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Rural Secondary STEM Teachers' Understanding of the Engineering Design Process: Impacts of Participation in a Research Experiences for Teachers Program

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Though STEM teacher professional development is known to be beneficial, it is not available equally to educators in all geographic regions. Rural educators face unique challenges not often experienced by their urban and suburban counterparts. This study investigates the impacts of a Research Experiences for Teachers (RET) program on rural math, science, and technology education teachers' perspectives on how these experiences changed their understanding of the engineering design process (EDP). From 2016 to 2019, eleven rural secondary STEM teachers engaged in a six-week professional development experience focused on research and implementing the EDP. These teachers were rural "solitary" STEM teachers, which meant they were the only teacher of their subject in their school building. This qualitative study used a thematic analysis approach to code and analyze individual and focus group interview transcripts. The results were analyzed to determine how the RET experiences impacted the teachers' perception of how the EDP is used in problem-solving activities and how it could be integrated into their classroom practices. Results from this study show that the teachers developed a more authentic conceptual understanding of the EDP, which led to increased insightfulness on how to engage students in authentic engineering design activities that strengthen future workforce skills. This study demonstrated that an authentic engineering-based RET program can increase rural teachers' commitment and readiness to incorporate the EDP into regular classroom practices. Further, this program resulted in teachers gaining a much more nuanced understanding of how the EDP's non-linear steps and iterative nature contribute to creating authentic problem-solving challenges for students. In particular, the teachers realized the necessity of creating less prescribed challenges that require students to draw upon the constellation of skills necessary to design optimal solutions, resulting in higher-caliber opportunities to develop future workforce skills. These findings emphasize the critical need to design professional development experiences that target the unique needs of rural STEM teachers. Additional research is needed to tease out the extent to which teachers' increased commitment to using the EPD and a more nuanced understanding of the EDP translate into sustained changes to classroom practice.

***Keywords*: rural teachers, STEM education, engineering design process, research experiences for teachers, professional development, qualitative methods**

Science, Technology, Engineering, and Mathematics (STEM) education is a significant dimension of national conversations on education. The skills necessary for students to be successful in the future workforce include collaboration, communication, critical thinking, and creativity (i.e., the 4 C's) as well as other 21st century skills such as problem-solving and design thinking, referred to in this document as "workforce skills" (National Science and Technology Council, 2018; P21, 2019). Exposing teachers and students to the engineering design process (EDP) has become a national imperative to prepare students for the future workforce as effective implementation of the EDP incorporates many desired future workforce skills. However, the ability to effectively integrate the EDP in school classrooms usually requires targeted professional development explicitly focused on the understanding and implementation of the EDP (Parker et al., 2020). Providing opportunities for teachers to improve their teaching practice is essential for improving the student learning experience (Anderson & Tully, 2020; Darling-Hammond & Baratz-Snowden, 2005; Guskey, 2002; Landis et al., 2011; Wei et al., 2009). Specialized professional development experiences are vital for rural educators because they face challenges that differ from those encountered by teachers in urban or suburban school districts. Rural educators often lack access to professional development about the EDP (Parker et al., 2020; Showalter et al., 2019) and require unique solutions to their professional development needs.

Professional Development in STEM Education

Integrating engineering or scientific research into teacher professional development has shown to increase teachers' awareness of the need to incorporate authentic learning activities into their classroom practices regularly (Barrett et al., 2015; Barrett & Usselman, 2005, 2006; Basalari et al., 2017; Bowen et al., 2018, 2019, 2021; Farrell, 1992; Kantrov, 2014; Silverstein et al., 2002, 2009). Teachers have reported a shift in their pedagogical approach to incorporate the use of more workforce skills in the classroom as a result of participating in targeted professional development (Bowen & Shume, 2018, 2020; Darling-Hammond & Baratz-Snowden, 2005; Stewart, 2014; Webb, 2015). Through such pedagogical approaches, teachers provide opportunities for their students to engage in authentic 21st century learning (Landis et al., 2011). Comprehensive programs designed to target these pedagogical shifts, such as the National Science Foundation's (NSF) Research ss for Teachers (RET) Program, can provide highly effective professional development for teachers (Bowen et al., 2018, 2019, 2021; DeJong et al., 2016).

Barriers for Rural Educators

Though STEM teacher professional development is known to be beneficial, it is not available equally to educators in all geographic regions. Rural educators face unique challenges not often experienced by their urban and suburban counterparts. Geographically, the distance between cities, towns, or educational communities creates barriers to finding and attending high-quality professional development activities (Showalter et al., 2019). Rural educators often teach multiple courses and grade levels, requiring substantial time commitments to prepare lessons for multiple course subjects and student knowledge levels (Barley & Brigham, 2008; Goodpaster et al., 2012). Given the additional planning load necessary to design course materials for such a wide variety of curricula, these teachers face significant barriers to making transformational changes in their teaching practices. Rural school structures may also be more resistant to change, increasing the difficulty for STEM educators to implement innovative teaching methods

(Goodpaster et al., 2012). Moreover, rural schools face funding barriers for providing quality professional development and properly equipped educational facilities (Player, 2015; Williams, 2010). Compared to urban and suburban educators, rural educators also report less access to quality professional development, professional learning communities, and other collaborative supports such as common planning times and opportunities to observe their peers (Glover, 2016; Lavalley, 2018; Wei et al., 2009).

Rural Educators in STEM Education

Over and above the barriers commonly experienced by rural educators, rural STEM educators face additional layers of challenges. Rural areas in the United States have higher teaching position vacancy rates in STEM content areas than non-rural areas (Dee & Goldhaber, 2017; Player, 2015). Due to the large number of vacancies, it can be difficult for rural STEM educators to receive support and proper mentorship from their peers and supervisors (Lavalley, 2018), one of the primary negative factors of rural STEM educator retention (Goodpaster et al., 2012). These teachers also reported a lack of access to research and specialty community-based or university-based resources and programs due to the lack of offerings and the geographical distance necessary to attend (Player, 2015).

The EDP for Rural STEM Educators in RET Programs

There exists a significant need for more engineering-related professional development for rural educators (Ficklin et al., 2020). RET programs are an example of how teachers can engage in engineering-focused professional development by participating in authentic research projects. The outcomes of one RET program that engaged high school science teachers in rural Michigan showed the teachers developed a positive change in attitude toward using engineering in the classroom and an increased amount of integration of engineering concepts into their classroom activities (Yelamarthi et al., 2013). The teachers also reported an increased understanding of the concept of the EDP and the use of collaborative instructional practices (Yelamarthi et al., 2013). In other engineering-focused RET programs, teachers reported learning the benefits of using the EDP to increase student engagement (DeJong et al., 2016), developing higher levels of confidence in integrating the EDP into their science instruction (Pinnell et al., 2013), and enhancing their instruction by incorporating authentic engineering applications (Reynolds et al., 2013). Effective RET programs can improve participants' confidence and readiness to integrate engineering concepts into their classroom practices through the use of the EDP.

Professional development centered on the EDP needs to foster depth of understanding about key aspects of the EDP. When designing solutions to a given problem, engineers implement the EDP. This process consists of several constructive steps, such as asking questions, conducting research, and creating prototypes. It is a non-linear iterative problem-solving process that is inherently open-ended, with multiple solutions being plausible. Integrating the EDP into classroom activities allows students to utilize and develop future workforce skills. However, the EDP can be messy, and integrating it effectively into classroom activities requires a skilled pedagogical approach. For example, when implementing activities that utilize the EDP in the classroom, the teacher should promote a student-centered classroom management approach to guide student thinking and promote student learning by asking probing questions (Garrett, 2008; Krahenbuhl, 2016). In this role, educators are auxiliary to student learning, contrary to many traditional teaching methods. Many teachers are hesitant to undertake this approach because this teaching style may be unfamiliar, and they have not had the proper training (Cejka & Rogers, 2005; Guzey et al., 2014; Hammock & Ivey, 2017; Lottero-Perdue & Parry, 2017).

The RET program in this study was uniquely designed to engage rural teachers in authentic research by utilizing the EDP. The focus was the process of engineering design and not on gaining additional or specific content knowledge; nonetheless, content knowledge was implicitly learned through the RET activities. A concrete understanding of the EDP is at the forefront of engaging students in authentic design experiences that foster future workforce skills.

Research Question

The current research project reports data collected from an NSF-funded RET program at a university in the upper Midwest. The RET program provided "solitary" rural STEM teachers with an immersive research experience focused on the knowledge and skills required to integrate the EDP into their classroom practices within an agricultural framework. The research question guiding this study was: How do rural secondary mathematics, science, and technology education teachers describe the impacts of an engineering-based RET program on their understanding and approach to integrating the EDP into classroom practices?

Program Description

The three-year RET program in this research study was conducted from 2016 to 2018 at a university in the upper Midwest of the United States. The researchers also used a one-year no-cost extension in 2019 to offer additional professional development activities both virtually and on-campus. The participants included five in-service and five pre-service teachers each year, with one in-service and one pre-service teacher working in a pair throughout the program. The six-week program engaged the teachers in research incorporating the EDP through an agricultural context since agriculture is a significant influence in the region. The faculty-led research projects incorporated the development of electrical hardware, software design, and bio-based materials to investigate sustainable materials and precision agriculture. A few project examples include Electrical Properties of Bio-Composite Materials, Development of Thermoplastic Bio-Based Composites for 3D Printing, Measurement of Plant Growth Effect on Wireless Sensor Signals, Statistical Analysis of Moisture Sensor Performance, and Development of Bio-Based Resins from Vegetable Oils.

Program activities incorporated some of the best practices that research literature suggests on effective professional development. Some of these include consistent interaction between the teacher participants and the project team (Guskey, 2002; Guskey & Huberman, 1995; Parker et al., 2015; Sunyoung et al., 2015), multiple opportunities to model the desired K-12 learning activities (Bang, 2010; Guzey et al., 2014), and shared experiences with colleagues (Barrett & Usselman, 2005, 2006; Fullan & Hargreaves, 1992; Guskey & Huberman, 1995; Loughran, 2002). During the academic year, follow-up collaborations were provided to support each participant as they translated their research experience into classroom practices. Other support systems were provided, such as equipment and materials to incorporate newly developed classroom activities and the establishment of a virtual rural STEM educator professional learning community. At the conclusion of each summer experience, the teachers created a poster for a campus-wide research symposium and presented their research to several different audiences.

After the teachers implemented one of their new lessons, they were required to reflect and refine the lesson design as part of the submission and approval process for the teachengineering.org website managed by the University of Colorado at Boulder.

Methods

Given the interpretive nature of the research question driving this research, thematic analysis was selected as this study's methodological approach. Thematic analysis is a process for finding patterns of meaning in qualitative data through cycles of reading and rereading to identify key themes (Braun & Clark, 2006; Flick, 2014). Using NVivo software, researchers coded the data and collated codes into themes. As described by Braun and Clark, a theme "captures something important about the data in relation to the research question, and represents some level of patterned response or meaning within the data set" (2006, p. 82). The data were analyzed to identify patterns of meaning in the teachers' viewpoints on how the engineering-based RET experience influenced their classroom practices.

Study Participants

This research study included five in-service and five pre-service teachers each year, with one in-service and one pre-service teacher working in a pair throughout the program. The in-service teachers were classified as "solitary" rural secondary STEM teachers, meaning they were the only mathematics, science, or technology education teacher in their school building for grades 6-8, 9-12, or 7-12. To recruit in-service teachers for the program, the researchers contacted the local Regional Education Associations in the upper Midwest region of the United States to identify teachers that met this qualification. The researchers contacted these teachers by email to determine their interest in participating in the RET program; consent to participate in the research study was obtained separately. Although pre-service teachers were part of the RET program, for this research project, the researchers focused only on the research outcomes of the in-service teachers.

Seven teachers participated for one year, and four participated for two years; therefore, a total of eleven in-service teachers participated in the RET program and research study. Three participants were male, and eight participants were female. All the in-service teachers taught either mathematics, science, or technology education (referred to in this study as "STEM" courses). In some cases, they taught more than one STEM subject with some additional non-STEM teaching responsibilities, such as English Language Arts or social studies. Table 1 describes the RET in-service teachers who participated in this study. For the remainder of the article, study participants will be referred to as "teachers," and their content area will be referred to as "STEM."

Table 1

RET participant descriptions

Participant Pseudonyms	Years of Participation	Gender	Grades Taught	Subjects Taught
Amber	2016, 2018	Female	8-12	Biology
David	2016, 2017	Male	7-12	Biology, Chemistry
Austin	2016, 2017	Male	7-12	Math, Science
Kayla	2016	Female	9-12	Biology, Chemistry
Leigh*	2016	Female	7-12 4-8	Biology, Chemistry, Science ELA**, Science, Social Studies
Jake	2017	Male	8-12	Science
Anna	2017	Female	7-12	Science
Ashley	2017, 2018	Female	9-12	Math, Science
Erin	2018	Female	7-12	Science
Jessica	2018	Female	6-8	Science, STEM, Social Studies
Emily	2018	Female	K-12	Technology Education

* Leigh taught in two different schools and multiple subjects during the research project
** ELA=English Language Arts

When a STEM subject is listed in the table, it indicates the teacher was the only one who taught that subject in the school building for the grade levels listed. If a teacher taught more than one course within a specific subject area, it was common for them to refer to their courses using a general term (i.e., using the term "science" to describe multiple science courses) instead of referring to each course separately.

Data Collection

Individual in-person interviews were the primary method of data collection for this study. The semi-structured interview protocol consisted of a set of core questions asked at every interview, along with additional probing questions posed by the interviewer to explore topics of interest raised by the participants. Each summer, every teacher was interviewed individually during their time on campus participating in the RET program. The teachers who returned for a second summer in 2017 participated in group interviews. Additionally, second interviews were conducted in the fall with the teachers who participated in 2018; most of these interviews took place in person, but a small number were conducted over the phone due to geographic distance. The interviews, approximately 30–45 minutes in length, were audio-recorded and transcribed verbatim for analysis.

Data Analysis

To search for patterns of meaning in the interview transcripts, the researchers followed Braun and Clark's 6-phase guide to perform thematic analysis. In particular, the researchers undertook an iterative process that involved the following phases described by Braun and Clark

(2006): "1) familiarizing yourself with your data, 2) generating initial codes, 3) searching for themes, 4) reviewing themes, 5) defining and naming themes, 6) producing the report" (p. 86). Importantly, this methodological approach does not consist of a linear set of steps completed sequentially, but rather a "more recursive process, where movement is back and forth as needed, throughout the phases" (Braun & Clark, 2006, p. 86). The themes produced by this thematic analysis are consistent with Patton's (2015) criteria of internal homogeneity and external heterogeneity. In other words, each theme is coherent within itself but distinct from the other themes.

Findings

The thematic analysis produced four themes that captured repeated patterns of meaning expressed by the teachers during their interviews. The four themes are an increased focus on the EDP, the teachers' development of a more authentic and sophisticated conception of EDP, teachers' recognition of the importance of student metacognition during the EDP, and teachers relating and empathizing with students' experiences implementing the EDP.

Theme 1 - Increased Focus on EDP

Teachers were immersed in experiencing and implementing the EDP while engaged in authentic engineering research projects daily throughout their summer experience. For some teachers, the centrality of the EDP in their daily work during the summer experience served to reinforce the importance of having students apply the EDP in their classrooms. For others, their RET experience initiated a major change in their view on the role of the EDP in their teaching. For example, Jake said,

> I have seen how this engineering design process works . . . It's a blueprint. It's a road map, whatever you want to call it, to succeed at designing. I've never shared that with students before. I've never cared about it before. This has been kind of eye-opening.

Similarly, Amber explained,

> Before I came, it [knowledge of EDP] was very, very limited. It wasn't something that we really focused on when I was in my undergrad [degree program]. It was definitely not something we focused on when I was in school, like high school or anything. Before the [RET] program at all, I had very limited knowledge . . . That's really my main focus coming out of this summer. I really want to incorporate more engineering design into all of my classes.

One of the most prevalent themes was that teachers came to recognize and deepen their understanding of the value of making room for classroom learning experiences that engage their K-12 students in the EDP.

Theme 2 - More Authentic Conceptions of EDP

Over the course of the program, most teachers developed a more nuanced and sophisticated conception of what the EDP is and how it works. Through participation in the RET program, many teachers came to more fully understand that the EPD is not a linear set of steps but rather an iterative process that involves a kind of messiness that is not neat and straightforward. Leigh explained,

> Kids really like black and white and I think it's why teachers go there so often. . . . Realistically, I think that's the easier way to go and so a lot of us get stuck doing that because the kids like it because there's a clear yes, no, there's a clear right, wrong . . . but that's not realistic. Real life isn't all black and white, it's not right and wrong, you've got errors and you've got troubleshooting and you've got all of these steps in between.

Like other teachers in the program, Kayla expressed an increased commitment to providing her students with classroom learning experiences that aligned more authentically with the fundamental nature of the EDP. She said,

> Looking back at how I've been teaching where it's like I kind of lost that in-between problem-solving–research component. I've wanted them to have their results without having to put all the effort in, I guess? And I'm realizing now that that's not the path that I want to go down, that staying more true to the ingenuity and the design process and research process . . . I really have, like I said, really gotten that sort of renewed, I don't know what to call it, the renewed idea or the renewed, lack of a better word, passion for the research that goes into it and the real experience of it.

Teachers came away from their RET experience with a deeper understanding of the iterative nature of the EDP, particularly with regards to the role of multiple design revisions based on repeated testing. This increased awareness translated into an increased commitment to attending to the authenticity of classroom EDP experiences for students.

Theme 3 - Importance of Student Metacognition about EDP

Many teachers reported that prior to participating in the RET program, they would have their students apply the EDP without engaging in authentic reflection about it. Some teachers indicated that when they had their students use the EDP in class, the learning activities involved moving through the steps of the EDP without calling attention to explicitly identifying the steps. Others indicated EDP steps were named, but they missed opportunities to have students reflect on their use of the EDP. A representative quote from Jessica stated,

> I think really looking at reflecting on what went right, what didn't go right. I want to really bring in that reflection piece and making sure that students are writing down their steps. What step of your engineering design process are you in? What is happening? Make sure you're writing data. Because I know I haven't really expected them to do that before, and I think that's a huge piece to this [RET] project, was the reflection on data, and more purpose behind it versus just build it and move on.

When Erin described the changes to her classroom practices after participating in her summer RET experience, she explained,

> I probably focused on one, the authenticity, and then two, the redesign a lot more this time around because historically we just do a project and then the project's over. So now we spend a little bit of time, "Okay, take those questions that your classmates asked you and how is that going to change where you go moving forward?"

After participating in the program, teachers reported increased awareness of the importance of slowing down and making time for students to recognize the steps of the EDP as they progressed through class projects. They also acknowledged that students need time to record their reflections and to ensure they are truly using their collected data to make design decisions. Teachers related this change toward fostering small and large group reflection in the classroom with the daily conversations and weekly research meetings that took place during their summer experience.

Theme 4 – Relating to Student Experiences with EDP

Another theme that emerged in this study came from what teachers gained through direct participation as a team member working through problem-solving while engaged in the EDP. Teachers discussed insights that arose from reflection on their summer experiences that allowed them to better understand and empathize with what students experience when engaged in design-based learning activities in the classroom. For example, Emily explained,

> I think for us to go through and experience the frustrations of certain things and just to know if we bring this back to the classroom, this is what students are going to be feeling, and working together with a team, and trying to throw in your ideas, and then come up with an idea that all of you are excited about doing.

A quote from Anna describes her increased awareness of the need for students to have sufficient time and opportunity to grapple with the EDP, a realization experienced by several teachers.

> Like I said, it's been a long time since I've been in a lab and done some actual hands-on research. And I think, well I know, I forgot that sometimes the problem-solving part of things takes longer and that piece of things actually sometimes takes more of the time than the actual product, once you get the process down. . . . And so I'm excited to take that kind of process back to the kids and being able to kind of present them with a problem of, "This is what we want, how do we get there?" And seeing the different paths that they take because depending on how they decide to go about it, they'll all run into different problems.

The RET summer experience brought several opportunities for teachers to step into the shoes of their students. Teachers reported that through their RET experience, they were reminded that feelings of uncertainty and frustration are a typical part of engaging in the EDP and that working together as a team requires time to explore potential solutions and work out the differences between team members.

Discussion

This research project investigated how rural mathematics, science, and technology education teachers described the impacts of an engineering-based RET program on their understanding and approach to integrating the EDP into classroom practices. Looking across the four themes produced by this study, two notable impacts are worthy of further consideration.

First, the teachers gained a stronger appreciation of the importance of using the EDP to engage students in authentic problem-solving as part of their regular classroom practices. They expressed an increased commitment to granting students more responsibility for navigating their way through the process and providing additional time to struggle with the iterative nature of designing. This outcome supports existing research reporting that teachers are significantly more motivated to integrate the EDP into their classroom practices after participating in an authentic engineering-focused RET program (Bowen et al., 2018, 2019, 2021; DeJong et al., 2016; Yelamarthi et al., 2013). Teachers in this study also expressed ownership and buy-in for implementing the EDP due to increased familiarity with the nature of the EDP and readiness to translate it from an engineering research setting into a classroom setting. Similar to the findings of Du et al. (2019) and Hart (2018), this shift in thinking demonstrated they felt more confident to use the EDP as part of their teaching, compared to other teachers who may have been hesitant due to the lack of training and expertise with implementing the EDP (Cejka & Rogers, 2005; Guzey et al., 2014; Hammock & Ivey, 2017; Lottero-Perdue & Parry, 2017). This outcome is especially important for rural teachers who lack access to high-quality engineering-based professional development compared to urban and suburban teachers (Lavalley, 2018; Wei et al., 2009).

Second, the teachers gained a more sophisticated perception of what is genuinely involved in conducting an engineering research project and the extent to which the steps of the EDP are nonlinear and deeply intertwined. Participation in an immersive engineering research program provided these teachers the authentic experience needed to gain perceptive insights about nuances involved in conducting a formal engineering design-based project. Through this understanding, these teachers realized that their previous teaching lacked authenticity with regards to the EDP's "messiness." Teachers reported that participation in this RET experience created an awareness of the necessity to develop less prescribed instructional scenarios and allow students more time for the iterative aspect of design projects. In this way, students will have more opportunities to develop the knowledge and skills needed to persevere through the problem and produce more optimal solutions, building students' foundations for future workforce skills.

Conclusion

Rural educators, particularly in the STEM fields, encounter unique barriers when seeking to incorporate more engineering-related activities into their classroom practices (Barley & Brigham, 2008; Goodpaster et al., 2012; Player, 2015; Showalter et al., 2019; Williams, 2010). These teachers need increased access to high-quality professional development activities in order to become adequately prepared for engaging their students in learning activities focused on the EDP, a vital dimension of promoting future workforce skills. This study demonstrated that an authentic engineering-based RET program can increase rural teachers' commitment and readiness to incorporate the EDP into regular classroom practices. Further, this program resulted in teachers gaining a much more nuanced understanding of how the EDP's nonlinear steps and iterative nature contribute to creating authentic problem-solving challenges for students. In particular, the teachers realized the necessity of creating less prescribed challenges that require students to draw upon the constellation of skills necessary to design optimal solutions, resulting in higher caliber opportunities to develop future workforce skills. Overall, through participation in this RET program, the teachers gained a broader appreciation of the EDP's impacts on student learning and engagement. These findings emphasize the critical need to design professional development experiences that target the unique needs of rural STEM teachers. Additional research is needed to tease out the extent to which teachers' increased commitment to using the EPD and a more nuanced understanding of the EDP translate into sustained changes to classroom practice. Professional development that increases rural STEM teachers' readiness and commitment to implementing authentic EDP experiences in their classrooms is an essential pathway to developing rural students' future workforce skills.

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