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Understanding How Students Experience Community-Engaged Engineering: A Phenomenographic Approach

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1. Background

1.1 Community-Engaged Engineering as a Context for Learning

Engineering education in the United States has increasingly shifted toward approaches that integrate technical learning with real social and environmental contexts. Scholars argue that engineering practice is inseparable from the societal conditions in which it occurs, challenging historical notions that frame engineering as purely technical work [1], [2]. As global challenges such as climate change, infrastructure inequity, and public health disparities become more visible, engineering programs are reexamining how students develop the capacity to respond responsibly and collaboratively to complex problems. Community-engaged engineering has emerged as a compelling pathway for bridging technical competencies with social responsibility by grounding engineering work in reciprocal partnerships with communities [3], [4]. Community-engaged engineering differs from traditional experiential or project-based learning by emphasizing shared problem framing, collaboration with diverse stakeholders, and respect for local expertise. Rather than designing solutions for communities from a distance, students work directly with partners such as nonprofit organizations, neighborhood groups, or municipal agencies to co-create solutions that reflect local priorities and constraints [5]. These interactions expose students to social systems, histories, power dynamics, and cultural practices that profoundly shape engineering outcomes [3]. Through this engagement, students reconsider what constitutes a "problem," who defines it, and how engineering solutions evolve through negotiation and dialogue [6]. Community-engaged engineering thus positions engineering as both a technical and relational practice, aligning with broader movements emphasizing humanitarian and socially just engineering [7]. Pedagogically, community-engaged engineering broadens students' understanding of engineering practice. Research demonstrates that work with real communities enhances reflection, empathy, communication, and ethical reasoning as these competencies are central to responsible engineering [8], [9], [10], [11]. These experiences help students navigate ambiguity, balance competing priorities, and consider the long-term societal impacts of technological decisions. Such preparation aligns with U.S. accreditation expectations, which emphasize the need for engineers who can evaluate global, economic, environmental, and societal impacts of engineering solutions [12]. While existing research often highlights measurable outcomes of community-engaged learning such as improved technical skills, civic motivation, or successful project deliverables much less is known about how students, faculty, and community partners themselves conceptualize community engagement in engineering [13]. Understanding these varying conceptions is essential because community-engaged engineering is enacted differently across institutions, disciplines, and community settings. Participants' interpretations influence how they approach collaboration, define success, and understand their professional responsibilities. Several theoretical frameworks support community-engaged engineering. Participatory design, community-based research, and humanitarian engineering emphasize co-creation, shared ownership, and responsiveness to context [14]. Communities of Practice theory further conceptualizes learning as participation in joint activity, highlighting how novices and experts develop shared meaning through collaboration [15], [16]. Together, these perspectives reinforce the idea that engineering knowledge is socially situated and evolves through engagement with others. This study uses phenomenography to examine the qualitatively different ways students at a Midwestern U.S. university, engaged in community-based engineering projects, conceptualize their work. By analyzing how students experience community engagement, the study offers insights into how these practices shape evolving understandings of what it means to be an engineer [17]. The study thus addresses a critical research question for engineering educators:

Research Question: RQ 1: How do students experience and make sense of community-engaged engineering?

RQ 2:What does this reveal about their developing identities as ethically and socially aware professionals?

2. Theoretical Framework: *Community of Practice (CoP)*

The conceptual foundation for this work draws on Lave and Wenger's [18] Community of Practice (CoP) framework, which views learning not as knowledge transmission but as increasing participation in a shared practice. Within a community of practice, newcomers engage peripherally through legitimate participation and gradually move toward fuller membership as they gain both technical skills and an understanding of shared norms, identities, and purposes. Applied to engineering education, this perspective highlights learning as *social participation* rather than isolated skill acquisition. When students engage in authentic community-based projects, they enter a space that bridges academic and professional domains. They interact with community partners, interpret real-world constraints, and reconcile competing perspectives. Such experiences position them as emerging practitioners, learning through participation in the broader social and ethical systems that shape engineering work [19]. The community of practice framework also emphasizes the significance of ***boundary crossing*** moments when learners move between different social worlds, such as between the university and the community organization [20]. These encounters expose learners to multiple forms of expertise, prompting negotiation of meaning and the integration of new perspectives. For engineering students, boundary-crossing experiences may involve translating technical knowledge into accessible terms for non-experts, reconciling conflicting stakeholder priorities, or confronting the societal consequences of design decisions. Such moments of negotiation and meaning-making often serve as developmental thresholds points at which learners expand their awareness from task execution to reflective understanding. Thus, the CoP framework provides a useful lens for interpreting how students learn not just *what engineers do* but *who engineers are* in relation to the communities they serve.

3. Methods

3.1 Context: Engineering Projects in Community Service (EPICS)

The Engineering Projects in Community Service (EPICS) program was established at a large Midwestern university in the mid-1990s to integrate engineering education with community engagement [5], [21]. The program enables students to apply technical knowledge to real challenges faced by nonprofit and community organizations and has since expanded nationally as a model for service-learning in STEM education. EPICS emphasizes long-term partnerships rather than short-term volunteer work. Students collaborate in multidisciplinary teams across multiple semesters to design and deliver solutions addressing community-identified needs [22]. Projects span areas such as access and abilities, education, and environmental sustainability. Because projects continue over time, students may enter at different phases of development, from early design to implementation, while ensuring continuity for community partners. The team-based structure reflects professional engineering practice, requiring students to coordinate across disciplines, manage ambiguity, and respond to real-world constraints. Working closely with community partners also fosters social awareness and empathy. Pedagogically, EPICS aligns with experiential learning, engaging students in cycles of action, reflection, and revision that support both technical growth and professional development [5]. With nearly three decades of implementation, EPICS represents a well-established model for integrating technical rigor, reflective practice, and community engagement.

3.2 Project Description

During the semester examined in this study, student teams worked on projects addressing concrete community needs through sustained collaboration with local partners. One team partnered with a transitional housing center to develop a website and resource dashboard that centralized information on employment, healthcare, childcare, and transportation services. The platform emphasized accessibility, intuitive navigation, and multilingual support, with iterative revisions informed by staff feedback and residents' digital access constraints. A second team collaborated with a local elementary school to improve the student dismissal process. To address safety concerns and inefficiencies, students designed a mobile application enabling parent check-ins and more coordinated student release. Iterative testing highlighted the need for simplified interfaces and backup solutions when internet access was unreliable. Across both projects, students engaged in iterative design cycles involving needs assessment, prototyping, testing, and refinement. Ongoing interaction with community partners required students to adapt to evolving requirements and align technical solutions with human-centered needs, reinforcing skills central to professional engineering practice.

Data Collection

Although semi-structured interviews are the primary mode of phenomenographic inquiry, this study relied on written student reflections produced as part of end-of-semester assignments. Written responses have been used effectively in prior phenomenographic work because they capture participants' own words and focus of awareness in a less mediated form. In this case, students were prompted to reflect on their experiences in community-engaged engineering projects, with attention to design, teamwork, impact, and professional growth. These reflections were treated as equivalent to interview transcripts for the purpose of analysis. Importantly, phenomenography does not require interviews per se; rather, it requires access to participants' expressed ways of experiencing the phenomenon and sufficient variation across accounts to construct categories of description. The shared prompt ensured comparability across participants, while the open-ended format allowed students to articulate their interpretations in their own terms. All students completed the reflection using the same assignment structure. Students selected two thematic domains (Personal and Professional Development, Social Impact, Academic Enhancement, or Ethics) and wrote at least 300 words per theme. Each reflection was required to include three components: (1) reflective observation of specific experiences from the semester, (2) conceptualization connecting those experiences to broader ideas within the selected theme, and (3) forward-looking application describing how the learning would be used in future contexts inside and outside EPICS. Guiding questions were provided to stimulate depth but did not require identical responses. This shared structure supported consistency across accounts while preserving variation in how students experienced community-engaged engineering. Sampling in phenomenography is typically theoretical and purposeful, aiming to maximize variation in participant perspectives rather than achieve representativeness. The dataset for this study included reflections from 25 students, yielding over 20,000 words of text. This size aligns with established phenomenographic practice, ensuring sufficient variation to capture different ways of experiencing the phenomenon while remaining manageable for in-depth analysis. While written reflections do not allow for follow-up probing or clarification, categories were repeatedly checked against the full dataset and grounded in participants' language to maintain analytic rigor.

3.4 Phenomenography as a lens on experience

To explore how students make sense of complex, socially embedded learning experiences, this study employs phenomenography [23], [24]. Phenomenography is a qualitative research approach developed to investigate the qualitatively different ways people experience, perceive, or understand a given phenomenon. Rather than measuring how much participants know, it seeks to describe the range and structure of variation in their experiences. Phenomenography is underpinned by a non-dualistic ontology, which assumes that experience is constituted in the relation between the person and the phenomenon not located solely within either [23]. Its interpretivist epistemology recognizes that multiple, equally valid ways of understanding coexist within any population. The analytic goal is to identify categories of description that capture these variations and to map their structural relationships into an outcome space, which represents the collective ways of experiencing the phenomenon. This approach has been used extensively in studies of learning and professional identity to illuminate developmental patterns in awareness [25]. In engineering education, phenomenography offers a powerful means to uncover how students shift their focus of awareness from narrow technical mastery toward broader, integrative understandings of practice [26].

3.5 Data Analysis

Phenomenographic analysis was conducted following the iterative and cyclical steps outlined by Ashworth and Lucas [25] and Cope [27]. Importantly, the dataset was treated as a **single pool of meaning**, rather than analyzed case by case, consistent with phenomenographic principles. The procedure unfolded as follows:

1. **Familiarization** - All reflections were read repeatedly to gain a holistic sense of how students described their experiences.
2. **Condensation** - Meaning units were identified within the texts; these are chunks of data that reveal how students conceived of their learning, teamwork, design process, or project impact.
3. **Comparison** - Meaning units were compared across the dataset to discern similarities and differences in focus of awareness.
4. **Grouping** - Similar ways of understanding were clustered into provisional categories.

5. **Articulating** - The essential meaning of each category was captured and articulated.
6. **Labelling** - Concise labels were assigned to convey the core meaning of each category.
7. **Contrasting** - Categories were refined through contrastive comparison, ensuring that they were distinct from one another while also capturing the variation within the dataset.

This process was iterative and required returning to the full dataset multiple times, re-reading transcripts in light of emerging insights. Categories were continually checked against raw data to maintain fidelity to participants' accounts and to guard against imposing researcher assumptions.

3.6 Outcome Space

The final stage of analysis involved arranging the categories into an **outcome space**-a structured representation of the collective range of ways students experienced community-engaged engineering. Consistent with phenomenography principles, categories were not tied to individual students but represented the variation across the group. In many cases, categories were **hierarchically inclusive**, with broader, more complex ways of experiencing encompassing narrower, more technical or instrumental perspectives.

3.7 Ensuring Trustworthiness

Several strategies were employed to enhance trustworthiness. First, students' own quotations are used extensively in the Results section to anchor each category in the participants' words. Second, the research team engaged in *peer debriefing and negotiated consensus*, discussing preliminary categories and refining them collaboratively to reduce the influence of individual bias. Third, attention was paid to reflexivity, with researchers critically examining how their own preconceptions might shape interpretation. Finally, the outcome space was assessed against established criteria for quality in phenomenography: categories were distinct, logically related, and captured the critical variation present in the data with as few categories as possible.

Research Team Positionality

The research team includes faculty affiliated with engineering education and community-engaged learning contexts. This positioning provides contextual familiarity with the pedagogical structure and professional norms of community-based engineering. At the same time, it carries the potential to privilege developmental interpretations of student growth. To mitigate this, the analysis emphasized grounding each category in participants' language, engaging in peer debriefing across researchers, and repeatedly returning to the full dataset to test category boundaries against disconfirming evidence. The goal was not to evaluate program effectiveness, but to describe the variation in how students experienced community-engaged engineering.

4. Results

The paragraph below showcases the results from the phenomenography analysis. It focusses on five categories of description: i) conception of impact, ii) conception of design, iii) teamwork and leadership, iv) learning and identity development and v) awareness of power and ethics. The results also showcase the structural relations and outcome space.

4.1 (a) Conceptions of Impact

Students varied in how they conceived the impact of their projects. At the most ***transactional level (Conception I)***, impact was equated with the production of a tangible artifact, a functioning website or app that met immediate partner needs. Students equated success with technical delivery. For example one student said, "*Our actions as a team focused on the website which, in many situations, acts as a patch for some of the underlying problems that may cause homelessness."* Similarly another student said, *"I feel good because we finally got it to work. That's how I know we made an impact."* ***The relational conception (Conception II)*** emphasized user experience and access. Students began to view impact in terms of how design choices supported real people's ability to access resources or services. For instance, one student said, *"Even something that seems small, like redesigning a card layout or rewording a filter, can have a real impact if it means someone can find help more quickly or without confusion."* Similarly, another student stated, *"I realized impact isn't about the code it's about who can actually use what we build."* At the ***systemic and civic level (Conception III)*****,** students recognized community complexity and the limits of technical solutions. A student said, *"Seeing how many barriers people face made me understand that our tool can only address a small part of a much larger issue, but it can still make their day-to-day challenges a little easier."* This progression from artifact as output, to design as access, to technology within systemic constraints illustrates students' increasing awareness of the complexity of defining community impact.

4.1 (b) Conceptions of Design

Students' descriptions of design evolved from technical mastery to co-creative partnership. Initially, students viewed design as ***technical construction (Conception I)***- learning code, implementing functions, and debugging issues. A student shared, *"For example, I learned how to use CSS properly, how to use Tailwind while reworking the filter, how React hooks worked better while reworking storage, and how state and the DOM interact in React."* Another student mentioned, *"Most of what I did was fixing the backend and making sure it didn't crash pretty much engineering in the purest form."* In the ***iterative relational conception (Conception II)***, students began to integrate testing and feedback, recognizing design as cyclical rather than linear. For example, one student said, *"There is a lot of testing and revision based on the tests… many small tweaks alongside several larger changes that multiple user testers need or request."* Another student expressed, *"We realized through user testing that what made sense to us was confusing to others, so we redesigned our navigation menu completely."* At the ***co-creative systemic level (Conception III)*****,** students described design as shared meaning-making with partners. One Student said, *"There were many times we would present to them, and they would ask for changes that would cause a major rework of the project, such as the queuing system."* Another student stated, *"Designing the crisis hotline page was especially impactful because it required me to think about how people in urgent situations interact with technology under stress."* Here, design expanded from a technical act, to a reflective and iterative process, to a mutual, empathic collaboration highlighting growth from product-focused to human- and system-focused engineering practice.

4.1(c) Teamwork and Leadership

Students' reflections on teamwork revealed a progression from coordination to facilitative leadership. At the ***basic coordination stage (Conception I)***, teamwork meant dividing labor efficiently and completing assigned parts. One student said, *"We all took one part of the website so we wouldn't overlap."* In the ***relational conception (Conception II)*,** teamwork was viewed as communication-driven collaboration, emphasizing knowledge sharing, documentation, and mutual accountability. A student said, *"When working with code I often struggle to understand new code written by someone else. This is usually due to a lack of comments and the use of new commands that I have not seen before."* Another student said, *"We made a communication log to make sure everyone knew what was done and what needed attention. That changed the way I thought about teamwork."* At the ***boundary-spanning level (Conception III)***, students described acting as facilitators across team and community boundaries. For example one student said, "I needed to understand not only his feedback but also the context in which it was given. This required active listening and the ability to put myself in his shoes." Teamwork thus evolved from division of tasks → communication for shared understanding → leadership as empathy and facilitation.

4.1 (d) Learning and Identity Development

Students' conceptions of learning ranged from acquiring technical knowledge to cultivating civic identity. Early reflections focused on ***technical and procedural learning (Conception I)***. For example a student said, *"I learned how web development worked, how websites are made, how the backend and frontend interact, how hosting works, and so much more."* Another student said, "I didn't know how databases connected before this; now I can build one from scratch." Next, learning was understood as ***professional formation (Conception II)***, incorporating reflective habits, time management, and collaboration. One student expressed, *"We need to prioritize testing earlier in the process and form habits like keeping detailed notebooks to track progress and decisions."* Another student said, *"I started to see learning not as memorizing but as managing complexity-how to plan, test, and explain my work."* At the ***highest level (Conception III), students integrated values of social responsibility and empathy into their self-concept*** as engineers. One student said, *"Visiting [partner organization] showed me how much care and effort go into supporting individuals experiencing homelessness. This experience helped me grow personally and professionally."* Another student mentioned, *"Working on this project made me realize that engineers are part of a larger ecosystem of people who depend on our decisions."*

4.1 (e) Awareness of Power and Ethics

Students articulated varying awareness of power dynamics and ethics in community engagement. At the most ***latent level (Conception I)***, students recognized that design decisions carry implications for user experience. One student said, *"It hit me that even font choices send messages about who this is for."* In the *relational awareness stage (Conception II)*, students recognized asymmetries between technical expertise and community knowledge. For example a student said, "We needed to stop assuming we knew what they needed the teachers and parents were the real experts." At the *ethical and civic stage (Conception III)*, students articulated responsibility for equitable participation and inclusion. One student said, "Most of the volunteers hadn't even interacted with Google Maps, which makes me believe that… we need to make a constant effort of teaching people how to use it." Another student said, "If our design excludes someone, even unintentionally, then we've failed as engineers." Across this continuum, awareness expanded from unconscious influence to recognition of asymmetry to ethical agency and inclusion representing the highest level of engagement in the community context.

4.2 Structural Relations and Outcome Space

Across all categories: impact, design, teamwork, learning and identity, and power and ethics students' reflections revealed a coherent and developmental structure that illustrates increasing sophistication in how they experienced community-engaged engineering. This developmental trajectory is not merely linear; rather, it represents a deepening awareness of what it means to be an engineer situated within a social, ethical, and civic ecosystem. At the **foundation**, students articulated *artifact-centered experiences*, describing engineering primarily as a technical pursuit aimed at producing deliverables, meeting deadlines, and demonstrating individual competence. Their focus rested on functionality, efficiency, and completion characteristics that align with early, peripheral participation in a professional community of practice [18]. Success in this conception was defined through tangible outputs rather than through processes of reflection or collaboration. At the **intermediate level**, students demonstrated *relational or collaborative understandings*. Engineering work became a shared process of negotiation, communication, and co-creation. Students began to describe learning through dialogue with community partners, usability testing with end-users, and coordination within their teams. These conceptions signal a shift from individual performance to collective meaning-making where empathy, listening, and responsiveness are central to effective engineering practice. Students at this stage positioned themselves as active members of the community of practice, moving beyond mere contribution to developing mutual engagement and shared understanding. At the **most advanced level**, students described *systemic or civic-oriented experiences* in which engineering was redefined as a vehicle for ethical responsibility, equity, and social transformation. Their reflections revealed an expanded sense of accountability that extended beyond immediate partners to broader communities and systems. Students critically examined questions of access, power, and sustainability, emphasizing the civic implications of their work. Engineering, at this level, was experienced as both a technical and moral enterprise as an act of participation in a larger social system oriented toward justice and inclusion. Several ***critical thresholds*** marked students' transitions across these conceptions. Partner engagement required students to navigate authentic professional relationships; usability testing illuminated the lived realities of end-users; and liaison or leadership roles compelled them to balance technical, interpersonal, and ethical demands. These threshold experiences catalyzed shifts in perspective from focusing on *what* was being built to *who* it served and *why* it mattered. Table 1 provides an overview of the outcome space; the sections below elaborate each category using illustrative quotations that anchor the categories in participants' language.

Table 1. Summary of phenomenographic outcome space across five categories of description (Conceptions I-III).

Category of description	Conception I (Technical / Artifact-Oriented)	Conception II (Relational / Collaborative)	Conception III (Systemic / Civic-Oriented)
Impact	Impact as delivery of a working artifact and technical completion	Impact as access and usability for real users	Impact as partial contribution within broader community systems and constraints
Design	Design as technical construction (coding, debugging, implementation)	Design as iterative improvement through testing and feedback	Design as co-creative meaning-making shaped by partner needs, context, and stress/urgency
Teamwork & leadership	Teamwork as division of labor and coordination	Teamwork as communication, documentation, shared accountability	Leadership as facilitation and boundary-spanning empathy across team–partner contexts
Learning & identity	Learning as acquiring technical/procedural skills	Learning as professional formation (planning, reflection, collaboration)	Learning as civic/professional identity tied to responsibility and care for stakeholders
Power & ethics	Ethics as latent recognition that design choices affect users	Ethics as awareness of asymmetries in expertise and knowledge	Ethics as agency: responsibility for inclusion, equity, and participation

The **final outcome space (see Figure 1)** can therefore be represented as an *inclusive hierarchy* of awareness each conception encompassing and expanding upon the previous one:

1. **Technical / Artifact-Oriented:** Focused on product functionality, efficiency, and technical mastery.
2. **Relational / Collaborative:** Centered on empathy, co-design, and communication within teams and with partners.
3. **Systemic / Civic-Oriented:** Integrates ethical reflection, power awareness, and civic identity within engineering practice.

Progression across these conceptions reflects a shift in students' ontological and epistemological relationship with engineering from *doing for* to *doing with*, and ultimately, *doing as part of* a civic system. At the highest level, students recognized that community-engaged engineering extends beyond problem-solving to participating in relationships of *mutual learning, shared agency, and social change*.

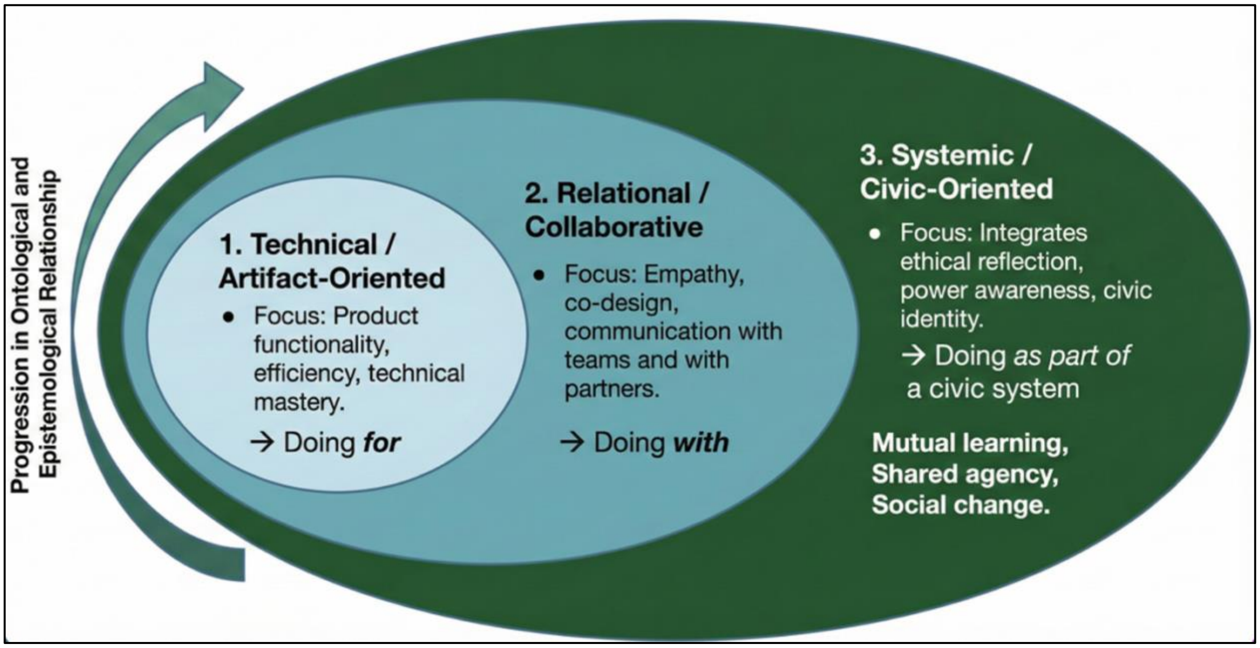

Figure 1: Outcome space

Across all aspects, the developmental trajectory moves from *technical performance* (Conception I), through *relational understanding and collaboration* (Conception II), toward *systemic and civic engagement* (Conception III). This mirrors a progression from *doing for* to *doing with* to *doing with awareness of systems* an increasingly complex and ethically grounded understanding of engineering practice.

5. Discussion

5.1 Developmental movement within a community of practice

The outcome space suggests that students' experiences of community-engaged engineering can be understood as qualitatively different ways of *participating* in engineering practice, rather than simply different levels of skill. Across categories, students' awareness shifted from an artifact-centered orientation (delivering features, meeting deadlines, "making it work"), to a relational orientation (negotiating meaning with teammates and partners), and in some cases toward a civic/systemic orientation (recognizing structural constraints, power, and responsibility). Interpreted through a Communities of Practice lens [18], these patterns resemble movement from legitimate peripheral participation toward more central participation, where *what counts* as engineering expands beyond technical execution to include relationship-building, accountability to stakeholders, and ethical judgment. Importantly, phenomenography does not claim that all students progress in the same way or at the same rate. Instead, the outcome space maps a developmental range of *possible* ways of experiencing community-engaged engineering within this course context. The hierarchy observed here is therefore best read as an inclusive structure of awareness: later conceptions incorporate and extend earlier ones (e.g., technical competence remains present, but is re-situated within relational and civic purposes). This framing clarifies how community engagement can function as professional formation not by replacing technical learning, but by broadening what students notice, value, and take responsibility for in engineering work.

5.2 Boundary crossing as a mechanism for shifts in awareness

Findings further indicate that certain course features acted as *threshold experiences* that supported shifts in students' focus of awareness. Partner engagement, usability testing, and liaison/leadership roles repeatedly appeared as moments when students encountered misalignment between academic assumptions and community realities. These moments functioned as boundary-crossing experiences [20], requiring students to translate across domains, reconcile competing priorities, and interpret feedback shaped by lived context rather than disciplinary convention. Students who described boundary-spanning work did not only report improved communication; they articulated changes in what they considered legitimate evidence for design decisions (e.g., user confusion outweighing developer preference), and what they considered successful outcomes (e.g., access, clarity, inclusion). This aligns with the idea of brokering in communities of practice: some students began to mediate meaning between the team's technical logic and partners' situated expertise, learning that engineering decisions are negotiated within social systems rather than optimized in isolation. In that sense, boundary-crossing tasks may be a plausible mechanism explaining why some students moved from "doing for" to "doing with," and eventually toward a more systemic framing of impact.

5.3 Civic professionalism, power, and ethical agency

At the most comprehensive end of the outcome space, students' reflections resonated with civic professionalism [28], where technical work is understood as public-facing practice with moral consequences. In these accounts, engineering was not positioned as neutral problem-solving; rather, it was framed as participation in systems that can either widen or reduce inequities. Students' attention to accessibility, digital literacy, and the risks of exclusion reflects an emerging ethical agency showcasing an understanding that design choices embed values and distribute benefits unevenly. The *power and ethics* category is especially important because it shows variation not merely in *ethical topics* students mention, but in *ethical stance*. Some students acknowledged designer influence as an abstract fact; others recognized asymmetries of expertise and authority; and a smaller subset articulated responsibility for inclusion and equitable participation. This distinction matters for engineering education: it suggests that ethics in community-engaged work is not only about compliance or professional codes, but about how students learn to locate themselves within relationships of power, knowledge, and accountability.

5.4 Implications for engineering education design

Taken together, the outcome space suggests that instructional design can intentionally support movement from technical/artifact-oriented conceptions toward relational and systemic/civic orientations. The following pedagogical implications are explicitly aligned with the identified categories of description:

1. **To support movement beyond artifact-centered (Conception I) orientations**, instructors should design for reciprocity rather than only deliverables. Framing projects

as co-produced work where community partners shape definitions of success helps students experience engineering as relational collaboration rather than technical execution alone.
2. **To deepen relational conceptions (Conception II)**, structured feedback loops that privilege user meaning can shift attention from internal technical logic to external access and usability.
3. **To foster systemic/civic awareness (Conception III)**, rotating boundary-spanning responsibilities such as liaison roles can expose more students to negotiation across domains.
4. **To strengthen the power and ethics category**, explicit instruction on accessibility and inequity legitimizes these concerns as central engineering considerations rather than peripheral reflections.

These implications do not require reducing technical rigor. Instead, they reposition technical work inside a broader conception of engineering practice one that better matches the socio-technical realities graduates will face and meet the professional requirement set by ABET [12].

6. Limitations and future work

This study is limited by its reliance on end-of-semester written reflections from a single institutional context. In phenomenography, the purpose of sampling is not statistical representation but to capture the critical variation in ways a phenomenon is experienced. Accordingly, the claims of this study are bounded to describing a defensible outcome space for this course context rather than estimating prevalence of conceptions or predicting outcomes. While 25 reflections yielded sufficient breadth to identify stable categories through iterative contrastive analysis, a larger and more diverse sample across institutions and project types would strengthen transferability and allow future work to examine how frequently different conceptions are taken up.While written reflections can function similarly to interview transcripts in phenomenography by capturing participants' focus of awareness, they reduce opportunities for probing and clarifying meaning. Additionally, students may tailor reflections to perceived course expectations, and the dataset cannot establish how stable these conceptions are across time or contexts. Future research could strengthen transferability by (a) incorporating follow-up interviews to test category boundaries, (b) comparing outcome spaces across different community contexts or engineering subdisciplines, and (c) examining how specific pedagogical elements (e.g., frequency of partner interaction, degree of co-definition, role rotation) shape the distribution of conceptions over multiple semesters. Including community partner perspectives could also illuminate whether students' more advanced conceptions align with partner experiences of reciprocity and value. Finally, while phenomenographic category construction requires interpretive, iterative reading to preserve the structure of awareness in participants' accounts, future work could explore the use of NLP-assisted or LLM approaches to support triage and auditing of large reflection corpora. Such tools would be used to accelerate retrieval and transparency (e.g., surfacing representative excerpts), not to replace the interpretive judgment required to define and validate phenomenographic categories.

7. Conclusion

This phenomenographic study mapped the qualitatively different ways undergraduate engineering students experienced community-engaged engineering in an EPICS context. The outcome space revealed a coherent range of conceptions across five aspects impact, design, teamwork/leadership, learning/identity, and power/ethics structured as an inclusive hierarchy from artifact-centered participation, to relational collaboration, and in some cases toward systemic/civic orientation. Rather than treating community engagement as a uniform intervention with a single outcome, these findings show that students inhabit meaningfully different forms of engineering practice within the same course. Boundary-crossing experiences especially partner engagement, usability testing, and facilitation roles appear to be pivotal in shifting students' focus of awareness from "what we built" to "who it serves," and further toward questions of access, power, and responsibility. By making this variation visible, the study offers both a conceptual contribution (a phenomenographic outcome space for community-engaged engineering experience) and a practical contribution (design levers instructors can use to support deeper, more ethically grounded participation). Ultimately, community-engaged engineering can function as professional formation when curricula intentionally support students in integrating competence, collaboration, and conscience as inseparable dimensions of engineering practice.

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