculum, are unlikely to have long-term impacts (Byrk et al., 2010). This lesson has implications for supplementary STEM programs that are developed for elementary students such as Engineering is Elementary and FIRST Robotics. These programs provide evidence of the interest and resources that are available for supporting more intensive science learning for elementary students. While valuable, such opportunities are optional enhancements to the curriculum and instruction that not all students receive, and only those that participate can benefit and only for the duration of the program. As a strategy for improving the quality and availability of science learning opportunities, it is reasonable to expect that a STEM-focused school would offer stronger prospects for enduring impacts on students from groups underrepresented in STEM.

Inclusive STEM High Schools (ISHSs)

Early efforts to develop STEM-focused schools at scale have focused primarily at the high school level, due largely to partnerships formed with industry and institutions of higher education, as well as the economic development imperative driving many of these initiatives. Notable efforts include the Texas High School Project (THSP), the North Carolina New Schools Project, and the Ohio STEM Learning Network. Unlike many states that have funded more diffuse STEM education efforts, these states have deliberately created plans to provide increased STEM learning opportunities to groups traditionally underrepresented in STEM fields—females, African Americans, Hispanics, and students from families of limited economic means—by establishing ISHSs at scale. These schools accept students on the basis of interest rather than aptitude or prior STEM achievement. The chief aim of an ISHS is to develop students' STEM interest and expertise rather than select students who have prior demonstration of STEM talent.

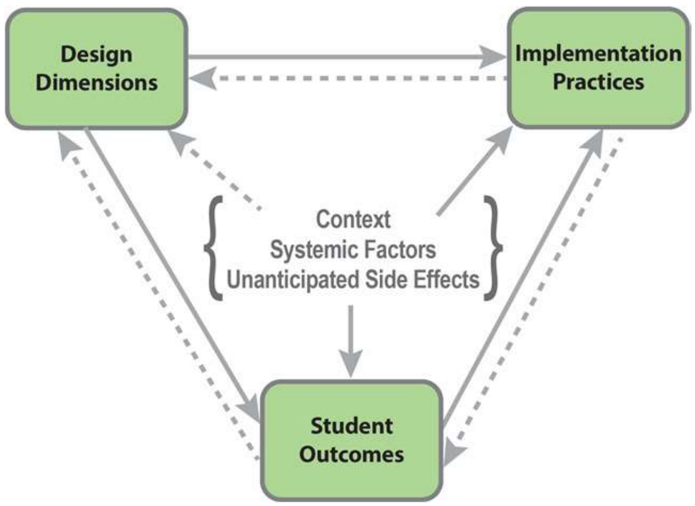
The Opportunity Structures for Research and Inspiration (OSPrI) (Lynch et al., 2015) and Outlier S3 (Century et al., 2015) projects have helped articulate the ISHS model and its range of implementations and variations. The Outlier S3 project has also helped establish the attributes and components of STEM-focused high schools (LaForce et al., 2016). Although the requirements for a STEM designation are viewed differently by different educators and policymakers, most agree that a STEM-focused high school offers a greater number of STEM courses than is required by state and or/college admissions, and that these courses have greater depth than the minimal state graduation and college admission requirements. In addition, STEM-focused high schools often integrate STEM topics throughout the curriculum, including representation in the core humanities and language arts. In all cases, it is imperative that the number and scope of STEM courses, and the courses that include STEM integration, be curricular requirements for all students attending the school—there cannot be an opportunity for students to "opt out." Other key components found to be common among STEM-focused high schools include a project-based learning approach, research experiences for students, technology integration within teaching and learning approaches, career connections, early college and internship and/or mentorship opportunities.

Lynch and colleagues on the OSPrI project have provided further insight into the critical components of STEM-focused high schools. For their study design, OSPrI researchers conducted case studies of eight exemplar inclusive STEM high schools. Products resulting from these case studies include an ISHS logic model built from their exemplar schools that include Early College high schools with a STEM focus (that offered both college and high school credits), tech-savvy schools that relied entirely on project-based learning (an instructional practice emphasizing student production of knowledge via projects and research), and career/technical education high schools that prepared students for college and careers such as agriculture or health sciences through early experiences in those fields. In addition to efforts by the OSPrI team to define and explore the implementation of ISHSs, an important question is the effectiveness of these schools in comparison to other, more traditional high schools. Since 2011, Means and colleagues (2016) on the iSTEM project have been conducting a large-scale controlled longitudinal study of the impacts of inclusive STEM high schools, exploring the extent to which these schools contribute to improved academic outcomes, interests in STEM careers, and expectations for postsecondary study.

Conceptual Framework

This study was guided by a conceptual framework that was used in prior research of STEM-focus schools (Means et al., 2008). In this framework, there are three primary dimensions for understanding STEM-focused schools (see Figure 1). These dimensions include the program's design, the program as implemented, and student outcomes. These dimensions interact with and are moderated by contextual factors, systemic factors, and unanticipated side effects. A STEM school's design dimensions include such components as its mission, administrative structure, schedule, curriculum, pedagogical approach, and outside partnerships. These components include those features of high-quality schools generally, as well as components integral to the school's STEM focus. The implementation practices capture how the design components are operationalized. For instance, a school may have design goals for STEM-related community involvement that is put into practice through a particular initiative such as school gardens that allow students to plant and care for their own herbs and vegetables. The third dimension, student outcomes, are the student impacts and experiences resulting from participating in STEM-focused school programs. These outcomes include student achievement on standardized assessments, participation in STEM learning experiences, practice of STEM skills, and the development of STEM identity and efficacy as STEM learners.

FIGURE 1
eSTEM CONCEPTUAL FRAMEWORK



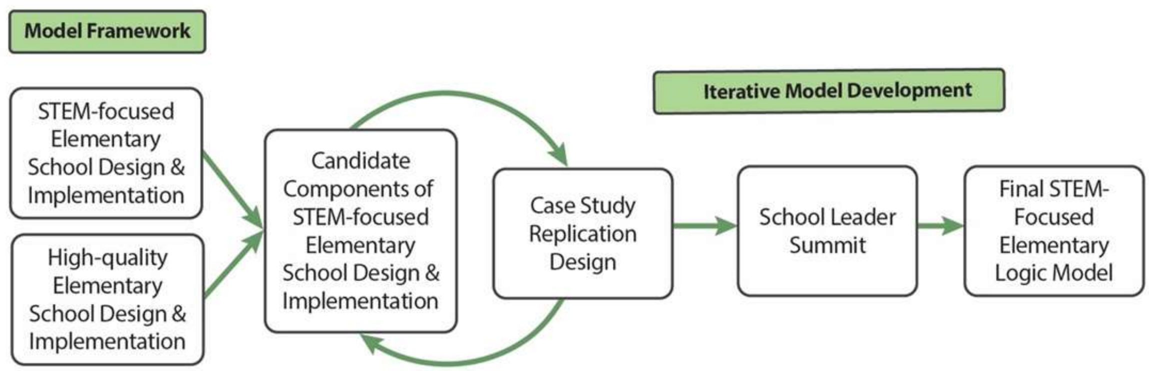
In this project, we conceived of student outcomes as the student impacts and experiences resulting from participating in STEM-focused schools. These outcomes included student achievement and performance on standardized assessments, but also encompassed participation in STEM learning experiences, practice of STEM skills, and outcomes including STEM identity and efficacy as learners. Building on school design and implementation components identified in the OSPrI (Lynch et al., 2015), iSTEM (Means et al., 2016), and Outlier S3 (Century et al., 2015) projects, as well as essential features of effective elementary schools identified by Byrk and colleagues (2010), this project initially identified 20 candidate components for eSTEM schools. These 20 components served as a template logic model which was refined and honed with evidence from case studies of five exemplary STEM-focused elementary schools.

METHODS

This research involved multiple case studies (Yin, 2003) and cross case analyses (Stake, 2006) of exemplar inclusive, STEM-focused elementary schools. As indicated in Figure 2 we began with an initial hypothesized model framework derived from literature on existing exemplar elementary school design and from prior work on exemplar Inclusive STEM High Schools (Lynch et al., 2018). From this information, we composed candidate components of STEM-focused elementary school design and implementation. Data from the case studies were used to inform the candidate components as well as allow for emerging components that were not identified a priori. We used replication case study design to construct the descriptions of the school critical components so that we could both develop individual descriptions of the schools as well as a synthesis model that were the common components across the schools (Yin, 2003). The replication logic in the research design requires a theoretical framework as a precondition to function as an initial template to describe the components and interactions at each school.

In this type of research design, the expectation is that the model framework is a prediction, which will be modified based on the evidence gathered. We used the candidate critical components as a model framework—i.e., a template—when we visited the first school, and modified it based on the evidence we gathered as we visited each school. The multiple cases, bounded by school, were treated as a repeated experiment. After the first case had been completed, the replication logic corroborated, qualified, and/or extended the findings of the prior cases. In this way, the synthesis template shifted based on the evidence gathered at each school, becoming more sophisticated with each of the five school visits. We did not propose to establish frequency or prevalence of the STEM-focused activities and structures at each school but attempted to deliver a robust description of the mechanisms by which the STEM-focused activities are enacted and sustained.

FIGURE 2
eSTEM PROJECT APPROACH



School Selection

After soliciting nominations from experts in the field of STEM schools, 74 school nominations of exemplar elementary STEM-focused schools were received. The research team reviewed information available to the public about the schools such as websites and evaluated the level of apparent STEM infusion. Additionally, the research team screened for selection protocols such as inclusive admission (e.g. lottery). A length of operation of 4 or more years was considered sufficient to consider the school well-established. Among the 10 schools most highly rated, five schools were selected for case studies (Peters-Burton, House, Lynch, & Han, 2018). These schools were Walter Bracken STEAM Academy (Las Vegas, NV), Weaver Lake Elementary (Maple Grove, MN), Summit Road STEM Elementary (Reynoldsburg, OH), Brentwood Magnet Elementary School of Engineering (Raleigh, NC), and Douglas L. Jamerson, Jr. Elementary School (St. Petersburg, FL). From these schools, we sought to find critical components related to STEM education. A brief description of each school is provided below.

Walter Bracken STEM Academy (Walter Bracken)

Situated in a low-income neighborhood in Las Vegas, Nevada, Walter Bracken Elementary's history spans from being an underachieving school to earning state and national recognition over the course of 10 years. After spending two years in Need of Improvement status in 2002-03, it earned a five-star rating on the Nevada School Performance Framework every year since 2010. In 2013 then Principal Katie Decker was recognized as the *Principal of the Year* by the Magnet Schools of America and the school was recognized as a National Blue Ribbon School. Bracken was ranked 12th in achievement among 216 elementary schools in the Clark County School District in 2014. In 2017, Bracken received the 2017 National Title I Distinguished School Award, received the Elementary Magnet School Merit Award of Excellence, and was recognized as 1 of 8 inaugural designated state STEM schools in 2017.

Weaver Lake Elementary (Weaver Lake)

Located in Maple Grove, MN in the Twin Cities area, Weaver Lake Elementary is an award-winning science, math, and technology magnet school serving grades PK-5. The STEM focus at Weaver Lake Elementary emerged from a district and regional effort to desegregate schools. In 2004, the Osseo district, in collaboration with Northwest Suburban Integration District (NWSISD), determined that Edgewood Elementary in Brooklyn Park would become a STEM-focused magnet school as part of a district-wide effort to improve racial integration among local schools. The Osseo district is one of seven districts that are members of the state-mandated integration district. The conversion of Edgewood to a STEM school was part of a decision by NWSISD and Osseo Area Schools (District 279) to adopt a school choice model to encourage families to send their children to racially diverse schools outside of their predominantly white neighborhoods. Students from across the seven NWSISD districts were eligible to apply to attend the magnet school. Edgewood soon attracted more students than could be accepted. In 2008, Edgewood Elementary was closed and the entire staff and student body were moved into Weaver Lake Elementary in Maple Grove which had been a neighborhood school since 1991. The Weaver Lake neighborhood students were assigned to other schools in the district and Weaver Lake became a STEM-focused magnet school.

Summit Road STEM Elementary (Summit Road)

Summit Road STEM Elementary is located on the outer edge of Reynoldsburg, Ohio, a suburb of Columbus. It was the first STEM-focused elementary school in the district and is now one of several schools in the Reynoldsburg City Schools K–12 STEM education program. With this K–12 pipeline, students at Summit Road STEM Elementary have the option to continue with a STEM-focused education. Summit opened its doors for the 2011-12 school year, serving a maximum of 100 students per grade in grades K-4. It is an inclusive school, open to any elementary-age student in the district through a first-come, first-served enrollment process. Since the school's opening, high enrollment demand has resulted in waiting lists of students from the district who are interested in attending Summit. The founding principal, Dee Martindale, led a school design team in 2010-11 with 20 educators from across the district. After three years of Principal Martindale's leadership, Melissa Drury moved from being an instructional coach to become principal in 2014, holding the position for 4 years. From the founding of the school until the 2017-18 academic year, leadership was made up of staff members who were present during the school's design process. In 2018-19, Christopher Menhorn became the third principal at Summit Road STEM Elementary. Summit Road STEM Elementary was rated Excellent with Distinction on the Ohio State report card in 2011-12 and received a National Blue Ribbon School distinction in 2016.

Brentwood Magnet Elementary School of Engineering (Brentwood)

Brentwood Magnet Elementary School in Raleigh, North Carolina was established in 1957 and was converted to a magnet engineering school in 2008. In 2006, Wake County Public School System, which Brentwood is part of, was setting up a variety of magnet elementary schools. Through a survey, county parents at that time indicated that they preferred Brentwood Elementary have a STEM magnet theme, with a particular focus on engineering. Wake County now has 27 magnet elementary schools, and all students residing in the county may apply for admission to any of them. About one-third of Brentwood's students are admitted through the magnet program, and the other two-thirds come from the surrounding neighborhood. Brentwood has received awards and recognition for its program and student results. It was named the 2018 STEM School of the Year by STEM in the Park at Research Triangle Park, the 2018 and 2015 Magnet School of Excellence by Magnet Schools of America, and the 2018 and 2016 Advocates for Health in Action Gold Award School. In 2017, Brentwood Elementary was a Nationally Certified Magnet School, in 2017 and 2015 received Magnet School of Distinction recognition from Magnet Schools of America, in 2016 was named North Carolina STEM Model School of Distinction, and was honored with the 2015 Donald Waldrip Merit Award School from Magnet Schools of America.

Douglas L. Jamerson, Jr. Elementary School (Jamerson)

A magnet school that opened in 2003, Douglas L. Jamerson, Jr. Elementary, Center for Mathematics and Engineering, has established itself as an exemplar of STEM learning. After it opened, Jamerson applied for and received a Magnet Schools of America Award of Merit in 2007 and has maintained its quality in mathematics and engineering education since then. When Jamerson opened, Pinellas County Schools was establishing magnet and attractor schools to create some diversity because it did not have a desegregation plan. The district had chosen to establish magnet schools—including Jamerson—in the South County in an effort to attract a diverse population of students. As a countywide magnet, Jamerson is open for any child in the Pinellas County Schools area to attend. It is currently the only STEM school in the Pinellas County district.

Data Sources

Schools were selected for their ability and willingness to provide complete and accurate descriptions to address the research questions, while also balancing concerns related to efficiency and feasibility (King, Keohane & Verba, 1994). Case studies involved two to four researchers visiting on site for three days. Data sources included public information about the school including websites and public databases; interviews with school leaders, district leaders, teachers and school partners; focus groups with parents and students; and classroom observations of teachers at each grade level. Classroom observations were conducted with two observers, one using the Reformed Teacher Observation Protocol (RTOP, Piburn et al., 2000) and Lesson Flow Classroom Observation Protocol (Lynch & Hanson, 2005) that was modified for elementary classrooms. After the site visit, all teaching staff were sent a survey about the presence of candidate eSTEM components in their school.

As mentioned earlier, this work was guided by the three-dimensional framework of program design, program as implemented, and student outcomes. School artifacts and interviews with STEM program founders provided insight into the STEM program design, and school observations and interviews with school staff, parents, students, and community partners provided insight into the STEM program as implemented. Student outcomes resulting from participation in STEM-focused schools were documented through interviews with students, parents and staff about student experiences and areas of growth resulting from the STEM school design.

Coding Procedures

The data from each case study school were transcribed and interpreted holistically. Data sources were consolidated by researcher, instrument, and participant type. All data sources were coded in Dedoose by at least two researchers using the previously mentioned set of 20 a priori codes, seen in Table 1 which expanded to 26 components as each case was analyzed and new components emerged. Emergent components included categories such as physical space, STEM teacher transformation, climate of intellectual safety and the use of evidence to drive continuous improvement processes. Researchers discussed discrepancies in coding until consensus was reached.

TABLE 1
eSTEM CANDIDATE COMPONENTS

Learning Opportunities
STEM is integrated throughout school curricula School schedule includes more than required minutes of science instruction School programs are coherent and supportive of STEM Instructional approaches include project-based learning and other reform strategies Teaching & learning emphasize inquiry or design thinking Students learn and use workplace and life skills Students experience autonomy in learning Teachers facilitate student interest in STEM Out-of-school programs and resources provide STEM-rich experiences Students participate in service learning or other community activities
School Staff
Teachers are supported in STEM through collaboration, training, and resources Teachers are open to innovation and continual learning
School leadership is inclusive and focused on instruction
Assessment
Dynamic assessment systems inform instruction
Technology
Technology is integrated into activities of both students and teachers
Families and Community
School establishes and maintains a community presence Parents are included in classrooms and the school School population represents district or local community
School Culture
Trust and respect are shared among staff and students School builds college awareness, college-going culture, and career awareness

Cross Case Analysis

A cross case analysis was conducted to determine the most prominent and utilitarian components that were common in all five schools. First, all 26 components were placed on a matrix and examples for each school were placed in the matrix if they were available. Researchers rated and discussed the prominence and utility of each component for the synthesis model. Nine components were eliminated because they were not represented in all schools, even though the components may have been critical for individual schools. Two leaders from each of the five schools were convened to discuss the synthesis model. The cross-case analysis resulted in 17 common components which were confirmed by leaders of the five case study schools, as shown in Table 2.

TABLE 2
COMPONENTS OF SYNTHESIS MODEL

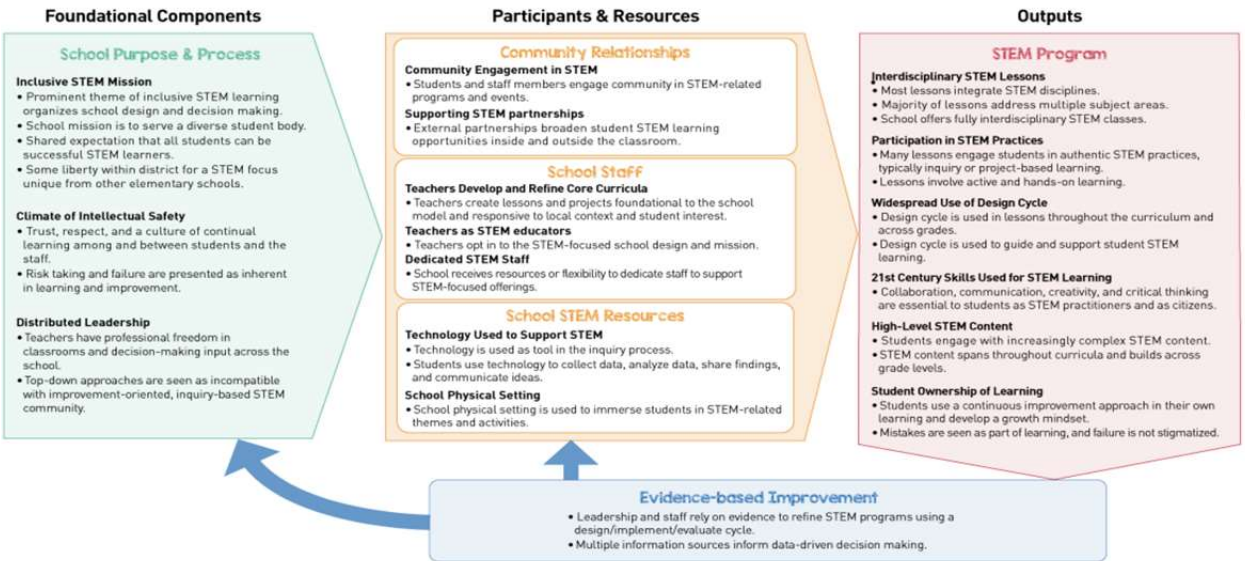
School Purpose and Process
Inclusive STEM mission Climate of intellectual safety Distributed leadership Evidence-based improvement
Community Relationships
Community engagement in STEM Supporting STEM partnerships
School Staff
Teacher develop and refine core curricula Teachers as STEM educators Dedicated STEM staff
School STEM Resources
Technology used to support STEM School physical setting
STEM Program
Interdisciplinary STEM lessons Participation in STEM practices Widespread use of design cycle 21st century skills used for STEM learning High level STEM content Student ownership of learning

FINDINGS

This study was driven by the interest in identifying the critical components shared by well-established eSTEM schools and how the critical components combine to provide a design framework of eSTEM schools. To address these questions, the data from the five case studies were analyzed to identify the practices and structures that were common among the case study schools and were attributed to be essential (by the researchers and the respective school leaders) to each school's success as a STEM-focused school. This analysis revealed 17 components of school design organized within five categories, namely Inclusive STEM Mission, Climate of Intellectual Safety, Distributed Leadership, Evidence-based Improvement, Community Engagement in STEM, Supporting STEM Partnerships, Teachers Develop and Refine Core Curricula, Teachers as STEM Educators, Dedicated STEM Staff, Technology Used to Support STEM, School Physical Setting, Interdisciplinary STEM Lessons, Participation in STEM Practices, Widespread Use of Design Cycle, 21st Century Skills Used for STEM Learning, High-Level STEM Content, and Student Ownership of Learning. Definitions and examples from the case study schools, selected for descriptive purposes, are provided below.

The critical components were organized to follow the design framework shown in Figure 3. Represented in the left column are those that serve as foundational components for the STEM school design. The school's inclusive STEM mission, the climate of intellectual safety, and the structure of distributed leadership provided a purpose, climate and bedrock structure for the case study schools. In the middle column are the components representing school participants and resources, which include staff, school STEM resources and community relationships, that serve as the means to enact the schools' STEM-focused designs. The right-most column are the resulting enactments of the STEM programs, including interdisciplinary STEM lessons, student participation in STEM practices, widespread use of a design cycle, 21st century skills used for STEM learning, high level STEM content, and student ownership of learning. The final aspect of the design framework is the process of evidence-based improvement, in which school leaders and staff relied on data as they continually refined their STEM programs and practices.

FIGURE 3
eSTEM DESIGN FRAMEWORK



School Purpose & Process

Among the three foundational components that make up the School Purpose & Process components are an Inclusive STEM mission, a Climate of intellectual Safety, and Distributed leadership among school staff.

Inclusive STEM Mission

This component of STEM-focused schools is the prominent theme of inclusive STEM learning that served to organize the school design and decision making. As noted by Stemler, Bebell & Sonnabend (2011), "school missions can serve to represent the core philosophy and working ethos of a school and that a shared mission may be a necessary prerequisite for an effective and highly functioning school" (p. 391). Stemler et al. (2011) also documented that a wide range of school effectiveness research has consistently shown that "commitment to a shared mission statement is one of the leading factors differentiating more effective schools from less effective schools" (p. 391). Among the STEM-focused elementary schools in this research, the school's missions were to serve a diverse student body with the expectation that all students can be successful STEM learners.

As an example, Douglas L. Jamerson, Jr. Elementary Center for Mathematics and Engineering in St. Petersburg, Florida invited students of a broad range of backgrounds to enroll and worked to ensure all students participated in rich STEM learning experiences. To begin, student applicants were selected using the district's lottery system that is designed to attract a diverse population of students, including students with disabilities and English Language Learners. Once enrolled, all students engaged in specialized engineering curriculum and magnet theme-based activities daily, regardless of race, gender, or ability. Students with autism were mainstreamed into general education classrooms throughout the day in a co-teaching model with the support of paraprofessionals. All students routinely participated in collaborative engineering design challenges within heterogeneous groups. This enabled students to both understand different perspectives and learn from the strengths and needs of individual classmates. When creating integrated units of study, teachers worked to develop students' knowledge throughout the unit using a variety of hands-on and interactive experiences (e.g., testing strength of materials and shapes before designing a bridge). This provided an entry point for all students into the culminating design challenge. STEM-based field trips (off campus, on campus, and virtual) provided experiences that leveled the playing field for students from disadvantaged backgrounds in addition to opening all students' eyes to new potential STEM-related fields of study.

Climate of Intellectual Safety

Cohen, McCabe, Michelli & Pickeral (2009) provided a literature review establishing that a "growing body of empirical research indicates that positive school climate is associated with and/or predictive of academic achievement, school success, effective violence prevention, students' healthy development, and teacher retention" (p.181). Consistent with this evidence, the case study schools in this research indicated that a climate of intellectual safety provided an atmosphere where both students and staff could participate in trying out new ideas and activities without fear of failure or shame was a significant component of their school models. This climate emphasized trust, respect, and a culture of continual learning as foundational to a STEM community. The staff presented risk taking and failure as inherent in learning and improvement and promoted a respectful tone and style among and between students and the staff.

At Summit STEAM Elementary in Reynoldsburg Ohio, for example, trust and respect were widely shared among staff and students. Students' descriptions of the learning environment reflected an environment in which intellectual safety underpinned STEM practices and mindsets as they reported feeling acceptance and belonging at school. One student said, "No one judges, and anyone can fit in. There's no bullying – there are very strict rules about bullying. The school is not just for one type of people, but they help everyone work toward one goal." This type of atmosphere was established and maintained through the school's emphasis on values and habits of mind that encourage students to practice curiosity, complex thinking, compassion, collaboration, and communication each day. These values are repeated each morning immediately after the Pledge of Allegiance and are supported through a variety of structures and practices. Students are also encouraged to adopt a growth mindset through the use of a continual engineering design process, and staff emphasize at every grade that learning is a process that often requires revision and persistence.

Distributed Leadership

Distributed leadership has been described as an organizational quality in which leadership practices or routines are carried out by multiple individuals with a focus on leadership as the set of interactions between people that constitute the leadership practice (Spillane, 2005). One recent systematic review of prior research found that when distributed leadership includes shared decision-making, greater buy-in on the part of stakeholders is reflected in greater participation and that schools with distributed leadership practices have greater student achievement (Hitt & Tucker, 2016).

At the eSTEM study schools, school leaders provided teachers with professional freedom in their classrooms and input into school decision-making across the school. This distributed leadership was critical as leaders saw top-down leadership approaches to be incompatible with an improvement-oriented and inquiry-based STEM community. Rather, staff were encouraged and supported to engage in continual improvement and innovation in their pedagogical practice, which allowed them to model authentic reflection and continuous improvement for students.

The teachers at Walter Bracken STEAM Academy in Las Vegas, NV, for example, enjoyed high levels of autonomy in their work through significant input into what happened in their classrooms as well as in the school. Much of this was accomplished through a grade level team structure where teachers spent an hour together each week for common planning time, homework coordination, discussion of lesson plans, reviews of assessment data, and designing projects. School leaders provide these teacher Professional Learning Committees (PLCs) significant latitude to design lessons, set classroom practices, and determine what professional development and resources they need to enact their plans. PLC leaders, who rotate in this role each year, also attend weekly school leadership meetings where school-level decisions are made through consensus. Any requests for resources or other supports are made as a grade level team and presented to leadership. Since consensus has already been reached within the grade level team about such requests, the principal knows that any requests will benefit all the students at the particular grade level. The organizational structure provides both latitude for innovation, as well as a mechanism to foster this innovation. As a result, Bracken built an environment where teachers were open with each other and with their students as they strove to innovate and improve in their pedagogical practice.

School Purpose & Process Summary

Taken together, these three foundational components helped the schools establish cultures and practices that involved all students and teachers in high ambitions regarding STEM mastery, encouraged all to participate in intellectual risk taking, and presented school improvement as the work of all school members. In essence, these schools strove to function in ways similar to learning organizations described by Senge (1990) which emphasize the disciplines, among others, of shared vision, personal mastery, and team learning. As such, the they resembled organizations described by management theorists which are focused on knowledge creation, seeing this process as "a way of behaving, indeed, a way of being, in which everyone is a knowledge worker" (Nonaka, 1991, p.97). Among these STEM-focused elementary schools, staff and students alike shared in the goals and practices that support STEM inquiry and ongoing refinement of ideas and practices, and integrated this into everyone's way of being in school.

Participants & Resources

Seven components characterize the critical participants and resources involved in enacting the STEM programs offered at the five case study schools. These components were Community engagement in STEM, Supporting STEM partnerships, Teachers develop and refine core curricula, Teachers as STEM educators, Dedicated STEM staff, Technology used to support STEM, and the School physical setting.

Community Engagement in STEM

In most schools across the country, engaging family and community members with school activities is typically done on an occasional and inconsistent basis (Cross, 2004; Weiss, Lopez & Rosenberg, 2010). This is a critical limitation since meaningful and sustained family and community engagement has been demonstrated to improve student academic achievement (Henderson & Mapp, 2002).

At the schools in this study, however, the involvement of community and family members in school STEM-related activities, such as school projects and exhibitions emerged as one of the critical components supporting the STEM-focused elementary schools. One example of community engagement was found at Weaver Lake Elementary where students studied pollinators over several years of their science curriculum. As students reached fifth grade with deep knowledge of the importance of pollinators and threats to their survival, they wrote letters to community members who were in positions to improve conditions for pollinators. Students generated actions that the community members could take and wrote to persuade community members to adopt their ideas. One set of letters, for example, encouraged leaders of a large corporate office near the school to replace existing landscaping with pollinator-friendly plantings. Teachers reported that some letters were successful, and students had seen their suggestions adopted by community leaders.

Supporting STEM Partnerships

Partnerships between STEM-focused schools and STEM professionals have been included in multiple prior examinations and conceptualizations of secondary STEM-focused schools (Peters-Burton, Lynch, Behrend & Means, 2010; Subotnik et al 2009; LaForce et al., 2016). Such partnerships can ensure that students are prepared to participate in real-world STEM fields. STEM experts can strengthen STEM curricula and provide STEM-focused teacher education and development. In addition to student professional preparation, such partnerships have been shown to support STEM-related capacity building of staff and enriching the learning experiences of students (Watters & Diezmann, 2013).

Each of the STEM-focused schools in this study had significant and ongoing relationships with external STEM partners. Partners helped to broaden student STEM learning opportunities inside and outside the classroom by providing STEM resources, expertise, and opportunities for students to engage with STEM professionals and authentic STEM experiences. At Brentwood Magnet Elementary, for example, the school received school design consulting, teacher coaching and resource recommendations from Engineering faculty at the nearby campus of North Carolina State University Engineering Department during its transition to an engineering magnet school. Now, years later, the relationship with NC State has evolved so that when Brentwood needs an expert in engineering, the STEM lead teacher can call NC State and a professor or graduate student is available to help. These partners are able to advise on topics including engineering content in the curriculum and engineering designs and projects for students. While local industry partners such as SAS, Linovo, CW Network, Cisco, and Red Hat are valued contributors to regular activities such as the annual Engineering Night, the continuing partnership with NC State is an influential on the STEM learning opportunities at Brentwood throughout the year.

Teachers Develop and Refine Core Curricula

School-wide curriculum reform efforts that include teachers in the shared practice of designing and refining curriculum and instructional approaches have been characterized as "essential for transforming reform from an incidental and isolated process in one part of the school, towards being a sustainable and coherent change for the whole school" (Handelzalts, 2019). Teacher communities engaged in curriculum design provide opportunities for teachers to jointly participate in lifelong learning within their disciplines while also focusing teacher attention on students and pedagogy (Grossman, Wineburg, & Woolworth, 2001). According to Ho (2010), teacher involvement in curriculum design can contribute to prioritizing student needs and interests and can improve staff morale and school culture.

This effect was seen in the case study schools as well. In addition to the support provided through community engagement and external partners, teachers mainly designed the programs and experiences provided in STEM-focused schools. Teachers at the five exemplar schools in this study had significant authority and responsibility, as they created lessons and projects that were foundational to the school STEM program and responsive to local context and student interest. Using a constant process of piloting, revising, and then testing instructional approaches and programs, teachers developed a sense of ownership of the school's STEM-focused curricula and helped to refine this curricula over the years. Teachers' innovation of and co-development of lessons is a regular practice and cultural value at Weaver Lake. Both teachers and school leaders view this as essential to the success of the STEM model at the school. At the time of the school's transition to becoming a STEM focused school, school leadership opted not to adopt a curriculum package, but instead engaged the teachers in co-developing lesson materials. This created a set of unique lessons considered years later to be an essential part of the school programs. Teachers continued to develop their own lessons and projects, sometimes starting with external materials such as FOSS kits or Project Lead the Way materials, but always made the lessons their own. Teachers integrated STEM themes into curriculum materials purchased by the district, adding in technology and engineering content, and customizing content to meet their students' needs. One long-term teacher said, "You know, there is not a teacher in the building that does the same thing every year. Maybe we use the same base, but we are always trying to make it better. How can I improve it? What can I change to make it better? The biggest thing, I think, is that STEM isn't a kit—it's creating an experience and continuously making it better. It's better when we make it [the curriculum] ourselves."

Teachers as STEM Educators

Prior research has established strong connections between teacher comfort and teacher self-concept with teaching efficacy (Appleton, 1995) particularly when implementing innovative content such as integrated STEM (Guskey, 1988). Nadelson et al. (2012), for example, demonstrated that a program designed "address teachers' comfort with teaching STEM, pedagogical contentment with STEM, and knowledge of how to implement inquiry to teach STEM led to increased teacher efficacy within the domain" (p.79).

In the five case study schools, teachers had a choice to join and participate in each school's STEM-focused design and mission. When existing schools became STEM-focused schools, teachers had options to transfer to other positions if they didn't want to be part of the transition. During the first years of being a STEM school, teachers participated in support provided by external STEM partnerships to develop STEM pedagogical content knowledge. Over time, teachers developed identities as STEM educators and professionals. As teachers became more confident and experienced teaching STEM content and processes, the professional development for teachers became less about gaining STEM expertise from others, and instead became self-directed and collaborative among the teaching staff. One teacher from Summit Road felt that to succeed at their school you don't need to be a STEM content expert, you do have to have flexibility and see things from a STEM inquiry point of view. "You have to have the quality of curiosity and be willing to fail. You have to be willing to stray from the plan, and be comfortable with that. We have several teachers that would be awesome, hitting it out of the park in another school, but they are thrown by the open endedness."

The experience at Weaver Lake also exemplifies this component. When the school transitioned to a STEM magnet school, teachers were given the choice to opt-out of the STEM program in favor of a transfer to a different school. Only three teachers out of a staff of over 30 decided to leave Weaver. Following the transition, the STEM-integrated programs at Weaver were developed collaboratively by administrators and teachers. In the beginning, many teachers approached this work with limited science backgrounds and relied upon the high-quality professional development provided by the Science Museum of Minnesota. The Science Museum of Minnesota's role over the years has been scaled back, and Weaver teachers now participate in Professional Learning Teams (PLTs) that meet monthly to monitor student academic growth data and adjust curricula collaboratively. A school leader explained that as teachers began to believe in their ability to modify and adapt the school curricula, they came to embrace the idea that science doesn't belong to any one person. They came to see that STEM-focused teachers work to provide rich learning opportunities through inquiry-based, hands-on classroom science and math activities. Teachers and students learned to find the scientists in themselves through simulation, exploration and discovery.

Dedicated STEM Staff

Prior research on STEM-focused schools highlighted the importance of related to staff roles. LaForce et al. (2016) included Staff Foundations as one of eight elements of STEM-focused secondary schools, including STEM-focused instructional leaders and non-instructional staff that support STEM. Lynch et al. (2015) also articulate the importance of the school staff as one of 14 critical components of STEM high schools, including staff who made possible internships and other learning opportunities outside of classroom walls. Notably among the elementary schools in this study, staff were organized in unique ways that helped the school feature strong STEM learning experiences.

Among the five case study schools in this study, each had some staff dedicated to support STEM-focused offerings. In one case, additional funds made a position possible for a lead STEM teacher. Without additional funding, the other schools made STEM-focused roles possible through reassignment and creatively re-defining roles.

For example, at Summit Road the art teacher was an integrated STEM teacher. Instead of offering a traditional art class, Summit offered students in grades 1 through 4 a twice-weekly class called Innovation Station. This class interwove the study of artistic techniques with science and engineering design, for example by helping students apply their observations from the natural world to creative projects. In one project, students made models of animals known to live in their nearby wetlands. They used upcycled materials and worked through each step in the engineering design cycle as they constructed model animals with movement by integrating pneumatic mechanisms. The lesson integrated art, engineering and science standards.

Technology Used to Support STEM

Technology used by students as part of their STEM learning experience served as a key resource for the STEM-focused case study elementary schools. Integration of technology into classrooms and lessons offers both promise (Lee, Linn, Varma & Liu, 2010; Hsu et al 2016) and known challenges (Keengwe, Onchwari & Wachira, 2008) and many variables affect its impact and experience, including the type of technology device or platform used, the skill and attitude of teachers leading lessons integrating technology, and the design of the lesson using technology.

In the five case study schools, students used technology within the entire inquiry process including collection of data, analysis of data, sharing findings, and communicating their ideas. At Walter Bracken STEAM Academy this was evident in multiple ways. Since 2017, all Bracken students have had iPads for their individual use at school because of the school's goals that all students develop digital competence, learn to work independently and take ownership of their learning. Students often used the iPads to practice their reading and mathematics skills, and to submit projects and homework assignments. In addition, students routinely used technology during in-class activities. For example, in a mathematics lesson observed in second grade students used iPads at various activity stations. While students at one station worked with the teacher, those in another activity station used an app on their iPads to practice math facts using an adaptive Bingo game. In a third activity station, students used desktop computers to practice addition and subtraction skills. Students at the fourth activity station completed a paper worksheet as a group with 10 addition and subtraction questions, and a QR code printed next to each problem. When students solved the question as a group, they used their iPads to scan the QR code and reveal the correct answer. At Bracken, students often took online quizzes and tests for formative assessment and formal testing. The technology allowed for the prompt communication of data to staff for monitoring student progress and providing students with any necessary support.

School Physical Setting

Prior research shows that a school's physical space is an important consideration along with decisions about curricular resources and pedagogical practices, as school buildings and grounds are being reconsidered as physical spaces that reflect the pedagogical practices and cultural values of a school community (Malinin & Parnell, 2012). Other research on elementary school design (e.g., Tanner, 2009; Yarbrough, 2001) identified positive correlations between specific school design features and student achievement measures.

In this study, each of the case study schools had maximized their internal and external spaces to immerse students in STEM-related themes and activities, and to enrich the learning environment. Physical resources in these schools included art installations, local wildlife settings, hallway displays, and school gardens. These features were not extravagant, but instead leveraged available resources (such as nearby wildlife and empty wall space) to craft an engaging STEM school environment. Walter Bracken STEAM Academy, for example, intentionally designed the physical space of their campus to support and reinforce the school's shared values and STEAM theme. The school gardens were a prominent feature of Bracken's campus, and also prominent in the school's STEAM curriculum. Each grade level had their own garden space, and participated in the care and harvesting of vegetables, herbs, and flowers, while each grade level had a science curriculum that incorporated garden experiences. Student involvement in school gardening activities such as those at Bracken have been found to promote science learning more effectively than science curriculum alone (Klemmer, Waliczek & Sajicek, 2005; Smith & Motsenbocker, 2005).

Another example of physical school design noted at Bracken was its decentralized library, used to encourage and support students in reading. Classrooms and staff offices across the school had bookshelves each containing a subset of the school's early reader collections. Students used a database to find out where the book they were interested in could be found and other adults were happy to chat with students about the books on their shelf. Instead of "library time", students could be seen entering and exiting classrooms and offices on their own to select and borrow books. This approach was considered by Bracken staff to be an important part of the school's strong reading culture and high scores on state standardized reading tests, consistent with research such as Maxwell and French's (2016) investigation showing increased engagement and active learning among elementary students using a learning commons space compared to a traditional library.

Participants & Resources Summary

Among the seven components that articulate the STEM-focused participants and resources at the case study schools, the cumulative effect is one of providing a rich, engaging and varied STEM learning environment through creative use of resources. These schools involved teachers in developing core STEM curricula resulting in a sense of ownership of and identification in their daily STEM practice in the classroom. They leveraged staff positions to involve more staff in STEM beyond grade level classrooms. And they engaged both community members and local STEM experts as well as the school setting itself to enrich these learning experiences and expand their shared community of STEM practitioners.

STEM Program

Grounded in the foundational components and generated through the school participants and resources were the STEM programs enacted in the case study schools. Key to the implementation of these STEM programs were critical components including the daily use of interdisciplinary STEM lessons, routine student participation in STEM practices, widespread use of a design cycle, 21st century skills used for STEM learning, high levels of STEM content, and an emphasis on student ownership of learning.

Interdisciplinary STEM Lessons

Use of interdisciplinary STEM lessons, an approach common among the STEM-focused elementary schools in this study, is supported by prior research. Becker and Park (2011) conducted a meta-analysis to show improvements of student learning when STEM subjects were integrated within lessons. An additional improvement occurred when all STEM subjects were integrated, rather than only science and mathematics. Moss, Benus and Tucker (2018) found students gained in executive function performance when subjects were integrated. The importance of developing students' disciplinary literacy skills in science classes has recently come to the fore with the advent of the Common Core State Standards for English Language Arts and Literacy in Science (CCSS-ELA). The inclusion of literacy standards for each K-12 grade level focused on informational and expository texts indicates that the creators of CCSS-ELA have "have acknowledged the recommendation of numerous researchers: that language should play a more prominent role in science instruction" (Osborne, 2014). Using the CCSS for Mathematics (practices), CCSS for ELA and Literacy, ELPD Framework (ELA practices), and NGSS (science and engineering practices), Cheuk (2013) developed a diagram of relationships and convergences within the standards, revealing multiple points of intersection between math, science, and ELA. This intersection of standards is the opportunity teachers can use to build interdisciplinary lessons since they are able to address standards across disciplines.

Most lessons at the five case study schools were characterized by their interdisciplinary approach, integrating knowledge and methods of one or more STEM disciplines both in classrooms and in STEM-focused classes or workshops. Some instruction was discipline-specific, often math and reading, yet the majority of lessons at these schools addressed multiple subject areas and intentionally integrated STEM content with other disciplinary content. At Jamerson teachers implemented the school's specialized engineering and mathematics curriculum throughout the day, also integrating it into special subjects like physical education, art, and music. Students learned standards-based skills during the mathematics block and applied them during the engineering block. Mathematics standards in the measurement and data domain were reinforced weekly in the science lab, where primary students learned to use tools and to measure with accuracy and precision. Students in the upper elementary grades then applied these skills when completing engineering challenges. Since engineering design challenges required the application of content knowledge and skills learned throughout the school day, this helped students make real-world connections to their work. In addition, specialists in music, art, and physical education developed yearlong curriculum maps that align with the engineering units of study and mathematics concepts taught in K–5. They implemented their curriculum along the same timeline as the classroom teachers, reinforcing key vocabulary and concepts. For example, physical education teachers taught throwing a ball as a pushing force, where the amount of force applied to the ball affects the distance it travels. Students also viewed music, art, and physical education as extensions of the integrated engineering curriculum.

All five of the case study schools also infused STEM teaching with art education. Some schools, such as Bracken, formalized this process by identifying their school as having a "STEAM" focus. Proponents of this approach (e.g., Bequette & Bequette, 2012) argue that arts and STEM can be fused seamlessly together for the betterment of both subject areas. One STEM topic that has particularly benefited from STEAM approaches is the engineering design cycle, where students design and develop solutions to problems, test their solutions through one or more prototypes and then reflect and improve on their results. A clear example of this approach was seen at Jamerson elementary, where students learned the engineering design process of "Plan, Design, Check, and Share" starting in kindergarten. This cycle was employed widely, including a third-grade lesson on insulators and conductors and designed insulators with the goal of keeping ice cubes from melting. Students worked with a variety of materials including cardboard, styrofoam, and aluminum foil to create vessels that kept the lowest temperature. Art educators note that engineering has much in common with functional design as taught in art classrooms (e.g., Zande, 2011). As Bequette and Bequette (2012) note, "Art, like engineering, is concerned with finding answers to problems and seeking visual solutions using the design process" (p. 44). Regardless of whether or not a school has adopted a STEAM model, STEM programs can be enriched through integration of the arts. Integration is most successful, however, when art and STEM teachers understand each other's positioning and when a collaborative approach is used for lesson ideation and design (Bequette & Bequette, 2012).

Student Participation in STEM Practices

As noted in *A Science Framework for K-12 Science Education* "students cannot fully understand scientific and engineering ideas without engaging in the practices of inquiry and the discourses by which such ideas are developed and refined" (National Research Council, 2012, p. 218). The rationale for emphasizing the practices of science and engineering in the framework and throughout the Next Generation Science Standards is based on the substantial body of evidence on how students learn science, and demonstrates how "science as content" and "science as a set of activities" are deeply linked (National Research Council, 2007). Providing students with consistent, ongoing practice in the activities that scientists and engineers engage in helps them build an epistemology of science, directing student attention toward how we know what we know—specifically through first-hand experience with practices related to hypothesis generation, experimentation, evaluating evidence, and communicating scientific ideas, carried out while engaging in critique, contribute to the construction of knowledge (Osborne, 2014).

Toward this end, the case study schools in this project all provided significant opportunities for students to participate in authentic STEM practices, typically through inquiry activities, independent research and presentations, or project-based learning. These experiences provided all students with opportunities for active and hands-on learning. They were also intended to help support and sustain student interest in STEM disciplines. An example of this was evident at Summit Road STEM Elementary, where students were encouraged to develop questions and define problems and to design approaches to answering those questions and addressing the problems. In one case, when students wondered how they could retrieve playground balls that often fell or rolled into the small pond in the front yard of the school, the staff didn't provide a solution, but supported students to use the school's adopted inquiry cycle of "imagine, plan, design, improve and share" to develop and deploy their own solution for rescuing their playground balls.

Widespread Use of Design Cycle

Engaging in science and engineering practices helps students develop a holistic understanding of the disciplines in STEM (National Research Council, 2012). One of the most prominent engineering practices from the *Next Generation Science Standards* is engineering design. Engineering design is broadly a problem-solving process that is product-driven and involves multiple phases including defining a problem, gathering ideas, testing ideas, and refining the product (Johri & Olds, 2011). In the elementary classroom, the same design cycle can be used when students work collaboratively to solve a problem in a way that develops a product (Pleasants & Olson, 2019). Teaching through engineering design is new in elementary classrooms. Teachers find value in it (Capobianco, Delisi, & Radloff, 2018), but it is not pervasive in classrooms due to the need for professional development experiences and the challenges imposed by an already tight teaching schedule (Capobianco, Diefes-Dux, Mena, & Weller, 2011).

Across the case study schools in this study, however, one of the most prominent STEM-focused features was the use of an inquiry cycle or design cycle in lessons throughout the curriculum and across all grades. The number and definition of steps in the cycles varied across the schools but generally included steps for students to identify a question or issue, generate possible solutions or designs to address the issue, articulate specific plans for a selected solution or design, put the plan into practice and gather feedback, and then use the feedback to refine and improve their plan. These design cycles were familiar to all students across the study schools, and served as orienting devices to guide and support student learning experiences.

The Engineering Design Process (EDP) used at Brentwood Magnet Elementary, for example, included the 5-step cyclical process of "Ask, Imagine, Plan, Create and Improve." This cycle was used in all classes and with all content areas. Brentwood staff explicitly guided students in the use of the EDP to help them engage with content and projects by showing them how to focus their questions, consider all possibilities, manage their time and resources, implement their designed solution, test and observe this solution, and make improvements based on their observations and feedback. Administrators, teachers, parents and students consistently described the cyclic process in the same way. A fifth grader at Brentwood explained, "Everyone here at the school knows the engineering design process. Imagine what we could build. Plan out your design. Improve it for your second design. We write down what we can do to improve it, ask what could be better and create it again. We think of ourselves as engineers – even if it isn't our professional job, everyone is an engineer – even if it is in a tiny way – I think everyone can be an engineer and we can all make a difference."

In a Brentwood 5th grade class observed during a math lesson, students were working at four different stations. At one of these stations, a pair of students worked on a design for a water well – an activity the rest of the class had earlier completed. Because these students' first design didn't work, they were using their prior experience to create a second well design using different materials. They explained without embarrassment or apology, "We have the chance to improve it" referring to the "Improve" stage of the EDP. They saw the repetition of the cycle as simply part of engineering design and a routine part of learning.

21st Century Skills Use for STEM Learning

The students of today will be working in settings where complex and non-routine challenges outpace routine work. As technologies continue to change social interaction and the nature of work in many fields, an emerging body of research suggests that a set of skills known as "21st Century Skills" are increasingly valuable and even necessary to succeed now and in the future. Proponents of the 21st Century Skills movement emphasize that schools must help students build skills—such as adaptability, complex communication skills, and creativity—that will help them use their content knowledge most productively (Dede, 2010; Rotherham & Willingham, 2009). In particular, researchers have identified science learning experiences and project-based learning as strong contexts for helping students develop important 21st Century skills (NRC 2010; Musa, Mufti, Latiff, & Amin, 2012).

Consistent with this view, evidence of emphasis on 21st Century Skill development was seen in the five schools in this study. The school staff at these schools saw 21st Century skills as essential for students' success as future STEM practitioners and STEM-fluent citizens. To this end, students were frequently given opportunities to practice and improve these skills and were supported by staff in this development process. A school leader from Brentwood said, "I tell the parents if [their children] can communicate their thoughts, think critically, and problem solve, they can be successful in any realm that they choose." This school leader acknowledged that not all of their 500 students will ultimately end up working as engineers, and that many will "choose a different path, but those essential skills, I think, are beneficial for all of our students and families and community."

Jamerson also provided a clear example of how students engage in daily practice of 21st Century Skills in the classroom. Jamerson's Engineering Design Process challenges required students to put their content knowledge to use as well as practice collaboration, communication, and perseverance. In one design challenge for second graders, students collaborated to publish a report describing the features of an engineering design they created and how they used research and prior knowledge in its development. Students also shared their engineering design solutions at fall and spring Engineering Expos, presenting their engineering projects to peers, families, and community partners.

High-level STEM Content

The establishment of STEM-focused schools is often a strategy for districts and local education agencies to increase rigor within their portfolio of schools (Peterson, Bornemann, Lydon & West, 2015; Thomas & Williams, 2009), and the use of project-based learning has been found to be associated with higher levels of rigor in STEM high schools (Edmunds, Arshavsky, Glennie, Charles & Rice, 2017). At the secondary level, research has explored whether STEM-focused schools actually fulfill their promise of strong student achievement, with mixed outcomes (Means, Wang, Young, Peters & Lynch, 2016; Eisenhart, Weis, Allen, Cipollone, Stich & Dominguez, 2015).

Like STEM schools at the secondary level, the exemplar elementary schools in this study certainly ascribed to the ambition of engaging in more rigorous teaching and learning in their STEM-focused programs, and consider it a critical component of their school STEM models. In doing so, these schools engaged students with increasingly complex STEM content throughout the curriculum which built across grade levels. This included complex STEM content beyond district and state requirements as well as beyond what is offered in standard elementary curricula. In all five case study schools, student achievement scores in science, reading and mathematics bore this out.

At Summit Road STEM Elementary, lessons brought its environmental science focus to life by giving students direct learning experiences in the adjacent wetlands. These wetlands lessons were interconnected so that the activities provided learning foundations for lessons to follow the next grade level. Student visits to the wetlands and other environmental science work provided a context for working on many of the science content standards while also integrating practices of science and engineering along with other subjects. In the classroom, for example, first grade students incubated chicken eggs. Over the course several weeks, accompanying lessons covered second grade standards on life science, including observations of living things and their interaction with the environment.

Student Ownership of Learning

Research in psychology suggests that student agency and autonomy can be important for supporting student self-efficacy with respect to learning. In one study, students' beliefs in their ability to engage in self-regulated learning affected their self-efficacy for academic achievement as well as their academic goals and achievement (Zimmerman, Bandura, & Martinez-Pons, 1992).

A component common to the schools' STEM programs was the emphasis on providing students support to use a continuous improvement approach in their own learning, develop a growth mindset, and develop agency as learners. At each of these schools staff emphasized that mistakes are part of learning and encouraged students to develop the ability to take risks and to reflect on their own learning process.

Walter Bracken STEAM Academy provided a clear example of this approach, where staff strove to spur curiosity, inquiry, and creativity, ultimately fostering in students an ownership of their learning. In the classroom students were usually active, such as rotating among stations, working on long-term group projects, or participating in investigations facilitated by a teacher. Lessons were consistently designed to provide students with choices within projects and assignments. As one teacher explained, "Students always have choice. Students will learn more if they're engaged. If you don't take ownership of what you're doing, you'll be miserable." Although students had opportunities to move around and work actively, they were also engaged cognitively through inquiry and design thinking. Students and staff routinely discussed questions such as, "What do you think about that? How can we make that better? Is that the best solution?" These reflection opportunities created an environment where students were engaged and attentive to their learning and students felt involved. This learning style is in stark contrast to compliance-based learning in which the student is simply told what to do and follows directions.

Beyond lesson design, student ownership of learning was intentionally discussed and supported at the five study schools. Students were familiarized with learning strategies, what to do if they were struggling, and different ways to seek out help. Because learning, trying, and sometimes failing were often discussed explicitly, students understood learning as an ongoing process. A Bracken fourth grader said, "They [teachers] make sure we have self-esteem so we can keep going," adding that "…teachers are really supportive and they never really put you down. Next time you will get it. Next time we need a better system."

Evidence-based Improvement

While the current policy climate favors use of specific types of evidence (e.g. standardized tests), different actors within schools including teachers and administrators have a broad range of types of evidence they can draw from in their work to improve their schools and professional practices (Coburn & Talbert, 2006). The organizational structures and processes of ongoing improvement are also key features in a school that embraces evidence-based improvement (Hallinger & Heck, 2010).

The final component common across the five STEM-focused case study schools was that of school leadership and staff using evidence to continually improve their schools and refine their STEM programs. In these schools, data-driven decision making, informed by multiple information sources, was carried out through a design/implement/evaluate cycle. Parallel to the design cycle that staff use with students to support their learning, leadership and staff at the schools engaged in continual improvement and strived to continuously innovate in their school STEM design and curriculum.

At Brentwood Magnet Elementary, time was built into the teacher weekly schedule to review student performance data and make grade level plans. One day each week, grade level Professional Learning Teams (PLTs) analyzed data gathered from student performance to plan instruction. Brentwood also had a weekly Mathematics Team Time at each grade level to provide tailored mathematics instruction to students after reviewing individual student skills and performance. The Intervention Team consisted of teachers who met to observe student data from those who were below grade level performance to determine their progress. Brentwood was very transparent about their school-level test scores, and test score information was posted prominently outside of the office on a bulletin board for students, teachers, and guests to see. Brentwood used assessments from a variety of classroom-based, grade level-based, and state-level sources. The state and district provided many sources of information on student performance, however, Brentwood also administered school-selected additional assessments so they could work with additional details on student progress. Brentwood teachers used student data collected each month to inform decisions about individual student learning needs and supports.

Assessments at Walter Bracken STEAM Academy were strategically embedded in the school calendar so that feedback could be collected to make decisions at the school, grade, and individual classroom levels. Teachers and administrators use the information provided through data, analyzing it frequently to make nimble adjustments in their practices. The work of teachers was data-driven. Within grade levels, teachers compare student achievement data to ensure each class is making similar accomplishments. While teachers are free to use different types of instruction and different activities, they all check to see that they arrive at the 'same finish line' by regularly comparing their student data. Teachers report that the process of sharing data helps them strive to be better. In addition, the principal asks teachers to look to the highest performing teacher on a particular assessment, find out how the teacher achieved those results, and then consider if there are effective practices worth adopting in their own instruction.

STEM Program Summary

This final set of components focused on the enactments of elementary STEM, describing the components key to implementing elementary STEM programs and learning opportunities. This set of features portrays learning experiences where students actively participate in lessons in which STEM disciplines intersect and build to complex and rigorous content. These lessons challenge students intellectually, as well as provide them with active and responsible roles in their learning. In support of these experiences, students are mentored to use a standard design cycle as a familiar process or heuristic when facing new problems or questions. As well, they are supported in developing skills that help them work in a dynamic and collaborative context, employing adaptability, complex communication skills, and creativity as they face challenges side by side with their peers.

CONCLUSION

Building on the critical components known to characterize exemplar inclusive STEM high schools (Lynch et al., 2017), the goal of this study was to identify and define the critical components common to five exemplar STEM-focused elementary schools and to understand how their design provides unique STEM learning opportunities for students. The schools in this study were selected because each has demonstrated success in maintaining an effective STEM-focused school over time. Together, they provide significant insights into offering students a STEM-focused elementary school experience. Through cross-case analysis, 17 common components were evident as critical to the STEM school design and implementation. While the schools had these components in common, they were situated in unique contexts, with distinct histories, settings and communities. We speculate that other elementary schools that are successful in providing a rigorous and immersive STEM focus would also demonstrate these 17 components. The consistency of the components with prior findings from Inclusive STEM High Schools (ISHSs) (Lynch et al., 2017) and the research on effective elementary schools (Bryk et al., 2010) affirms the prior research as well as adds to the growing knowledge base of STEM education with a focus on elementary practices, curricula and culture.

The 17 components in this study articulated essential design elements related to each school's Purpose and process, Community relationships, School staff, School STEM resources, and STEM programs. These were organized into three sets of components within the logic model. First were those that were foundational for the STEM school design, which provided a purpose, climate and organizational structure. The inclusive mission, climate of intellectual safety and distributed leadership involved bringing all students and staff together to engage in STEM and to take risks as they address questions, solve problems, practice skills, and participate in the STEM learning community. These schools were consistently more diverse in student background than other schools in their districts, and performed in standardized assessments as well or better than other schools in their districts. The school's mission, support and leadership components provide a strong basis for accomplishing such outcomes.

The second set of components in the logic model describe the key participants and resources that provided the means for STEM program implementation. Together these seven components provide a rich, engaging and varied STEM learning environment. The schools involved teachers in developing core STEM curricula resulting in a sense of ownership of and personal engagement with STEM as a subject area. They leveraged staff positions to involve more staff in STEM beyond grade level classrooms. And they engaged both community members and local STEM experts as well as the school setting itself to enrich these learning experiences and expand their shared community of STEM practitioners.

The final set of components describe the implementation of the school STEM design, articulating the key features that could be seen in the classrooms. In this environment, learning experiences actively engage students in lessons that address interdisciplinary and rigorous STEM content. The lessons challenge and support students through the application of a consistent design cycle as a structure for facing new problems or questions. In addition, students are supported in their acquisition of 21st century skills that can help them work in a dynamic and collaborative context.

This project sought to help answer how schools can meet parent and community demand for STEM-focused education and how to provide more students with the inclination, inspiration and preparation to participate in further STEM studies in middle school, high school, college and beyond. The components and framework provided here are those that characterize five exemplar STEM-focused elementary schools and offer other schools insight for offering their own STEM-focused programs.

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