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Navigating Pre-college Engineering Teaching During COVID-19: A Review and Analysis of Teacher Experiences

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The start of the COVID-19 pandemic with its unique constraints led teachers of all disciplines, across all levels, to employ diverse strategies in their quick transition to online learning. Emerging literature has suggested readiness and resources for the transition to remote learning along with intrinsic and extrinsic factors such as student motivation and engagement to be frequent challenges faced by teachers. The purpose of this work is twofold: a) conduct a review of the immediate post-pandemic literature to summarize the study and challenges of teaching STEM courses during the pandemic, and b) summarize the study experiences of secondary teachers teaching a pre-college engineering course at the beginning of the pandemic. Collectively the literature review and experimental findings enable greater understanding and sense-making of adaptations made to prepare for future abrupt changes that may arise. Focus group data (n= 39) of secondary school engineering teachers were analyzed qualitatively using sensemaking theory to reveal several challenges faced and strategies adopted during this unprecedented time.

Our review of immediate post-pandemic literature suggests lack of student engagement and motivation, scheduling, access to the ‘right’ resources, and training with technology were the most frequent challenges experienced by teachers. Our empirical findings demonstrated similar challenges faced by a sample of pre-college teachers teaching a new engineering course which were summarized into four themes: teaching logistics, time management, available support, and regulations. The themes provide the foundation for mitigation strategies during a crisis or abrupt change in the future.

INTRODUCTION

Educational experiences immediately following the onset of the COVID-19 pandemic created unique environments to better understand how teachers navigated forced pedagogical transitions. The resulting conditions, particularly for STEM courses that traditionally leveraged in-person, hands-on, experiential learning activities, provide an interesting case for examining transitions to remote learning (Gillis & Krull, 2020; Marshall et al., 2020). This paper explores the experiences of secondary teachers teaching a new engineering course as they transition to remote learning immediately after the onset of the COVID-19 pandemic. Their experiences are framed by a review of the literature that emerged as a result of the pandemic coupled with an empirical analysis of survey data obtained from pre-college engineering teachers involved in a multi-institutional project designed to demystify engineering and democratize engineering education for all students in the United States (US).

The global pandemic created a scenario that required quick transitions, which were often completed with haste to limit gaps in service. These transitions were typically not smooth creating many ambiguities that make for a unique and intricate setting ripe for study, particularly within educational spaces. New challenges resulting from transitions forced upon teachers as a result of the pandemic are still yet to be fully uncovered and shared through the extant literature. This gap motivates our work to examine and chart examples of experiences and perceptions of pre-college engineering education during this unprecedented time. We address this gap through a complementary literature review and empirical study designed to answer our underlying research questions:

1. What are the study design and challenges surrounding pre-college STEM education around the onset of the COVID-19 pandemic.
2. What challenges did pre-college engineering teachers face at the onset of the COVID-19 pandemic

We begin by first providing some background information on the educational scene during the COVID-19 pandemic. This foundation sets the stage for the literature review section, which provides a summary of seminal work on pre-college STEM education around the time of the COVID-19 pandemic. The literature review is followed by an empirical study conducted with 39 participating pre-college teachers teaching a new engineering course. A sense-making and interpretive lens is used as a theoretical and methodological framework, respectively. The sum of the work is wrapped up within a discussion and implications for future research. The contribution of this work is to offer a conceptualization of the challenges, implications, and the role of COVID-19 (or other unforeseen natural disasters) on pre-college STEM education.

BACKGROUND

The world is in constant change, none greater than the recent changes caused by the COVID-19 pandemic. This unfavorable event was unexpected and affected all aspects of life, including formal education. Nobody had anticipated the drastic changes in their day-to-day living and way of communication. Isolation became a norm and true social, i.e., in-person interaction became nearly impossible outside of one's social bubble, making it difficult to build social knowledge.

The global pandemic led to school closings and forced teachers to quickly adopt new, or less explored modalities (e.g., distance learning, e-learning, and online learning) (Herro, 2022; Larson & Farnsworth, 2020; Makamure & Tsakeni, 2020). These modalities were not necessarily new, but the onset of the COVID-19 pandemic simply accelerated teaching shifts away from in-person settings toward remote or hybrid classrooms (Campbell et al. 2021; Deák 2022; Griesinger et al., 2023; Huang et al., 2020; Tsakeni, 2022). Students and teachers had to abandon face-to-face connections and connect to their peers and teachers through technological devices and the internet (Emiola-Owolabi et al., 2021b).

Students and teachers each had to make sense of the sudden changes through their extant knowledge and resources accessible during the state of emergency. Many solutions necessitated the use of technology (e.g., the internet and computers), which further exacerbated the challenges due to issues with access, connectivity, and tech savviness (Rassudov & Korunets, 2020). The disruption caused by the COVID-19 pandemic was a globally encompassing incident, but everyone experienced it differently based on a host of factors (e.g., predispositions and socio-economic status) (Deters & Paretti, 2021; Sealey et al., 2021). The resultant landscape also created a testbed to understand and recognize how teachers and students navigate teaching and learning engineering and/or STEM during unprecedented times.

Those teaching engineering and/or STEM courses were particularly challenged in their regular classroom duties because such courses typically include hands-on, design, or inquiry-driven content that focuses on developing students' critical thinking and problem-solving skills (Amedu & Hollebrands, 2022; Bourne et al., 2005; Canedo et al., 2021; Geczy et al., 2020; Hysaj, 2021; Meletiou-Mavrotheris et al., 2023; Rzanova et al., 2022). Such skills are regularly achieved using active pedagogical approaches (Lima et al., 2017), which require socially constructive and interactive learning with peers. Such skills can be demanding on pre-college students due to the required social constructive and interactive learning with peers and advanced metacognitive and cognitive capabilities (Brod, 2021). Active learning without a proper learning environment and guidance can lead to insufficient metacognitive and cognitive growth, especially for young students who are still developing such skills (Brod, 2021). Secondary engineering and/or STEM teachers leveraging hands-on activities and labs were faced with identifying alternative mechanisms to engage students in class content (Bansak & Starr, 2021). The sudden change in teaching modality and distress caused by the pandemic required teachers to make sense of it all in a relatively short period while advancing teaching and learning (Bansak & Starr, 2021).

Some researchers postulate that there can be growth from disruption (Bertling et al., 2020; Bishop, 2021; Davies & Bentrovato, 2011). It is our responsibility to learn from past events and prepare ourselves for future crises to avoid past pitfalls. The goal of this work is to review emergent post-pandemic literature and present empirical findings regarding the experiences of 39 secondary teachers teaching the Engineering for Us All (e4usa) program during this disruption. We frame this work by first providing some background information on COVID-19 and education. We then provide an immediate post-pandemic literature review aimed at identifying the challenges surrounding teaching pre-college engineering and/or STEM education, including more broadly STEM education. Next, we present empirical findings investigating the experiences of secondary school engineering and/or STEM teachers at the beginning of the pandemic and suggest implications and mitigation strategies for future crises. We explore the challenges faced by teachers teaching pre-college engineering and/or STEM courses during the onset of the COVID-19 pandemic. We define challenges as difficulties or changes teachers experienced as a result of the COVID-19 pandemic. The contribution of this work lies in the summarization and clarification of the diversity of challenges experienced by teachers when teaching pre-college engineering and/or STEM and the future considerations to be made if facing a similar crisis or abrupt change.

METHODS: LITERATURE REVIEW

The experiences of teachers teaching pre-college STEM courses, specifically engineering, have been studied in the literature before the pandemic (e.g., standards and implementation, evidence-based teaching, robotics education) (Borrego & Henderson, 2014; Eguchi, 2014; Roehrig et al., 2012; Watson & Watson, 2013), including comparisons of in person and online settings (e.g., Ford et al., 2018; Turley & Graham, 2019). There is a clear connection between teachers' challenges or stress factors and educational outcomes and experiences (Klassen & Chiu, 2010). This literature space has grown tremendously with the plethora of research that has emerged in the aftermath of the pandemic to capture the experiences of pre-college teachers and students. Several studies report on the challenges of teachers and students during the transition to remote learning, which did occur to a lesser extent prior to the pandemic (Bansak & Starr, 2021; Emiola-Owolabi et al., 2021a). Our review specifically examines the literature reporting on the experiences of pre-college teachers teaching engineering and/or STEM using modalities leveraged prior to or post-pandemic. This meant including literature prior to, during, and following the initial onset of the pandemic. This approach allowed us to leverage the most relevant articles to our study within and outside the onset of the COVID-19 timestamp.

Search process and analysis

The literature review was conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach (Page et al., 2021). An overview of the search process is captured in the PRISMA chart depicted in Figure 1. The first step was to search a string consisting of pre-college and (STEM or engineering) and education within SCOPUS, Web of Science (WoS), and Google Scholar databases. The OR operant is used to include any mention of engineering and/or STEM terms, while the AND operant was used to capture our focus in the pre-college level and education settings.

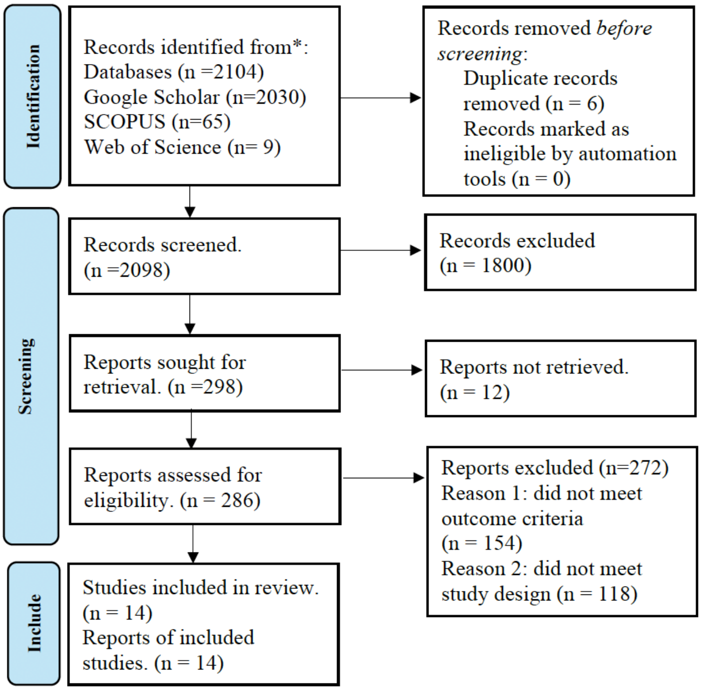

Figure 1. PRISMA chart.

The resulting papers were then downloaded and reviewed to identify and remove duplicate studies using Covidence, software for managing systematic reviews. The relevance of the remaining 2098 papers was then determined using a set of initial and secondary inclusion criteria listed in Table 1. The title and abstract of 286 articles were initially reviewed using the inclusion and exclusion criteria. An overview of the initial and secondary inclusion criteria can be found in Table 1. Our initial inclusion criteria excluded peer-reviewed articles disseminated in a language other than English or papers that were not peer-reviewed (e.g., grey literature). Our secondary inclusion criteria focused on STEM and/or engineering and pre-college studies for non-medical, business, finance, language learning, and other unrelated educational applications.

Table 1
Inclusion and Exclusion Criteria

	Inclusion criteria
Initial	Studies written in English
	Article and conference proceedings and books
	Peer-reviewed
Secondary	Studies focused on the challenges of transitioning to remote teaching during COVID-19, samples of pre-college teachers, as well as engineering and/or STEM contexts and specifically focused on perceptions and experiences

A total of 14 papers were full-text reviewed. This review included gathering full study records of each study before summarizing the articles. Study information included country of origin, year of publication, title of publication, keywords, data collection method, data analysis technique, resulting perceptions and/or experiences of participants, sample size, and content of teaching. An overview of the studies reviewed is first presented before summarizing the challenges and potential mitigation steps reported by the reviewed studies.

RESULTS: LITERATURE REVIEW

This section shares a summary of results pertaining to the preliminary review followed by the findings of our empirical study surrounding pre-college teacher's experiences (primarily challenges) teaching remote STEM/engineering education during COVID-19.

Summary of research studies reviewed

The reviewed publications were mostly conducted in the USA (10) with other studies being conducted in Canada (3) and South Africa (1). Included papers were published between 2011 and 2022 with the majority (5) being published in 2022. The studies primarily leveraged self-report surveys (9) for data collection.

Titles most frequently used the terms teachers, STEM, COVID-19, education and science which shows close relevance to our purpose for the literature review. The specific content areas explored by some studies included engineering and mathematical concepts like algebra. The experiences of teachers were most often explored (10) and the most prevalent participant size range among the reviewed studies was between 10 to 50 individuals (4). A full breakdown of data collection, data analysis, user group perceptions/experiences, and sample size can be found in Figure 2.

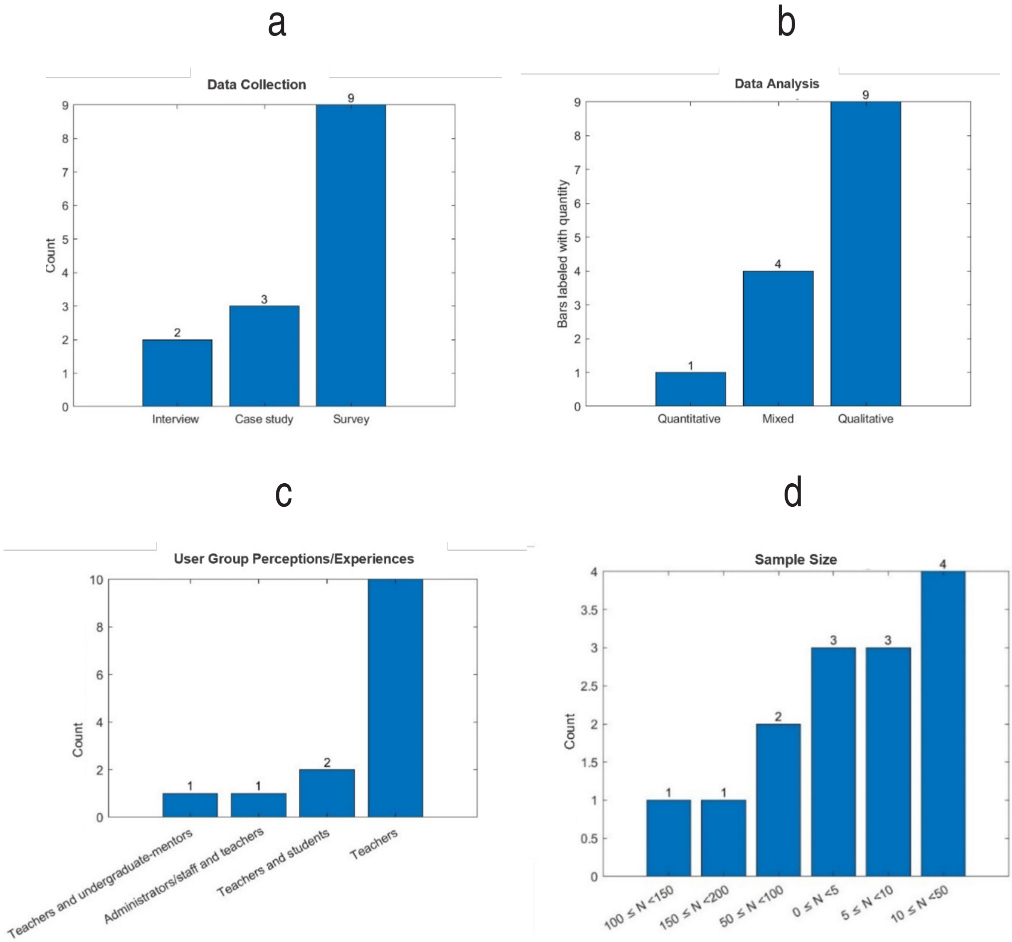

Figure 2. Bar summary of data collection of reviewed studies (a), Bar summary of data analysis of reviewed studies (b), Bar summary of user group experiences/perceptions of reviewed studies (c), Bar summary of participant size range of reviewed studies (d).

Review of challenges

A summary of challenges reported by the reviewed studies is presented in Table 2. The review revealed collaboration, participation and engagement, adaptation to technological changes, and disconnect between content-based and pedagogy-based coursework to be the most prevalent challenges pre-pandemic for engineering and/or STEM teaching (Belardo et al., 2017; Burrows et al., 2016; Kim & Keyhani, 2019; Nathan et al., 2011;

Nowikowski, 2017). Challenges such as adaptation to technological changes remained following the pandemic alongside new challenges, including navigating logistics, online technology, and a shortage of resources.

Table 2

Summary of challenges reported by the reviewed studies

Reference	Challenges
Amedu and Hollebrands (2022)	Teaching logistics and time and resource management; pedagogy, scheduling, family obligation, student feedback and interaction, assessment, and quality of resources.
Belardo et al. (2017)	Available support; collaboration, open-mindedness, and willingness to adapt to uncomfortable academic disciplines, finding another teacher willing to work with in the future, interdisciplinary teaching found intimidating.
Burrows et al. (2016)	Available support and time and resource management; Teachers express a need for enhanced content knowledge, project guidance, concrete activities for PD, classroom support (activities an personnel), classroom lesson plans, expert interaction, time management, and addressing surprises.
Code et al. (2020)	Available support; student access to tools, materials, and resources, and student motivation.
DeCoito and Estaiteyeh (2022)	Available support and time and resource management; unpleasant teacher experiences, self-efficacy, and technological competency.
Dhurumraj et al. (2020)	Teaching logistics and time and resource management; delivering creative and inclusive lessons and developing scientific skills through active learner engagement.
Holly (2021)	Available support and time and resource management; the gap to redress and resist racist educational practices, the perpetuation of prejudicial anti-Black traditions already detrimental to Black boys
Hutner et al. (2022)	Time and resource management; Achieving all together the habits of mind goals such as critical thinking, preparation for the future goals, such as preparing students for future courses, and science education goals.
Kier and Johnson (2022)	Time and resource management; attendance and students' absences
Kim and Keyhani (2019)	Teaching logistics; inclusion of graphic tablets to established teaching plans
Manuel et al. (2023)	Time and resource management; Findings reveal the significance of empowering teachers with professional development, around the implementation of novel pedagogical approaches, to both shape and inform their beliefs and practices.
Nathan et al. (2011)	Regulations; disconnect between the actual influences on teachers' judgments and the influences of which teachers are aware
Nowikowski (2017)	Teaching logistics and regulations; additional planning for connection between content-based and pedagogy-based coursework, administrative and program structural changes, reimagining the curriculum, meeting students' social and emotional needs, building community in the virtual environment, and reciprocal teacher professional development.
Ogletree and Bey (2021)	Teaching logistics and time and resource management; using platforms that offer ease of transitioning in and out of breakout rooms, offering the personal choice of background, scheduling socialization time online, and building upon the knowledge of the use of digital applications for learning purposes.

METHODS: EMPIRICAL STUDY

A US-based effort, e4usa, was launched in Fall 2018 to create an inclusive pre-college engineering curriculum that builds foundational professional skills through engineering design experiences (Carberry et al., 2022). The program aims to help democratize engineering education for all students and teachers (Dalal et al., 2022). The first cohort of teachers began their training during Summer 2019. They taught the first half of the curriculum in Fall 2019 with no disruptions but later found themselves having to adapt their teaching modality in Spring 2020 for a curriculum that had never been taught before. The purpose of this study was to examine and share the experiences of these teachers at the start of the COVID-19 pandemic. The pandemic produced a unique learning moment for all teachers, especially teachers who were faced with figuring out how to teach a brand new, hands-on curriculum for the first time using relatively unfamiliar modalities (Currie, 2023).

The work undertaken by the first part of this study enhanced our understanding of emergent challenges for pre-college engineering and/or STEM teachers from the literature. Participating teachers all taught the e4usa curriculum. We used sense-making theory to analyze the data collected from 39 teachers. We summarize the data by providing empirical study design and emergent thematic findings of key challenges reported.

Theoretical framework of empirical analysis

We adopted sense-making theory (Figure 3) to explore how pre-college engineering and/or STEM teachers made sense of the organizational, policy, structural, and personal changes that happened due to the COVID-19 pandemic. Sense-making refers to a process by which people construct meaning for phenomena they experience (Cornelissen et al., 2014). The process of sense-making starts with a teacher revealing their thinking and feelings about a situation that led to an understanding or belief and set of actions.

Our interpretation of sense-making assumes that specific events or situations may have triggered teachers to make interpretations based on the resources available to them. The teachers then planned and executed actions to best fit the students' needs within policy changes that may have happened in the school system. The insight acquired from doing analyses using sense-making theory through an interpretive approach provides salient inferences to better understand how teachers employed sense-making to make meaning as they related with their students and school administrators. Our goal in this work is to shed light on the context, interpretations, and actions teachers associated with their work at the start of the COVID-19 pandemic. We focused primarily on how teachers made sense of COVID-19-related changes in their classrooms at the start of the pandemic. This approach provided a means to investigate and situate the actions and meanings the teachers framed to make decisions in their remote classrooms in tune with the policy changes that happened in their school systems (Ferrare & Miller, 2020).

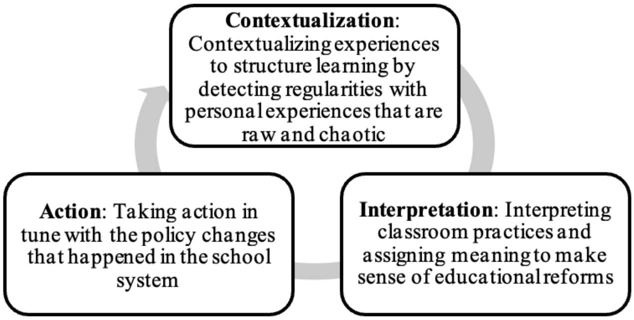

Figure 3. Sense-making theoretical framework as adapted from (Lycett & Marshan, 2016) and (Holt & Cornelissen, 2014).

Data collection and processing of empirical analysis

Focus group sessions were conducted with 39 teachers at the end of the 2019-2020 academic school year. Teachers were divided into 5 sessions conducted concurrently and facilitated by different members of the research team using the same protocol. The focus group protocol provided the participants with an opportunity to reflect on their experiences in teaching engineering to pre-college students at the start of a pandemic. Focus group questions included:

1. What barriers did you encounter in implementing the course?
2. What adaptations did your school district implement as a result of the COVID-19 disruption?
3. What kind of support are you receiving from the project team, the school administration, school districts, and parents?
4. How would you describe your level of professional freedom in delivering your curriculum during the disruption?
5. What would you say has changed regarding your own beliefs and perceptions, if any, regarding engineering teaching because of teaching online or in hybrid mode?
6. What resources would be beneficial for you if the next school year must adapt to a hybrid or an online modality?

All data were analyzed using the qualitative analysis tool, Dedoose. Two members of the team coded the data using an inductive analysis method informed by sense-making theory (Saldana, 2011). There were two cycles of coding with constant comparison of codes. Each data unit was coded and codes were reviewed and condensed into categories. Differences arising from the constant comparison of codes were resolved via iterative rounds of meetings to reach a unified agreement on the themes. The researchers attempted to collaborate and triangulate the teachers' sense-making perceptions for trustworthiness, reliability, and validity purposes (Lincoln & Guba, 1985).

This was achieved through iterative rounds of review and consensus-making among the research team. The analysis resulted in codes each containing sample teacher excerpts that contained instances where some combination of "context, interpretation, and action" were observed (Ferrare & Miller, 2020).

RESULTS: EMPIRICAL STUDY

Empirical studies

Participating teachers hailed from 14 different states and territories within the US. School setting included urban, suburban, and rural structured as public, private, charter, and magnet schools. Class sizes spanned very small (single digits) to over 100 students. Prior teaching experience for the teachers ranged between 1 and 25 years with most teachers (25) identifying as male and white (25).

Empirical study of challenges

The findings presented in the following subsections capture emergent challenges noted by pre-college engineering teachers. A total of four themes were identified: Teaching logistics, Time Management, Available Support, and Regulations. Table 3 lists each theme alongside specific challenges highlighted by participating teachers.

Table 3

Overview of themes and higher-level codes from teachers' sense-making

Themes	Specific Challenges
Teaching logistics	Technology needs and malfunctions
	Geography
	Available at-home resources and access to tools
	Teacher comfort and expertise
	Student engagement and learning outcomes
	Modality selection
Time and Resource Management	Onboarding to a new modality
	Conversion of lessons and assessments from in-class to remote
	On-demand adaptations
Available Support	Peer Support
	External support Networks
Regulations	Curriculum fidelity
	State, district, and other governing body standards
	Student safety
	Teacher liability

Teaching Logistics

This theme captures teachers' reported challenges with technology needs and malfunctions, geography, available at-home resources and access to tools, teacher comfort and expertise, student engagement and learning outcomes, and modality selection.

Technology needs and malfunctions

The remote work challenges for teaching logistics were mostly tangled with technological needs and malfunctions for teachers. Teachers mentioned an undersupply of computers in students' homes or a lack of necessary computer programs and configurations on students' personal computers. Teachers also faced a challenge with internet connectivity for themselves and their students. One teacher noted, "But we were to do Google Classroom and then anybody that didn't have the internet access because a lot of our students didn't have, they would do paper packets".

Another related challenge was the uneven distribution of technology to students and the availability and preferences for different teaching platforms. One teacher noted, "Each school had to disseminate computers and the number of computers and the number of computers we had to disseminate was much less than the need of our students".

Geography

Teachers acknowledged the adversities caused by the geographical location of their students. Some geographical challenges (e.g., living in underserved neighborhoods) were present prior to the pandemic, while others appeared unexpectedly (e.g., flood or infectious zones). Teachers from this study who were in lower socio-economic districts typically experienced challenges supporting their students while teachers from higher socio-economic school districts received resources to support their students (Garet et al., 2020).

Teachers pointed out the intricacy and differences in expectation versus reality of online teaching and learning. Specifically, one teacher contextualized uncertainty in the use of synchronous versus asynchronous modalities due to students' unpredictable geographical locations. For example, one teacher stated:

> My school was actually in a pretty difficult situation because my school district has a small number of students, but the students are scattered over a very big area. So distributing technology, providing them with the internet, all this was very difficult for my school district. So it was kind of a little tricky situation for the school district. But I feel the school learned a

> lot during the last, I will say, month of the COVID-19 session, and whenever school opens, and if it is required to do the online sessions, I think we'll be better prepared this time.

Available at-home resources and access to tools

Most participating teachers found resources for online engineering courses lacked support for experiential and hands-on dimensions of student learning. Examples include but are not limited to the lack of teaching resources and existing best practices, guidelines on how to lessen adversities caused by COVID-19, plan and timeline leading to improvised pedagogy, and evaluation frameworks to understand what worked and what did not work.

The e4usa program assisted teachers as they faced these challenges by assembling home box kits that contained all materials needed for hands-on engineering design activities. Teachers deemed these resources for students and teachers as helpful because they allowed everyone to gain a hands-on understanding of engineering design concepts. These classes also included optional technical demands, such as accessibility to 3D modeling software or computer-aided design (CAD) tools, that were not met because students were mostly learning from home. A teacher described: "We were doing our own projects and trying to go through that we had met with a brick maker and made their own bridge, kind of a community project and learn how 3D printing would go into designing."

Teacher comfort and expertise

Teachers also had a range of comfort levels with online teaching; for some, this was not a new modality, while for others this was a sudden and unexpected paradigm shift. Teachers tested different modalities (e.g., synchronous versus asynchronous) of teaching. Some found traditional didactic courses to work better in a synchronous mode, while design challenge projects worked better using an asynchronous mode. One teacher noted: "Whatever activity we were doing, the kids had to take it through the design process and create either PowerPoint of Google slide activity." While another teacher noted: "And then we would have class, 45 minutes a week, once a week. So, okay, those were synchronous sessions."

Student engagement and learning outcomes

Creating an environment of continual learning for students was found to be difficult to achieve, often contributing to students' lack of engagement or attendance. Teachers discussed conceptualizing these challenges and recognized the normal connections made with the students physically in class encouraging relationship-building between teachers and students. Teachers tried making sense of what the teacher-student relationship would look like in this new remote classroom. One teacher noted challenges in building relationships when sharing:

> What does that [relationship building in a full distance learning] look like, right? I don't think you can build them in the same way in a purely online space that you can when you're interacting with them one-on-one in the classroom or they're coming in to see you in your office. I think it'll be challenging.

Teachers also expressed concerns for groups who solely connect with their teachers remotely and never get to build or have that initial in-person connection. A teacher in an all-girls school mentioned:

> You know, I miss that and I just worry about starting the school year without that connection. I think it was easier because I had known the girls three-quarters of the year and we had classroom rituals and routines, but it was still very hard to not have that personal connection with the girls and that's something that's weighing heavily on my mind as we kind of plan for the fall.

Students were encouraged to reach out to teachers in a face-to-face environment to discuss issues. One teacher noted; "So I chose the second alternative for most of my course teaching was the recorded method." While another teacher noted: "We also did one hour a day of zoom meetings, you know, zoom office hours."

Modality selection

Participating teachers conceptualized situations that led to decisions made about how to teach in a remote environment effectively at the start of the pandemic. The teachers took COVID-19-imposed action to either teach asynchronously or synchronously and had to make quick decisions on which methods/resources were possible in tune with district policies, and which were better for their students. Depending on the resources available in each school district, some teachers made more use of asynchronous teaching because their students had limited technology/internet resources. For example, one teacher noted:

> For my physics classes, I did synchronous classes for about seven weeks. And then for my engineering class, which was a senior elective and the kids were working on the [external

> competition] collaboratively, they sort of - it was asynchronous, and the challenge didn't - they actually - the challenge didn't happen, like they didn't accept any submissions but the students still enjoyed, you know, working on what they set out to do.

Some schools allowed students to opt into an asynchronous synchronous schedule. This was hard on some students as they were not engaged in the processes. A teacher explained this saying:

> I think for us one of the big decisions was about where we fell on the synchronous versus asynchronous spectrum was something that we had to grapple with. We have a large international boarding community here, some who were staying local, some who were on their way back to China, and some who were in transit between the two, and that suddenly created time zone realities. So we had to decide to go largely asynchronous with a synchronous element to it where we could but that became more optional.

TIME AND RESOURCE MANAGEMENT

This theme captures teachers' reported challenges with Onboarding to a new modality, Conversion of lessons and assessments from in-class to remote, and On-demand adaptations.

Onboarding to a New Modality

Teachers scrambled to adapt to online course design and delivery. They were forced to make meaning of information presented through emails and other provided guidelines. Some teachers used what they were most comfortable with as the new medium for learning. One teacher noted:

"So what I did was I was already set up on Google Classroom, and I told my students already, if we have to close, everything is gonna go on Google Classroom".

The transformation from in-class to remote lessons sparked doubts among teachers on what needed to be kept and removed when reformulating their teaching material to accommodate an alternative modality. An area of concern was take-home assessments and academic integrity, and whether the students completed take-home work on their own. This is especially concerning in light of the emergence of artificial intelligence applications, which may come to threaten educational fairness, accountability, transparency, and ethics (Memarian & Doleck, 2023).

In addition to moving to online instruction, the hands-on nature of engineering made teaching and learning even more difficult. The e4usa course features a hands-on curriculum, with special attention to necessary supplies for the classroom. Moving hands-on experiences to remote, with no preparation time, meant that teachers had to be concerned with the resources students would have at home. This was complicated by an inability to simply go to a store and get materials. One teacher noted:

> I think the best thing would be to have the projects which could be completed with minimum tools and with minimum help or the help could be provided online in completing those projects. Because I believe that engineering projects require hands-on stuff, and they require substantial tools. I do teach according that can be done online programming, but you know, engineering just, you know, is a different thing than, you know, programming. So I believe that we have to have some, you know, online version of the engineering projects which could be done at home with the tools available to the students and online guidance should be enough for completing those projects at home. So I think that would be better.

Another teacher noted the need to transition to application modes of teaching that supported online learning:

> So, we ended up transitioning all of our kids from Inventor to Fusion. My civil engineering and architecture kids transferred from Revit, which is very industry standard, all the way over to something called Planner5D, which is more interior design. Fortunately, that class was upperclassmen, so I'll be honest, that class I think I had 87 percent attendance rate every day. I mean, they were really into it. So, we rolled it out where the kids would do that, and then we did Fridays where I would bring in guest speakers. So, they'd Zoom in. They were - that was entertaining to say the least. So, it's a very different feel. I think next year depending on the three different models I've heard of, I think everybody's kind of in the same boat. They're talking about three different models whether or not they go 100 percent online, whether they do some kind of a hybrid, or if they go back to school will have a tremendous impact on how successful the implementation will be when we start off this adventure with the next round of curriculum.

Conversion of lessons and assessments from in-class to remote

The teachers had to make sense of providing engineering instructions and assessments remotely for the students. Teachers found explaining and troubleshooting problems to become more time-consuming and harder to gauge if students got things right. Group activities and projects that were in-person had to suddenly change to a virtual group experience with no foundation in how a virtual group can function or be assessed. Teachers teaching engineering conceptualized challenges by assigning the students' group work. This was evident because of online challenges and overall student participation; teachers were skeptical about coordinating and certifying group work. Most teachers had little to no access to training, preparations, and guidelines on how to switch their courses to a virtual space. Design, delivery, teacher-student interaction, and assessment and feedback were all impacted and less carefully detailed due to COVID-19.

A key challenge with sudden teaching transitions to distant modes was the repercussions it may have had for students of all backgrounds. The in-person interactions may have allowed the teacher to close the learning gap between high and under-achieving students through interactions that could motivate students of all performance levels. The transition to distance education limited teachers' ability to gauge overall class progress, which led to some students opting to do nothing. Engineering teachers made sense of conceptualizing difficult decisions to convert their in-class assessment tests to take-home tests which were challenging. Some found the grade level and degree of autonomy of the course impacted student learning more than the assessments themselves. For others, the setup and delivery of remote assessments impacted what was made of student learning. One teacher noted:

> The only thing that was tough was assessments 'cause the standard format of testing, it just doesn't work electronically. Google Quiz works pretty well for quizzes because they're captured for a short period. But, the tests were more like I had to make up more lengthy and maybe a little more involved tests and make them take-home tests, basically open note, open book, open everything. It worked, but the grades were obviously a bit higher than they would be than if they had received it in the classroom. But, that's how we did it.

Teachers had to make sense of grading students' work by applying several grading approaches in response to the instant switch from in-person to remote/hybrid. The teachers had challenges designing and delivering assessments and had to find different mitigation strategies.

On-demand adaptations

Local policies were put in place mandating that students couldn't be penalized due to COVID-19 (Slavin & Storey, 2020). Students who may have done little work received grades of B. Other local policies related to no exams or promoting exacerbated this issue, which led to a reduction in incentive for students to complete work (García & Weiss, 2020). Students who relied on intrinsic motivation did well; others chose to do no work, but received decent grades. One teacher shared:

> We were in - as someone else did mention - kind of in an enrichment mode. My independent studies, they continued to do work. My lower-level students continued to do nothing. And so, it was kind of the those who will do, those who won't still didn't.

Some teachers found the end of the initial COVID-19 time period to be more informative. One teacher noted:

> So it was kind of a little tricky situation for the school district. But I feel the school learned a lot during the last, I will say, month of the COVID-19 session, and whenever school opens, and if it is required to do the online sessions, I think we'll be better prepared this time.

Another challenge was the backlog teachers got from students who were troubleshooting their problems, and who ended up taking more class time resulting in a reduction of the scope covered. One teacher mentioned:

> I just wanted to add one more thing. I think the switch over to distance learning, I think everyone did the best job that they could. But I think knowing that this is a possibility, like [REDACTED] had mentioned where you could do a hybrid model, I think you could plan ahead and prepare students to realize that at any certain point in time, we may be out of here. And like he was saying about the Macs, that's something they could troubleshoot in class together, so you're prepared for it when you leave. But, when they're all in their own homes, something that could be a five-minute conversation in class turns into a two-day affair of trying to get communication back and forth and to clear up the air when it's a simple raise of the hand. And you refer back to a project they did before, the light bulb goes on, and everyone moves forward. It takes longer to get anything done is what I found.

Successful knowledge transfer and problem-solving seemed to be dependent on parents for instruction, assistance, supplies, and differentiation in student effort.

Available Support

Peer support

Some teachers noted having either casual or official meetings with their teacher colleagues giving them a sense of ease and normalization. The networks of support, including the professional learning provided by a program like e4usa, enabled teachers going through similar experiences to give each other feedback and guidance on their lessons learned during COVID-19. Teachers discussed making sense of the challenges that the start of the COVID-19 pandemic presented them in terms of support from colleagues. The teachers made decisions from peer support and feedback they got from their peers teaching in a pandemic. Some teachers resorted to support outside their immediate circle. One teacher noted:

> "I think that at least half of us if not more are going to be going to this site relatively soon to find something. It's amazing what's out there and how little everyone actually knows."

The majority of teachers expressed positive, rather than negative outcomes from having meetings with teachers in their immediate circle. One teacher reflected saying:

> "I remember also as it was all starting to crash, having a very meaningful meeting with myself and various performing and visual arts people about how the heck are we gonna do this without having the lab. And it was a tremendous brainstorming and spit balling session that occurred, but that was probably the most useful thing that happened in the transition."

Support networks

Some teachers felt there was free reign at the beginning of COVID-19 as districts did not have immediate rules, regulations, or support for online learning. At the same time, teachers were given a short period (e.g., a week only) to adapt to the sudden changes due to remote teaching and learning. As such, teachers felt they needed to make use of brief periods where schools were closed for the switch from face-to-face to virtual learning and independently orchestrate their teaching the best way they could. The freedom in teaching sometimes resulted in a reduced workload for students, since teachers were unable to cover the same breadth and depth of content as before. One teacher noted this saying:

> "We had a system where Monday we pushed out the week's work, and then we would have scheduled meeting times with the students, whether they were e-mail, you know, I'll be there for an e-mail, or whether they were Zoom sessions. That was up to the teacher. And we also - I mean, I saw students who were totally out, who didn't do anything. I saw - and I heard from students saying it was very difficult for them to get things done. And then I had kids who would just do everything perfectly and - but we did reduce the amount of work that they were doing, and I think that was just because of the situation that we were in."

One major challenge was the available time in the "right way" and coordinating resources and modes of teaching effectively. One teacher mentioned:

> "But in the middle of those exams they came and essentially sent all the kids home and said, hey, look, we're not coming back after spring break, right. And so everyone spent spring break trying to figure out what we were going to be doing. And basically, we were just - I mean it was distance learning, but we were thrown in the deep end of that pool. We just didn't have a lot of experience collectively as a faculty with what distance learning looked like, how to do it, and so I think there was a lot of scrambling to do things. Our community gave us a lot of grace in that process. Our families and kids were very supportive and helpful and whatnot."

When experiential needs of the course were met, teachers found a lack of support for tracking supplies used by the student and associated independent learning gained from it. Some other teachers recognized the demands for hands-on work and physical resources needed to make learning in remote engineering courses happen. These teachers suggested that even if courses are fully transformed to an online format, additional thought, and support for in-home kits and supplies are needed to make courses experiential. Teachers expressed concern for parents/caregivers of children who inevitably had to go beyond caring for or babysitting students and constantly meeting their needs (including educational needs) at home. Parents were suddenly in charge of leading at-home engineering activities, as well as obtaining necessary supplies that would normally be distributed in the classroom. Relating to this, one teacher expressed saying:

> “But the problem arises for me is like, you know, we did one lab and that was fine. You know, I think the parents probably thought it was, you know, a novelty, right, to see their student running around saying, hey, do we have any string, do we have any this. But you know, what happens with like parent fatigue, you know, six months in when, you know, I’m in this engineering course and I’ve already used, you know, six rolls of duct tape, I’m asking you for - you know, I’m just like asking you for all this stuff. You know, I don’t know, I feel like maybe it’s just our population, but it could be something to consider, you know, with how much we’re having these girls engaged, their parents with, hey, you know, I need a little help or I need this stuff. Yeah, I’m just not sure how that will pan out.”

Teachers had to find and rely on available support to different extents depending on the resources and help available. While most teachers found having an immediate circle of support beneficial to their progress amidst the COVID-19 pandemic, they also noted that the resources were sparse, and information and care were provided as emergency measures and not necessarily through a well-thought-out framework.

Regulations

Curriculum fidelity

A unique facet of this study was the curriculum which was being implemented for the very first time at the time of this study. The curriculum had not initially been designed for use within an online setting, which brought about concerns regarding the fidelity of implementation. Teachers expressed an interest in modifications that provided an organized and process-oriented curriculum following the initial onset of the COVID-19 pandemic. The e4usa curriculum prior to the disruption had been conducted in schools as a standalone course. Remote implementation initiated by the pandemic resulted in the addition of remote teaching tips and assembling and disseminating a collection of recommendations from teachers to their peers. A desire of teachers was identifying ways to integrate the e4usa course within their broader school curriculum. Yet, diversities in the level of content covered were seen among teachers as they noted:

- "We were only we were able to get to unit two and kind of reveal a little bit of unit three".
- "We completely completed unit 4 and we were working on unit 5".
- "We got through five, you know, we were supposed to be getting on the six and seven, it just didn't happen".

State, district, and other governing body standards

The state, district, and other governing body standards can act as confounding and influencing factors to teacher's and their teaching experiences/perceptions. Overall, the district directives for online teaching regulations were spotty and variable across different geographic areas. One teacher noted:

> "In Pennsylvania here, our governor, sort of in part of the decree said that no student could fail, on account of the COVID outage, which got to kids very quickly, and that had a pretty big impact".

Some teachers found appropriate directions, such as a learning management system template, while others were given limited guidance and asked to figure out the rest on their own. Teachers expressed concern about not knowing what the state standards were and whether their students would truly pass if there was a state assessment in place.

Student safety

Teachers indirectly noted concerns regarding student safety from both a physical and mental health well-being perspective,

"…in terms of making and materials, one of the things that's always on the back of my mind is safety and liability, right. We can - in our minds, it's, oh, they can make this and it is safe, but you - it's really hard for us to see how the students will interpret that and, you know, how they interpret safety. And then ultimately should something not - something that shouldn't happen happen, then who is liable, you know. That's always on the back of my mind."

Yet some teachers found student acceptance and update with online education not a big issue. One teacher noted:

> "So, for the most part, they were very diligent, the distance learning did not prove a big issue with them".

Students needed instructions on how to protect their well-being and their families during the initial onset of the pandemic, support on how to overcome burnout, and motivation to learn in isolation with little social contact. Some teachers noted their classes getting completed earlier. One teacher noted: "March 13 was the last day of school." The lack of such directions caused stress for the teachers on whether they were providing the necessary support needed to safeguard their students.

DISCUSSION

We presented a review of the literature as well as an empirical study to gain more information on the challenges teachers faced in teaching pre-college engineering and/or STEM courses during COVID-19.

The literature review revealed the majority of studies exploring challenges faced by pre-college teachers during the onset of the COVID-19 pandemic used self-reported surveys to examine the phenomenon. Fewer studies employed qualitative and mixed or multi-methods analyses. The reported challenges were diverse, but the lack of readiness and resources for transition to remote learning along with personal factors (e.g., motivation and engagement) were noted as increasingly prominent and frequent. We also found that most studies during times of crisis collected and analyzed challenges and needs without reference to pedagogical frameworks, signifying a lack of theory and practice in this domain. We see the need to develop frameworks to study challenges during times of crisis to provide a foundation of effective practices that can be used if facing a similar disruption in the future. Some of our suggested areas for future work based on the challenges summarized from the review of the literature include developing educational frameworks accounting for personal commitments, creativity, equity, diversity, and inclusivity; cultivating a culture of failing forward and shared failed experiences; designing learning environments and tools tailored for distance education; providing platforms for mental health and well-being; improving student motivation in remote settings; developing new tools designed for remote learning; leveraging learning analytics to reveal teacher blind-spots; building out administrative support for distance learning; and developing an infrastructure for virtual hands-on engagement.

The empirical analysis revealed similar challenges as those found in the extant literature. The remote work challenges were mostly intertwined with a lack of resources for engineering teachers. The teachers took COVID-19-imposed action to decide how to teach and make last-minute decisions on which methods/resources were better for their students. As a result, students were often exposed to ad-hoc learning experiences. Most teachers had little to no access to training, preparation, and guidelines on how to convert their courses to a virtual space. Design, delivery, teacher-student interaction, assessment, and feedback were all impacted and less carefully detailed due to COVID-19. Engineering classrooms include technical demands that were not met in the transition to distance education because students were mostly learning from home. Successful teaching seemed to be dependent on having more time in a remote setting and leveraging parents for instructional assistance and supplies. Some teachers noted having either casual or official meetings with their teacher colleagues, which gave them a sense of ease and normalization. Yet most teachers noted a lack of support and guidelines for quality teaching and learning during unprecedented times. Adding to this issue were local policies such as mandating that students couldn't be penalized with a low grade due to COVID-19. Many engineering spaces that provided hands-on, experiential learning were shut down in favor of web programs and simulations. The result was both teaching and learning being impacted by COVID-19.

Comparing the literature review and empirical study results revealed some similarities and differences. Common facets within the three themes of teaching logistics, time management, and regulations included technology needs and malfunctions (Ogletree and Bey, 2021); available at-home resources (Code et al., 2020); teacher comfort and expertise (DeCoito & Estaiteyeh, 2022; Hutner et al., 2022; Nathan et al., 2011; Nowikowski, 2017); student engagement and learning outcomes'(Burrows et al., 2016; Dhurumraj et al., 2020; Kier & Johnson, 2022); onboarding to a new modality (Amedu & Hollebrands, 2022; Kim & Keyhani, 2019); support networks (Belardo et al., 2017); curriculum fidelity (Manuel et al., 2023); and student safety (Holly, 2021). Differences emerged when examining pre-pandemic and immediate post-pandemic challenges. Pre-pandemic major challenges were collaboration, participation and engagement, adaptation to technological changes, and disconnect between content-based and pedagogy-based coursework (Belardo et al., 2017; Burrows et al., 2016; Kim & Keyhani, 2019; Nathan et al., 2011; Nowikowski, 2017). Adaptation of technological changes remained during the immediate post-pandemic time, while new challenges, including logistical challenges, new technological challenges such as maintaining academic integrity especially through help-seeking behaviors not permitted in a face-to-face setting, and a shortage of resources emerged. Our qualitative analysis of pre-college teachers' challenges during the pandemic also showed diversity and change in the needs of the teachers as time passed. The findings from both the preliminary literature review and our study highlight the permanent and fluid impact of the global pandemic on the landscape of teaching and learning. Pre-college teachers need to continue their professional learning while making use of technology to accommodate the current and future generations of students who have become more accustomed with using such mediums since the pandemic.

IMPLICATIONS

Our review and analysis of the challenges reported by the teachers provides the foundation for potential mitigation strategies for challenges and approaches highlighted by the teachers. We find that such strategies can potentially simplify teachers' access to resources with timely problem-solving. The mitigation strategies presented are summarized and grouped based on the main themes and specific challenges/concerns from participating pre-college teachers.

Teaching logistics

Internet-based applications and resources were increasingly used by teachers and learners during social distancing brought about by the COVID-19 pandemic. These platforms can often experience malfunctions or interruptions due to a variety of reasons, such as increased use of the internet by each household, diverse qualities of internet connections, and students' lack of access to the internet due to personal or socio-economical reasons (Gillett-Swan, 2017). The reliance on this resource suggests the need for an offline repository of resources (e.g., smartphone applications that work offline) for teachers and/or students to navigate abrupt changes that may lead to internet disconnections. Teachers and students experienced challenges configuring and understanding technology in distance engineering education. The educational technologies we use are rarely designed with content-specific educational objectives (Dalal et al., 2021; Laurillard, 2009). Therein lies an opportunity for designers to leverage teacher knowledge and experiences to specifically create content-based technology tools that support engineering and other STEM learning offline. Effective teaching practices can take into consideration inputs such as the geographical location technology/internet availability, and accessibility needs of students in each course. The future design of teacher professional development offerings can similarly be informed by the constraints of resources, school environments, and geographical locations (Dalal et al., 2017).

Future work exploring teaching logistics needs to explore the identification of interventions to allow students to learn engineering concepts without the constant need for computers or the internet. In-person classes provide the opportunity for interaction with teachers to directly clarify student questions. Students often had little to no support during the onset of the pandemic. Findings from our study showed that teachers reported having different levels of knowledge, expertise, and comfort with transitioning to remote education. Developing different courses and training materials for teachers with varying comfort and knowledge with teaching online is imperative. Such training should further support teachers' professional and personal development and awareness of important personal factors such as self-efficacy, critical thinking skills, judgment, and feedback mechanisms.

One final potential avenue for advancement is the use of emerging artificial intelligence (AI) applications woven within learning management engines to track students' attendance and engagement in online courses. The creation of a personalized learning experiences has been shown to boost students' engagement (Dabbagh & Kitsantas, 2012). The data monitored and collected through the use of AI can be used to better facilitate student engagement and motivation at a much more nuanced level (Manwaring et al. 2017). The combination of advanced technological and offline support combined with personalized learning experiences for students and teachers accounts for failures in transitioning between technologies or modalities in education. These considerations provide a foundation for appropriate mitigation strategies to improve future efforts if and when another major transition occurs.

Time Management

Onboarding a new curriculum or technology into a classroom for the first time will undoubtedly have unanticipated challenges. This work revealed the importance of examining how such resources are designed to accommodate varying situations and modalities, which keys into implications for time management. The onset of the pandemic did not provide the necessary time typically needed to develop resources to support such transitions. We have the time now and should leverage what has been learned to develop online course design packages that account for varying teacher characteristics (e.g., prior teaching experience, previous engagement with remote learning, and level of classroom freedom) and offer specific guidelines around the degree to which course content can be modified, changed, or reformulated. Teachers can then choose a package according to their needs.

Having on-demand adaptations from both a policy and technology lens can further alleviate teacher challenges during a sudden transition to remote engineering education. Take-home kits designed for multi-purpose use and support of different types of engineering course projects are needed to reduce the initial time to transition. As an example, Ross et al. (2021, 2023) created a mail-in kit with necessary items for completing hands-on engineering and/or STEM design activities. Such examples address a major concern raised by teachers regarding the time it takes to implement major changes.

Available Support

Teachers flourish when they receive support from peers, administration, and broader community partners (Dalal et al., 2024; Kouo et al., 2023). Future work should explore the development of a communication platform or on-demand helpline for teachers to connect with colleagues or other human resources (e.g., mental/physical health counselors). Further aiding teachers to find like-minded teachers to consult with and complete tasks together may further enhance teachers' motivation and sense of peer support (Kouo et al., 2021).

Alternative resources should also be developed for teachers who do not have interest or time to engage with human support. One option is through the use of intelligent applications that could offer timetables, plans of action, guidelines, and practices on how teachers can make the best use of the free time provided to them to adapt to new systems of change and make and prepare instructional material effectively.

Regulations

To gain more feedback and a wider learning audience, opportunities may be identified where modules or components of programs like e4usa could be integrated as part of the school curriculum. Doing so may help share and disseminate learning objectives and assessment criteria/expected learning outcomes with teachers for the two curricula to be aligned.

LIMITATIONS OF THIS WORK

This section provides a brief summary of limitations applicable to our work pertaining to each of the preliminary literature reviews and empirical studies.

Review

As researchers and educators, the authors aim to practice inclusive and equitable ways of research execution and synthesis. The insights of the literature review provided are limited to the reviewed studies. We reviewed studies that had specifically noted our terms of interest in their articles. Other terms used for pre-college stem/engineering education were not searched in this review. We anticipate that future work may add to the terms used for online education (e.g., technology-based online education such as AI) and may hence broaden the types of challenges. Further, studies that were not conducted in English were excluded from this study.

Empirical analysis

The insights provided are limited to what was shared by 39 postsecondary teachers using one specific pre-college engineering curriculum, e4usa. Many of the authors were involved in the development of the curriculum and continue to support the program, which may provide a natural tendency to advocate for the program. No such bias exists for or against online education. The team's exploration in this space was due to the program being thrust into such a mode during the initial onset of the COVID-19 pandemic. Understanding the challenges experienced by teachers, examining if challenges can be harnessed as learning opportunities, and acting as a medium to account for and offer mitigation strategies for the future were emergent go3als for the program. Our goal in this work is simply to focus on the challenges faced and potential mitigation strategies, rather than assessing the usefulness of the program itself.

We recognize that our empirical analysis findings may not be generalizable beyond those participating in the e4usa program. The participants' responses in this study were most likely influenced by their diverse school environments and circumstances. Also, because this study's data is based on self-reports from the teachers, the findings of this study may have social desirability bias (Edwards, 1953). The scope of our study is focused on schools within the US. We recognize that the impact of COVID-19 on education was a global phenomenon, and teachers hailing from other countries may have experienced it differently from what we have reported based on our US sample.

CONCLUSION

This study explored pre-college teachers' experiences teaching engineering at the start of the COVID-19 pandemic and how teachers made sense of the challenges they faced during this period of time. Knowing how to teach during a time of crisis, such as a pandemic, is important in making sure that high standards of engineering education are maintained. Teachers in this study individually had to make sense of crucial decisions concerning how they would teach during this unprecedented event. Our empirical analysis showed that teachers simply reacted to the challenges of teaching during the pandemic. Despite all the challenges faced, pre-college engineering teachers continued to make sense of these situations and worked hard to deliver engineering content for their students. Although studies have shown that teaching is a stressful profession (Johnson et al., 2005), teachers shouldered these challenges amid their stress from the pandemic while also trying to help the students go through a stressful time.

Insights from the themes and suggested mitigation strategies provided can aid teachers, curriculum designers, and school administrators to situate meaningful interventions in developing engineering flexible curricula capable of being implemented regardless of modality. As engineering researchers continue to explore pre-college teachers' pandemic experiences, it is important to explore practices that can be helpful to teachers at the start of a future crisis such as a pandemic. One thing is for certain that engineering educators have work to do on augmenting how pre-college professional learning and curricula are delivered to reflect the proficiencies and skills teachers need to effectively teach online or in hybrid modalities following this unprecedented pandemic. This study, among others undertaken at the onset, provides unique information to better prepare educators for whatever comes next.

DECLARATIONS

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