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Improving Student Access and Success in Pre-Engineering through Human-Centered Design and Theory of Change

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Abstract

This paper presents a Complete Research study investigating the experiences and challenges of Pre-Engineering (PENG) students at a public regional MIDWESTERN University in the US. The creation of pre-engineering programs is one model that universities have employed to address accessibility to college engineering programs. The research study employs a human-centered design (HCD) process and a Theory of Change (ToC) framework in three-phase mixed methods approach to explore the student's attitudes, struggles, and learning experiences regarding the support provided in pre-engineering. Additionally, the study explores perspectives of their professors and academic advisors as they respond to insights gained from the students' data. The study findings highlight the value of orientation workshops, advising services, peer mentoring, collaboration opportunities, and hands-on activities in improving the Pre-Engineering program. The participation of stakeholders and the use of data-driven methods are essential to implementing an inclusive and encouraging atmosphere for pre-engineering students.

Introduction

Students take many pathways to pursue STEM careers and sometimes face barriers to earning a degree. These barriers may include departmental, institutional, and national policies and the frequency of institutional-level engagement with students [1]. One pathway includes Pre-Engineering programs, which provide essential competencies and information for students to transition to an engineering bachelor's program, considerably impacting their careers. The Pre-

Engineering program helps students improve their math and science foundations, providing academic support that can prevent them from not completing their bachelor's degree, repeating math subjects, or not enrolling in advanced engineering courses. School administrators frequently assess Pre-Engineering programs by measures such as student enrollment and academic performance; however, there is limited research on factors contributing to program effectiveness from multiple perspectives. This study examines the Pre-Engineering program by examining students' learning experiences, professors' perspectives, and academic advising expectations. The study analyzes the challenges students encounter upon enrolling in Pre-Engineering programs and their experiences throughout the program. The research uses qualitative methodologies, encompassing interviews with students, faculty, and advisers, to comprehend students' viewpoints, challenges, and support requirements. Furthermore, it examines academic support and mentoring techniques to pinpoint opportunities for enhancement. The findings seek to reconcile students' requirements, program objectives, and institutional support, offering practical insights to improve Pre-Engineering programs.

The Pre-Engineering (PENG) program at the public institution studied in this study helps recently enrolled college students prepare for engineering and computer science programs by improving their math and science skills. Direct admission to the engineering college is available to those with a high school GPA of 3.5 or higher, SAT score of 1200 or higher, or Calculus placement. PENG admits students who meet basic entrance requirements but not engineering college prerequisites. The program provides specific coursework and academic coaching to help students move into engineering after meeting specified benchmarks (e.g., passing Pre-Calculus and General Chemistry with a C). It prepares students for a challenging engineering curriculum.

Research Questions

1. How might we understand the Pre-Engineering program experiences of students at a Midwest public university?
2. How might we employ Human Centered Design practices to improve the design of the Pre-Engineering program and better support students?

The study aims to improve the PENG student experience at a Midwest public university, focusing on enhancing support for students transitioning into engineering.

Review of Literature

Low student enrollment and high retention rates, especially in STEM education, cause significant engineer shortages in developed nations like the US [2]. Diversifying the STEM workforce and removing barriers to minority, female, and low-income participation is crucial [3]. According to the pyramid effect, fewer students in K–12 engineering programs lead to fewer graduates [4]. Many colleges offer pre-college PENG programs to stimulate STEM studies and retain underrepresented groups [5]. RPI programs, including Tutor Time, RPI STEP, PREFACE, and GE Girls at Rensselaer, aim to increase STEM access for underrepresented and economically disadvantaged groups [6]. A Pre-Engineering Program at the University of Maine gives students interested in engineering a foundation in math, physics, and introductory engineering education [7]. [8] found that well-developed PENG programs at Oklahoma State University retained more students than regular university students. [9] said the University of Texas at El Paso (UTEP) CircLES program helps first-year students succeed and retain via non-credit courses and multidisciplinary learning communities.

Human-centered design (HCD) is a systematic and innovative problem-solving approach that involves a comprehensive understanding of the individuals being served, fostering empathy and insight into their unique perspectives while also considering technological feasibility and economic viability. Thus, prioritizing empathy, understanding needs, and meeting requirements [10]. IDEO's HCD framework includes three phases: inspiration, ideation, and implementation, which involve user research, idea creation, prototyping, and feedback. The HCD philosophy advocates that when designing technical systems, the primary focus should be on placing the end-users at the core of the design process, prioritizing their needs, preferences, and experiences [11]. UCD prioritizes user input, data-driven evaluation, and iterative improvement. The three fundamental principles of user-centered system design include an initial and ongoing emphasis on users, using empirical measurements to assess user behavior and usage, and adopting an iterative design approach that involves modifying and testing the system in simulated prototypes or solid form in repetitive cycles [12]. Human-centered design (HCD) application in various domains has become increasingly important in creating user-centric solutions. For instance, HCD effectively creates user-specific systems in education [13, 14] and healthcare [15].

Theory-driven assessment, particularly the Theory of Change (ToC), provides a structured framework for understanding how and why an initiative is anticipated to provide the desired results. It encourages participants to clearly articulate the ultimate goals and impacts while outlining the specific pathways and processes that will result in those outcomes [16]. ToC brings clarity, understanding, and better partnerships [17]. It improves stakeholder engagement in community-building and educational changes [18, 19, 20]. Program evaluation uses analytical techniques to assess a program's design, implementation, and outcomes [21]. Data analytics

improvements enable targeted student services [22] and student success [23]. K-12 PENG activities increase self-efficacy and engineering motivation [24], and Project Lead The Way experience raises GPAs [25]. The ToC approach provides a comprehensive framework for identifying and understanding community needs, designing tailored interventions, and monitoring progress toward desired outcomes. This research uses ToC and HCD to improve PENG program evaluations and include student viewpoints. HCD uses surveys, interviews, and workshops to identify student, faculty, and advisor needs, whereas ToC sets long-term goals and criteria for result assessment. Using qualitative and quantitative assessments, mixed methods improve PENG program results.

Interview Protocol Refinement (IPR) framework offers a methodical approach to enhancing interview questions and structure [26]. The four main stages of the IPR framework are: (1) matching research goals with interview questions; (2) creating an inquiry-based dialogue; (3) getting expert input; and (4) piloting and improving the protocol in response to participant feedback [27]. This iterative process enhances the clarity, consistency, and depth of data collection, producing deeper qualitative insights. The Interview Protocol Refinement (IPR) Framework has demonstrated efficacy in methodically developing semi-structured interview protocols by ensuring alignment with research objectives and strengthening the clarity of interview questions [28]. Given the exploratory nature of this study, using the IPR framework help ensure that interview questions accurately reflect students' experiences, challenges, and perspectives related to the Pre-Engineering (PENG) program. This study guarantees methodological rigor and enhances its credibility by incorporating the IPR framework.

Methodology

The study employs quantitative and qualitative methods to examine the challenges faced by Pre-Engineering (PENG) students at a public University, providing a comprehensive understanding of the program's effectiveness and areas for improvement. It includes three participant groups: current and former students, faculty members teaching PENG courses (e.g., MATH 090, MATH 105, CHEM 134, ENGR 100), and advisers.

Research Context

The Pre-Engineering program (PENG) at the public University in this research study was established in Fall of 2019 and is in its fourth year of operation. This program is designed to assist students in building and strengthening their math and science fundamentals to succeed in the CECS (College of Engineering and Computer Science) curriculum. This foundational knowledge is a significant determinant of engineering and computer science success. At the time of this study undergraduate students interested in Engineering or Computer Information Science could apply to the college and receive (1) direct admission to a CECS major or (2) receive admission into the PENG program. (Fig. 1)

1. Admission directly into a CECS major

Freshman Requirements:

- Students with a GPA of 3.5 or higher AND an SAT of 1200 (ACT of 25) or higher, or
- Students who have completed at least Pre-Calculus (Math 105 or equivalent) with a C grade or higher, or
- Students who place into Calculus 1 (Math 115) or higher on their placement exam or via the following automatic placements:
    - SAT math section score of 620 or higher
    - ACT math score of 26 or higher
    - 3, 4, or 5 on an AP Calculus exam
    - 5 or higher on an IB Mathematics SL exam or a 4 or higher on an IB Mathematics HL or HL Further exam

Transfer Requirements:

- Students who have completed Calculus II (Math 116 or equivalent) elsewhere with a C grade or higher AND have an overall GPA of 2.75 or higher.

2. Admission into the Pre-Engineering program

Freshman Requirements:

- Students who satisfy the university's undergraduate admissions standards, but do not meet the above admission criteria for direct admission into CECS.

Transfer Requirements:

- Students will be required to show an overall transfer GPA of 2.75 or higher.

Fig 1. Admission pathway to College of Engineering and Computer Science at a Public University

PENG students at the University work collaboratively with Student Advising and Resource Team (START) Academic Advisors to enroll in appropriate classes, ensuring and improving their likelihood of success in the rigorous curriculum ahead. START assists students in building a solid foundation for success as they begin their academic journeys, which includes a PENG specific orientation, class scheduling support etc. Students in the PENG program must complete the transition requirements (Fig. 2) and declare their major within one calendar year or during their first 30 credit hours whichever comes first.

Transitioning from Pre-Engineering into a CECS Major:

- Freshmen can transition once they successfully complete Pre-Calculus (Math 105) with a C grade or higher AND complete General Chemistry I (Chem 134 or 144) with a C grade or higher.
- Transfer students can transition once they successfully complete Calculus II (Math 116) with a C grade or higher.
- All students transitioning into a CECS major are expected to be in good academic standing overall (2.0 GPA or higher).

Fig. 2. Transitioning from Pre-Engineering into CECS major

The PENG program elements understudy include Orientation, academic advising, financial aid, class schedule flexibility, hands-on activities, student engagement, and resource utilization.

Participant, Data Collection and Analysis

The survey targeted the entire student population within the program. However, convenience sampling is utilized for interviews to recruit participants through announcements, leaflets, and emails. Data collection methods included online surveys using Qualtrics comprising Likert scales and open-ended questions and in-person or Zoom interviews, while the Interview

Protocol Refinement (IPR) framework was used to improve interviewing methods. The data collection and analysis process is illustrated in Fig. 3.

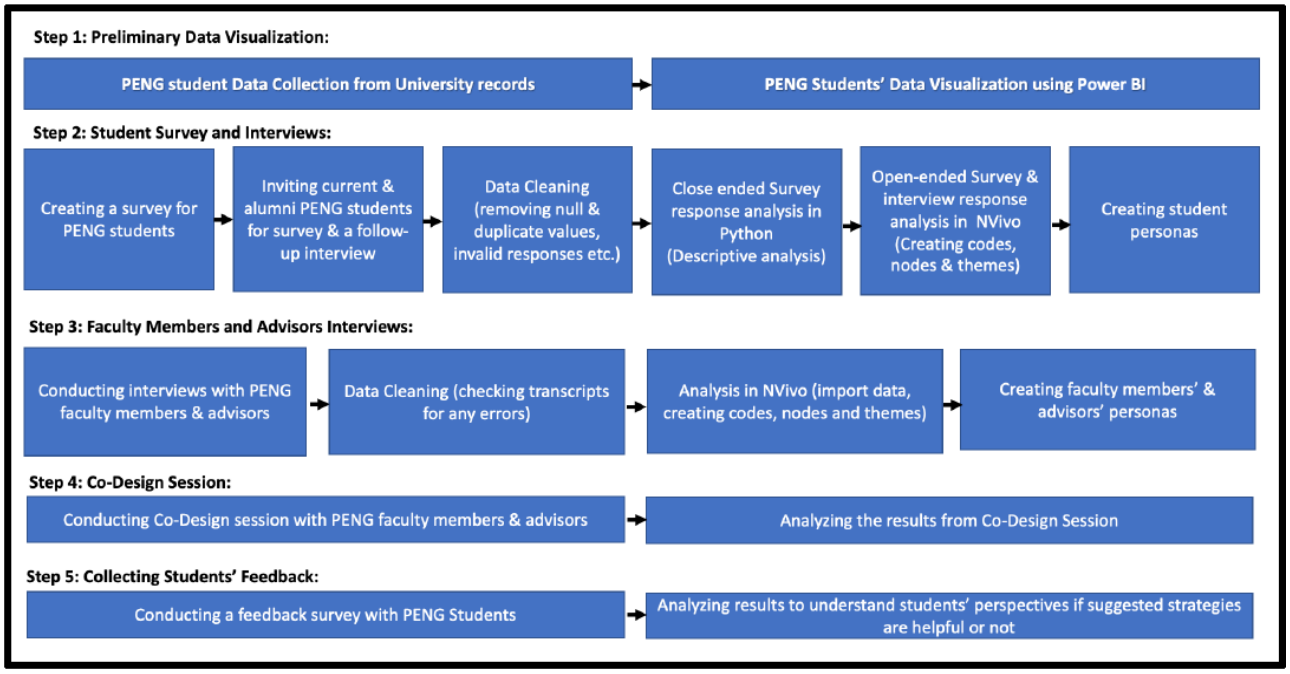

Fig. 3. Representation of process for data collection and analysis.

Phase 1: Student Survey and Interviews

Phase 1 involves survey and interviews of current students and PENG alumni to gather insights on their experiences and challenges in the PENG Program. Qualtrics was used to distribute surveys, with direct emails sent to all 834 students in the program. Additionally, flyers were posted on campus to encourage participation. Of the total population, 200 students (24%) responded, and after data cleaning, 172 valid responses were analyzed. The survey included Demographics, academic standing, and program experiences involving open-ended questions about PENG challenges faced by students and asking for ideas for improvement. The survey responses provided a diverse representation. These responses came from people of different ages, races, and academic backgrounds, where most respondents were engineering majors who performed well academically (GPA $\geq$ 3.5). It is important to acknowledge potential response biases as the students who responded may have been more engaged in the program or had

stronger opinions about their experiences. University primarily serves a commuter student population, so most respondents were employed part-time, with most students coming from communities within a 50-mile radius.

The survey responses provided an in depth analysis of students perspectives but recognizing the need for deeper insights, a follow-up interviews were conducted with selected students to further explore the challenges identified in the survey responses. A total of seven students from the survey sample participated in interviews, providing a qualitative complement to the existing survey responses. The sample size for additional interviews was relatively small, but it provides deeper insights into understanding student challenges in the PENG Program.

Phase 2: Faculty and Advisors Interviews

In phase two, 6 PENG faculty and 3 advisers were interviewed in-depth in order to assess the program's efficacy, identify areas for improvement, and make necessary adjustments. The selection of participants was predicated on carefully guaranteeing a varied representation in both advising and teaching roles. Key courses like MATH 090, MATH 105, MATH 115, CHEM 134, and ENGR 100 were represented by faculty members from the fields of mathematics, chemistry, and engineering. Important insights were also provided by advisers from the Math Learning Center (MLC), the START advising office, and the College of Engineering and Computer Science (CECS). A comprehensive grasp of the PENG program's support services, instructional efficacy, and student problems was guaranteed by this wide representation.

The semi-structured interviews, held on-campus or by Zoom, ranged from 20 minutes to 1 hour. The interview data were transcribed and processed with NVivo software to discern reoccurring themes. Combining this data with student surveys and interviews helped in a thorough understanding of the difficulties faced by PENG students. A peer review procedure was used to guarantee validity and reliability, with a different researcher examining the coding and themes independently whose feedback was integrated into the final analysis. The interview data facilitated the development of students, faculty and advisor personas, providing insights into their impressions of the obstacles and needs of PENG students, which informed targeted actions for program enhancement and student success.

Phase 3: Redesign and evaluation of the PENG program

Phase 3 encompasses two methodologies: a co-design workshop and an online survey. The co-design session, involving 6 faculty members, 3 advisors, and the Dean, produced concepts for program improvement. Co-design workshop encompassed icebreakers, the examination of student personas, prioritizing card sorting, and brainstorming utilizing the Theory of Change (ToC) framework. Participants discussed their viewpoints about the challenges students face to find potential solutions.

Activity 1 began with icebreaker introductions that let participants discuss their names, PENG connections, and personal interests (such as a favorite movie or book). They also expressed their goals for the session. This fostered a sense of connection and set a positive tone for the co-design process. In Activity 2, participants reviewed personas to understand the needs, frustrations, and

challenges of PENG students. This helped align the group's thinking with the target audience's requirements and informs the subsequent brainstorming and ideation process. Activity 3 involved task prioritization using 19 cards, each symbolizing a PENG student's need or challenge. Participants ranked student needs based on their evaluation of student personas rather than personal judgment, ensuring a data-driven approach to prioritization. This method allowed the workshop to focus on actionable solutions grounded in real student experiences. Thus, helping them identify the most significant student challenges. Furthermore, Activity 4 integrated individual ranks from Activity 3 into a collective prioritizing, involving five primary pain points identified and ranked jointly. This guaranteed consensus on the most pressing concerns to address during the session. Finally, Activity 5 focused on formulating solutions for the primary identified demands utilizing the ToC framework. A structured approach facilitated the formulation of plans to tackle the most pressing difficulties faced by PENG students. Fig. 4 illustrates the sample template for Table of Contents documentation.

Program:	[Name of program or initiative]
Goal:	[Overall goal of the program or initiative]
Inputs:	[List the resources, funding, staff, and materials required to implement the program or initiative]
Activities:	[List the specific actions or interventions that will be taken to achieve the desired outcomes]
Outputs	[List the immediate results or products of the program or initiative]
Outcomes	• Short-Term Outcomes: [List the immediate changes or results that are expected to occur as a result of the program or initiative] • Intermediate Outcomes: [List the mid-term changes or results that are expected to occur as a result of the program or initiative] • Long-Term Outcomes: [List the ultimate goals or results that are expected to be achieved as a result of the program or initiative]
Assumptions: (If any)	[List the beliefs, values, and expectations that underlie the program or initiative and may affect its success]
Risks: (If any)	[List the potential obstacles, challenges, or external factors that may affect the success of the program or initiative]
Monitoring and Evaluation:	[List the methods and tools that will be used to track progress, measure outcomes, and make any necessary adjustments to the program or initiative]

Fig. 4. ToC documentation sample template

Results

Phase 1: Student Survey and Interviews

Most participants indicated satisfaction (mean score of 3.63) with the University's admission procedure. Whereas, when inquired about the University's involvement in the admission process, satisfaction levels varied, with 66.41 percent expressing positive responses. The survey

participants evaluated the University's PENG program support to determine how likely they were to recommend it. The findings indicated that 45.04 percent of participants were "Somewhat likely" to recommend it, while 25.19 percent were "Extremely likely." The Net Promoter Score (NPS) technique is used to analyze the participants' overall satisfaction with the PENG program, showing a majority of the students as dissatisfied, i.e., 48.1percent were classified as Detractors, 36.6 percent as Passives, and 15.3 percent as Promoters. Also, ANOVA tests showed no statistically significant differences in satisfaction related to demographic parameters such as age, race, or parental education ($p > 0.05$).

Spearman correlation analysis indicated moderate positive connections between satisfaction and the categories "Coursework Confidence" (0.62) and "Orientation Rating" (0.57). The connections suggest that students' confidence in their curriculum and the quality of Orientation were crucial factors in determining their overall satisfaction. Additionally, regression analysis utilizing chosen predictors such as "Coursework Confidence," "Orientation Rating," "Professor Support," and "Employment Status" accounted for 63.6 percent of the variance in student satisfaction ($R^2 = 0.636$). "Coursework Confidence" exhibited the most significant influence, with a coefficient of 0.5039. An NPS analysis of orientation satisfaction revealed that 57.3 percent of respondents were Detractors, highlighting the necessity for enhancements in orientation programs. Through this mixed-methods survey and interview data analysis, the study gathered valuable insights into the challenges faced by PENG students. It offered actionable recommendations to enhance the program's effectiveness.

Phase 1 additionally uncovered significant student insights via open-ended responses and interviews. Students emphasized the necessity for individualized assistance and aggressive engagement from instructors and advisors. A student remarked on the absence of early assistance, stating, "If anybody is struggling at that point, a better early warning system is needed." Another individual noted the absence of guidance during their second semester: "I had to figure out my second semester all on my own, and it set me up for failure." Many students advocated for the compulsory utilization of services, such as the Math Learning Center, to guarantee participation with academic assistance.

Furthermore, there was a request for increased practical exercises and laboratory trips to enhance the curriculum, with one student stating, "More hands-on experiences or external visits." Ultimately, numerous students advocated for enhancements to the orientation process, with one remarking, "I feel like it was rushed... Having that initial help for those students, like, okay, are you on the right track?". Providing initial assistance to students, such as confirming their progress, is essential. These findings offer significant insights into the issues encountered by PENG students and propose actionable ideas for enhancing the program's support systems and student experience.

Phase 2: Faculty and Advisor Interviews

Prominent issues encompassed substantial student workload, academic demands, disengagement, difficulties in mathematics, and restricted resource accessibility. One advisor remarked, "Students are overly busy," underscoring the substantial academic and extracurricular pressures

PENG students face. Faculty members articulated worries over students' disengagement and lack of understanding of the significance of PENG courses, with one participant remarking, "Students feel like it is kind of a waste of time," significantly when the courses do not contribute directly to their degree requirements. Mathematical hurdles were emphasized since some students encountered difficulties with pre-calculus, especially given their disparate levels of preparation. One staff member remarked, "Teaching pre-calculus to students with different levels of preparation has been difficult."

The faculty and adviser interviews yielded significant proposals for enhancing the program. The most common recommendation was the importance of better communication and mentorship. One advisor proposed "Making students feel they are part of the program" to improve involvement. Another recommendation included upgrading advising services, leveraging student data to pinpoint challenges to student success, and providing support services, including a Blue Carpet program for first-year students and a summer bridging program. One participant said, "Mentorship is so important there to form a connection," highlighting the need for individual-level student support.

Phase 3: Redesign and evaluation of the PENG program

Phase 3 findings underscore critical areas for enhancement, including Orientation, registration, financial assistance, and academic support. ToC framework directed the formulation of pragmatic measures, such as enhancing Orientation and accelerating financial aid procedures, presenting recorded testimonials and documenting senior students' narratives. Proposals for

improving the orientation program, including specialized tracks for PENG students, improving the financial aid process and Peer mentorship were perceived positively.

Additionally, open-ended comments identified student needs, such as clear communication about program expectations and the need for flexible schedules. These findings evaluate the proposed solutions and ensure the strategies align with student needs and PENG goals. The co-design workshop and student feedback Survey yielded significant ideas for revamping the PENG program. The ToC architecture guaranteed that methods were pragmatic, quantifiable, and based on student requirements, providing a robust foundation for subsequent enhancements.

Discussion

Revisiting the research questions, this study aimed to explore how Pre-Engineering (PENG) students describe their experiences and how the PENG program can better support them. The results show that students frequently struggle with academic preparedness, navigating institutional systems, and balancing personal and academic responsibilities. These findings align with existing literature, which highlights the importance of academic support, effective advising, and tailored resources in supporting student success particularly in STEM. However, this study adds to the literature by emphasizing the unique needs for PENG students. The importance of these results resides in their capacity to guide focused strategies that address specific challenges encountered by PENG students, thereby supporting the broader objective of improving success and retention in pre-engineering programs.

This work attempts to expand the current state of knowledge on successful PENG programs. This study discusses student experiences in the PENG program and identifies the elements expected to improve their experiences. This work has shed light on the importance of PENG programs in higher education and the need for further research to identify the key elements contributing to their success. The research undertaken at the Public University has yielded significant insights into the experiences of PENG students, elucidating the challenges they encounter and identifying potential enhancements to support their needs better. The findings indicate that PENG students attending regional Colleges can benefit from initiatives that offer academic support services, registration assistance, financial aid, personalized early warning systems, and other types of support to help them overcome their obstacles. The study highlights several key areas where the PENG program might be improved. The findings suggest improvement in Orientation, peer mentorship, advising, hands-on activities, and more efficient use of data to assist students better

Overall, the success of PENG students is significantly impacted by this work. Educational institutions can enhance PENG students' overall academic experiences and provide them with better support by implementing the suggestions covered in this study. The study highlights the importance of PENG students' opinions for developing and improving PENG programs. Educators can gain a deeper understanding of the PENG program based on students' experiences and pinpoint areas for development by interacting with them and asking for their opinions, resulting in a more welcoming and encouraging environment for PENG students, eventually improving their performance.

The study also highlights the necessity of Human Centered Design methods for designing programs that support PENG students. This includes examining data on the PENG student's experiences to finding patterns and trends to create focused interventions and designing co-desing experiences with students and the faculty/advisors that serve them. This strategy can guarantee that PENG programs efficiently consider every student's needs, irrespective of their circumstances or background. Thus, the study points towards the importance of cooperation and partnerships in PENG instruction. Together, educators, administrators, industry leaders, and policymakers can build programs and initiatives that cater to the needs of diverse students and foster a more encouraging and inclusive atmosphere for PENG students.

This study used a combination of survey distribution, interviews, and collaborative design to obtain a comprehensive understanding of student experiences in the PENG program. While the survey captured broad insights from a significant portion of the student population, follow-up interviews yielded deeper qualitative information, and the co-design session enabled targeted program improvements. Future research should aim to expand participation in qualitative phases to enhance representativeness further.

Conclusion

Several colleges in the United States have implemented and supported the college-level PENG program. Much research has not been done to determine how effective these programs are or what elements are responsible for their effectiveness. This research provides a human centered model that administrators can employ to learn about their students experiences, invite faculty and

staff to gain insights about the students, and engage the college community in co-design experiences to reimagine improvement in support services.

In conclusion, the research described in this study significantly adds to PENG education research. The results indicate that comprehensive student support and increased chances for engagement and experiential learning can enhance the effectiveness of PENG programs. By enhancing PENG programs through these methods, we can facilitate equitable access to education and opportunities for all students, irrespective of their origin or circumstances, thereby enabling their success in engineering. These exploratory findings yield new insights into understanding PENG students' experiences at a Public University using human centered design processes. This includes redesigning the PENG program to support students better and use data more effectively to track, identify, and support students. Furthermore, the findings of this study have practical implications for both PENG educators and policymakers in higher education. The study offers suggestions for enhancing the PENG program and emphasizes for educators the significance of creating a welcoming and inclusive atmosphere for PENG students. The report highlights the significance of funding initiatives and programs that assist PENG students for policymakers.

The study also adds to the expanding corpus of research on inclusion and diversity in engineering education. The results imply that various intricately interacting elements, such as institutional culture, social support, and academic readiness, influence PENG students'

experiences. Interventions intended to assist PENG students must, therefore, adopt a thorough strategy that considers each element. Lastly, the study highlights the need for additional research.

Although the study's conclusions are instructive, they only include the experiences of PENG students at one public University. Future studies should duplicate and expand these findings in different contexts to gain a more thorough grasp of the elements influencing the effectiveness of PENG programs. This research offers crucial insights into PENG students' experiences and the elements that make PENG programs successful. The results indicate that PENG programs can be improved in several ways and that a comprehensive strategy is required to help PENG students. It offers educators and policymakers a road map for enhancing the PENG curriculum and promoting inclusivity and diversity in engineering. The results and suggestions of the study have significant ramifications for the future of the engineering profession and the achievement of PENG students. Additional research is required to expand upon these findings and enhance PENG programs.

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