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Charting a Research Direction to Explore Development of Sociotechnical Thinking in Engineering Design

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Abstract

Evident in calls such as the National Academies of Engineering Grand Challenges and United Nations Sustainable Development Goals, engineering problems are fundamentally sociotechnical. These problems both shape and are shaped by social, cultural, political, environmental, and other contextual elements. Sociotechnical design theories (e.g., Design Justice, Value-Sensitive Design, Engineering for Social Justice, and Feminist Design) offer insight into the expert-like practices engineers might engage in to address challenges, but how and where engineers develop the ability to engage in sociotechnical thinking throughout their careers is currently unclear. Sociotechnical thinking is inherently complex, and while many engineering educators regard it as a critical skill, relatively little is understood about the learning experiences and processes needed to promote sociotechnical thinking. The purpose of this paper is to synthesize the literature on cognitive development and sociotechnical design theories and to envision a research area related to students and professional development of sociotechnical thinking in engineering design. In cognitive development, I highlight literature related to college students and early career individuals' epistemological development. For sociotechnical design, I offer a brief overview of predominant theories and practices that are applicable within engineering design settings. I also highlight existing work in sociotechnical thinking in engineering education. By weaving together these strands of scholarship, I hope to make space for an emerging and critical area of engineering education research that can illuminate issues surrounding the development of vital engineering skills and ways of thinking. In this paper, I put forth a few questions and discuss potential opportunities to explore student and professional development in sociotechnical design. For instance, *How does Sociotechnical Thinking develop and change over time for engineering students and professionals? Can sociotechnical thinking be validly, reliably, and expediently measured, and what patterns and differences emerge across different engineering populations (e.g., by career stage, type of experience, identity-based characteristics, nature of work, etc.)? What kinds of experiences promote growth in engineers' ability to engage in sociotechnical thinking in design?* I hope these questions and others can encourage new conversations in ways that enhance engineering educators' language and, thus, the ability to discuss and engage with critical issues related to sociotechnical thinking and its role in engineering design.

Introduction and Motivation

Evident in such calls as the NAE Grand Challenges and UN Sustainable Development Goals, engineering problems are fundamentally sociotechnical. These problems both shape and are shaped by social, cultural, political, environmental, and other contexts in vast and complex ways. They involve significant interaction between diverse systems and stakeholders and require engineers to engage in sociotechnical thinking during design. By engage in sociotechnical thinking in design, I mean three things: (1) recognize the range and role of social, cultural, political, environmental, and other factors in engineering design processes and solutions, (2) analyze the ways design artifacts and processes reify, enable, and constrain sociotechnical design elements, and (3) evaluate and integrate sociotechnical dimensions into engineering solutions through specific and intentional design practices.

In the same ways that ignoring cost throughout the design processes will not result in an outcome with no monetary impact, ignoring sociotechnical considerations throughout design will not result in an outcome devoid of social, political, economic, etc. impact. Indeed, overlooking these dimensions can result in real and imagined design solutions that harm the environment, reinforce systemic inequity and injustice, and/or lead to designs for which there might be "unintended consequences" [1]-[3].

And while studies from engineering practice illustrate the importance of technical details and social, cultural, political, economic, etc. issues throughout the design process, ideologies of depoliticization [8] and technical-social dualisms [9]-[11] raise important questions about how and where engineers get opportunities to meaningfully engage in sociotechnical thinking in design. Indeed, there are growing concerns that as more engineering designs result in novel solutions and systems, engineers will struggle to take a sufficiently broad view of their social, ethical, and financial responsibilities [1]-[4]. Nonetheless, many engineers do engage in sociotechnical thinking in practice [12], [13], suggesting that engineers *do* eventually gain competence with this kind of thinking. However, *how* they develop these skills throughout their education and training is currently unclear.

Sociotechnical thinking in engineering design is complex and multifaceted, in that it requires the ability to account for different forms of information from different stakeholders with different motivations and values. And while it is recognized as a priority for engineering educators, many models of sociotechnical thinking resemble expert-like practices. Attention to the developmental aspects of sociotechnical thinking in design will help engineering educators gain greater competence and precision in the ways they address sociotechnical issues for engineers with different levels of experience and knowledge.

The purpose of this paper is to bring together different threads of literature to make space for new conversations about sociotechnical thinking in engineering design education and practice. I focus on design because it represents a logical place to start this research strand. Sociotechnical issues are most likely to surface in engineering design contexts. The interactions between and among different stakeholders provide useful settings to explore the social dimensions of engineering activities. The following sections will highlight some recent efforts in sociotechnical thinking research, describe some relevant sociotechnical design theories, and review cognitive development frameworks. I will then combine these separate areas of research in ways that offer new directions for research in engineering education and practice.

Relevant Literature

There are three major areas of research I seek to integrate. First, sociotechnical design theories offer a foundation for helping engineers incorporate various sociotechnical dimensions into their practice. Second, sociotechnical thinking in engineering education has emerged as a major focus of the community and researchers have leveraged these design theories to conduct cutting-edge research. Finally, by adding a developmental lens to the conversations around sociotechnical thinking in engineering design, I aim to engage in new scholarship and learning and different ways to scaffold engineers as they engage in sociotechnical thinking over time. I will address each topic in more detail in the following sections.

Sociotechnical theories of design

Sociotechnical design refers to different sets of theories and practices that consider sociotechnical dimensions of the design process. Each theory tends to vary in what it emphasizes or prioritizes, but all note the importance of what might traditionally be termed "non-technical" aspects of engineering design practices and decisions. (I recognize that to call something non-technical is to endorse the social/technical dualism I seek to address, but our current language for describing this is limited [1], [2].) For example, *Value-sensitive Design* emphasizes the ways different human values (e.g., community, independence, justice) are imparted onto and mediated by the design of systems and products [3]. This theory calls for practices that ask designers to consider a wide range of possible uses, misuses, appropriations, and other humanistic dimensions of design. Relatedly, *Design Justice* outlines methods to engage with stakeholders in ways that empower affected communities and incorporate diverse stakeholder feedback into design criteria [4]. This method offers practices that identify inequities in both engineering systems and artifacts practices that can address and design to make positive impacts in communities where solutions are implemented. *Feminist Design* urges designers to interrogate how gender affects and is affected by different technological developments (e.g., pregnancy tests, and breast pumps) and makes recommendations for integrating feminist thinking into the design of new objects and systems [5], [6]. *Engineering Design for Social Justice* focuses on six heuristic principles such as "identifying structural conditions," "acknowledging political agency," and "enhancing human capabilities" [7]. Aranda Jan et al. (2016, described below) developed a framework to consider 9 salient "contextual factors" for biomedical design. These factors range from consideration of the individual user or patient to a broad conception of systems- or societal-level stakeholders [8]. These theories and others (e.g., [9]–[11]) are instructive because they provide different sociotechnical lenses for engineers to consider as they engage in design. These theories also highlight the relatively broad space that comprises sociotechnical thinking in design.

However, when it comes to recommendations for practice, sociotechnical design theories typically offer models for expert-like practices and—reasonably—focus less on how engineering educators might scaffold learning for students and professionals in ways that account for prior knowledge.

Sociotechnical Thinking in engineering education

The second major area of literature relevant here is sociotechnical thinking in engineering and design. In recent years, sociotechnical thinking in engineering has emerged as a major focus of the research community, with a range of different approaches and foci. Sociotechnical thinking in engineering is discussed using a range of lenses and approaches within engineering education, and I will attempt to synthesize some of the cutting-edge research.

One major effort has been out of the Colorado School of Mines. Here, researchers explored a wide range of factors related to sociotechnical thinking in undergraduate engineering programs. They examined the perceptions and experiences of both students and faculty regarding sociotechnical integration and its impact on sociotechnical habits of mind [2], [12]–[14]. This work was conducted across a range of engineering curricular settings which included design as well as engineering science courses. One of their major research projects entails exploring student and faculty experiences of integrating different social justice principles in their courses. They found that students exhibit "liminal" engineering identities, meaning that their beliefs about their status as real engineers are not fully secure [15]. Moreover, they found that this liminal identity affected student beliefs about the role or importance of sociotechnical thinking in engineering.

These researchers also explored instructor experiences with implementing an assignment designed to help students engage in sociotechnical thinking and found several barriers and opportunities that concerned sociotechnical thinking [16]. For instance, instructors experienced challenges related to students' preconceived notions of engineering work and sociotechnical thinking (i.e., that real engineering is mostly technical). However, this is also presented as an opportunity to help students better understand the nature of engineering practice and demonstrate the ways engineering is inherently sociotechnical. Finally, their work also points to the need for an effective instrument to assess students' sociotechnical thinking. Such an instrument can illuminate demographic differences, such as how sociotechnical thinking differs by engineering discipline. The research on sociotechnical thinking in engineering at the Colorado School of Mines has laid a strong foundation on which to build our understanding of student and professional development.

At the same time, a team of researchers at the University of Manitoba developed a conceptual framework based on existing literature to characterize salient dimensions of sociotechnical thinking in engineering. Fajardo et al. (2022) synthesized literature related to sociotechnical thinking in both engineering education and practice and highlight six dominant aspects of sociotechnical thinking in engineering (e.g., cultural impact, sustainability, environmental impact) [17]. They used this framework to code senior design reports for the presence of different sociotechnical elements. Overall, they found that while most reports exhibited some sociotechnical thinking, the degree to which these dimensions were consistently and meaningfully considered throughout the projects was highly variable. Depending on the nature of the project, some teams more fully integrated sociotechnical concerns while others only superficially addressed them (e.g., in a brief section about ethical codes). This framework is useful in laying out the broad categories of discussion present in sociotechnical literature in engineering and offers a useful starting point on which to create a model. While the authors do note differences in how these dimensions were addressed across reports, it does not necessarily operationalize these differences.

Another recent effort has been out of the University of Michigan, where researchers are focusing more on sociotechnical thinking in design settings. One team is investigating the ways engineers consider and engage with different contextual factors during design (e.g., economic, institutional, political, and socio-cultural). Contextual factors are derived from research in biomedical device development in low-resource settings [8] and account for relevant sociotechnical dimensions that account for individual, physical/environmental, technical, and systemic/structural factors. Their work has examined how novice engineering design students engage with and consider contextual factors throughout the design process. They note how novice engineers tend to emphasize technical factors and distance themselves from social considerations [18], [19]. This work is informative in that it helps us better understand novice-like thinking and behaviors related to sociotechnical aspects of design and recognize where engineers might struggle or experience challenges (e.g., in incorporating social factors into the design). More recently, this team has begun to explore the expert designers' consideration of contextual factors in ways that can identify relevant differences between novices and experts. They have also begun to explore social engagement tools as a way to better support engineers in considering a wider range of contextual factors during design. Characterizing expert-like behaviors and practices in sociotechnical design is vital as it offers a model toward which design educators can guide learners.

Other researchers have critiqued the notion of integrating context into engineering education. Kleine et al. (2021) describe how contextual elements are typically integrated in engineering, and encourage engineering educators to integrate context in ways that move beyond doing so to improve understanding of core concepts and that illuminate engineers' role in complex sociotechnical systems [20].

Some researchers have begun to develop assessment tools for sociotechnical students' sociotechnical thinking. Muzzurco et al. (2020) developed a tool to evaluate sociotechnical thinking along three primary domains: technology, people, and broader context Their work found that both students and practitioners consider the technological aspects of a design problem, practitioners noted the importance of people and broader contexts more often than students. Smith et al. (2021) outline a framework for what they term "global sociotechnical competency" that describes learning outcomes (i.e., knowledge, skills, attitudes) along different content dimensions such as "sociotechnical coordination" and "navigating ethics, standards, and regulations", to name a couple of content dimensions [21]. This research and others noted above offer a useful means for describing the learning and development goals as it pertains to sociotechnical thinking (i.e., assessing sociotechnical thinking) but do not address how educators might scaffold and support engineers in realizing these outcomes.

The point here is that research on sociotechnical thinking in engineering education is a diverse and growing field and that there is potential to add to this vital work by giving greater clarity and granularity to the progression from novice to expert and a better understanding of the mechanisms that encourage development in sociotechnical thinking. Cognitive development frameworks can offer insight into the more specific ways learners change and grow over time.

Cognitive Development frameworks

Broadly, cognitive development refers to growth or change in the ways an individual makes meaning in the world. This development can be intellectual (i.e., a change in how individuals make sense of and evaluate learning or knowledge [22]), moral (i.e., a change in the manner and criteria upon which decisions are made [23]), conceptual (i.e., change in the way one understands and assimilates new experiences and ideas [24]), and other areas in which learning occur over time [25]. While there is a wide range of developmental models, I will highlight one here that offers a useful framework for charting changes in thinking and reasoning over time: Baxter Magolda's Epistemological Reflection Model (ERM) [26].

Baxter Magolda's ERM describes cognitive development in terms of the ways individuals make sense of, evaluate, interact with, and understand knowledge. This model is derived from Perry's intellectual development framework [27] and addresses salient dimensions of college learning environments. The categories, called "ways of knowing", range from *Absolute* to *Contextual*. *Absolute Knowing* corresponds to an overarching belief system where knowledge is generally regarded as sets of facts and learning is the acquisition of those facts. This position shares similarities to what has sometimes been termed the "banking model" of education, where knowledge is transmitted from an expert (or some authority figure) and stored in the minds of students [28]. On the other end of the model is *Contextual Knowing*, in which knowledge is understood to be situational, contingent, and subject to revision based on relevant information. This way of knowing shares similarities with constructivist worldviews, where knowledge is something that is distributed among individuals and is consistently re-evaluated and revised in light of new experiences [29]. Each way of knowing is characterized by how students perceive salient dimensions of a traditional learning environment. The ERM postulates that as students move through their undergraduate studies and into their professional careers, they progress from *Absolute* to *Contextual* ways of knowing. An abbreviated overview of the theory is provided in Table 1 below.

Table 1: Abbreviated summary of Baxter Magolda's Epistemological Reflection Model.

Domains	**Absolute**	**Transitional**	**Independent**	**Contextual**
Role of Learner	Obtains Knowledge	Understands knowledge	Thinks for oneself	Integrate and applies knowledge

Role of Peers	Share materials	Provide active exchanges	Share views	Enhance learning via contributions
Nature of Knowledge	Is certain or absolute	Is partially certain and uncertain	Is mostly uncertain and belief-based	Is judged on relevant evidence

The different ways of knowing are characterized by how students perceive salient aspects of their educational environment, referred to as "domains." For example, as students move from *Absolute* to *Transitional* ways of knowing, their beliefs about the role of a learner shift from thinking that the purpose is to obtain knowledge to a position where learning is more about understanding and applying knowledge. Notably, the progression from one way of knowing to another is often sparked by moments of cognitive dissonance [25], where an existing belief system is challenged or disrupted and ultimately results in new perspectives and beliefs (e.g., witnessing experts disagree on their interpretations of the same set of facts).

Combining these frameworks

In this paper, I hypothesize that sociotechnical thinking is *developmental* in that it involves progressing through different ways of thinking about sociotechnical aspects of design over time. A developmental lens can offer insight into relevant differences in ways of knowing and thinking and offer paths to more complex, useful ways of engaging in sociotechnical thinking. More specifically, I envision the potential to populate the cells of Table 2 below, which could be used to chart development along relevant sociotechnical domains.

Table 2. Hypothesized sociotechnical thinking developmental model with potential categories and dimensions.

		Potential Developmental Categories			
Potential Sociotechnical Design Domains		Recognize	Analyze	Evaluate	Influence
	Environmental				
	Cultural				
	Political				
	Ethical				
	Technological				

These domains could include, for example, some combinations of the six dimensions laid out by Fajardo et al. combined with the 9 contextual factors identified by Aranda Jan et al. Further, as this model is adapted to new engineering design contexts, additional relevant dimensions could emerge, while others could become less central. At any rate, such a model would offer insight for design educators in both assessments of existing knowledge and for charting growth and development over time or in response to various interventions.

Implications for Engineering Education and Practice

Sociotechnical thinking in Engineering Design is critical for competence in modern engineering practice, but it is also hard to do, and we know little about how or where it is developed. And without a better understanding of what comprises the progression from novice to expert ways of thinking, educators will encounter challenges related to sociotechnical integration. I envision a research direction for engineering educators that builds on the progress made by experts in sociotechnical design as well as cognitive development. This research would be focused on creating learning experiences that promote sociotechnical thinking within engineering curricula and professional development. By meeting learners where they are, educators can design learning environments that encourage sociotechnical thinking in ways that are engaging, relevant, and validating. And by knowing more about how sociotechnical thinking develops over time, we can be more effective in assessing prior knowledge and educating accordingly.

In the interest of being more concrete about what kind of research might emerge from interweaving these different areas of scholarship, I envision several questions that can be explored through this line of research and will address each in more detail.

1. *How does Sociotechnical Thinking develop and change over time for engineering students and professionals?*

Research in this direction could leverage existing dimensions of sociotechnical thinking research or contextual factors described (e.g., [8], [9], [17], [19]] to explore different ways of thinking and reasoning about these various domains. Researchers could develop design activities that can generate sociotechnical discussions and explore differences across groups of engineering students and professionals with different levels of experience. Alternately, the research could follow different cohorts of students and early career professionals and investigate the changes over time in how they consider and engage with sociotechnical dimensions of design. This kind of research could also illuminate salient experiences and challenges related to sociotechnical thinking as engineers move through their curriculum or profession. By charting the progression of development as it concerns sociotechnical thinking, engineering educators can better understand how to design appropriate learning experiences that validate and scaffold learners most effectively.

2. *Can sociotechnical thinking be validly, reliably, and expediently measured, and what patterns and differences emerge across different engineering populations (e.g., by career stage, type of experience, identity-based characteristics, nature of work, etc.)?*

Research here could develop surveys or questionnaires to assess engineers' thinking about different sociotechnical dimensions. One example could be in a form similar to the *Defining the Issues Test (DIT2)* or the *Engineering Ethical Reasoning Instrument* (EERI). These instruments present respondents with different moral and ethical dilemmas and ask individuals to rank the importance of different aspects of the dilemma. These instruments are designed to assess an individual's competence with moral or ethical reasoning based on the nature of their responses. A similar instrument here could present engineers with sociotechnical design scenarios and ask them to consider and rank different technical and non-technical dimensions. Such an instrument could provide valuable information to engineering educators, whether they are interested in assessing prior knowledge or measuring the impact of some kind of sociotechnical intervention.

Another avenue to address this question could be through the use of an open-ended questionnaire similar to the *Measure of Epistemological Reflection* (MER) [30]. This survey was designed to ask students about moments of dissonance or times when they needed to make a difficult decision about the domains of the ERM noted above in Table 1. Their responses are open-ended and coded according to the ERM. This kind of survey could be useful for understanding differences across larger groups of engineers and for exploring differences across relevant variables (e.g., discipline, race/ethnicity, gender, SES). Understanding differences across groups can inform more specific disciplinary practices and also identify places to offer more targeted support in scaffolding sociotechnical thinking.

3. *What kinds of experiences promote growth in engineers' ability to engage in sociotechnical thinking in design?*

One of the important points about most developmental frameworks is the idea that development often occurs in response to an individual's experience of cognitive dissonance and eventual resolution. Individuals grapple with new information and assimilate that into their existing belief systems, which in turn modifies their overall system of beliefs about the world. This process of dissonance and resolution is what characterizes change and growth over time. Applying a developmental lens to sociotechnical thinking helps us introduce questions about what kinds of experiences might create this dissonance and what kinds of behaviors lead to resolution. Understanding more about this question could be especially useful for instructors and curriculum designers. By knowing how to create this dissonance and how to best support its resolution, educators can more effectively help students gain sociotechnical thinking skills.

Conclusions

While many engineers do develop competence in sociotechnical thinking, they will typically begin as novices and develop over time and with more design experience. It is therefore important that engineering educators work to better understand how and in what ways this happens for students and professionals. Doing so will help educators meet learners where they are in terms of their cognitive development and to validate existing knowledge. In this paper, I attempted to bring together different strands of literature to advance conversations and research directions in engineering education—especially as it concerns areas of sociotechnical thinking. On the one hand, sociotechnical design offers a wide range of practices and theories that can inform context-specific practices. On the other, cognitive development theories help us understand how individuals might come to engage in sociotechnical thinking with increasing complexity and sophistication. I hope that this paper can spark new conversations and research projects in ways that help engineering students and professionals effectively grapple with modern challenges.

References

[1] K. Johnson, J. Leydens, B. Moskal, and S. Kianbakht, "Gear switching: From 'technical vs. social' to 'sociotechnical' in an introductory control systems course," in *2016 American Control Conference (ACC)*, 2016, pp. 6640–6645.

[2] K. Johnson *et al.*, "The Development of Sociotechnical Thinking in Engineering Undergraduates," in *2022 ASEE Annual Conference & Exposition*, 2022.

[3] B. Friedman and D. G. Hendry, *Value sensitive design: Shaping technology with moral imagination*. MIT Press, 2019.

[4] S. Costanza-Chock, *Design justice: Community-led practices to build the worlds we need*. The MIT Press, 2020.

[5] L. L. Layne, S. L. Vostral, and K. Boyer, *Feminist technology*, vol. 4. University of Illinois Press, 2010.

[6] F. Bronet and L. Layne, "Teaching Feminist Technology Design," *Fem. Technol.*

[7] J. A. Leydens and J. C. Lucena, *Engineering justice: Transforming engineering education and practice*. John Wiley & Sons, 2017.

[8] C. B. Aranda Jan, S. Jagtap, and J. Moultrie, "Towards a framework for holistic contextual design for low-resource settings," 2016.

[9] K. Shilton, J. A. Koepfler, and K. R. Fleischmann, "Charting sociotechnical dimensions of values for design research," *Inf. Soc.*, vol. 29, no. 5, pp. 259–271, 2013.

[10] D. A. Norman and P. J. Stappers, "DesignX: complex sociotechnical systems," *She Ji J. Des. Econ. Innov.*, vol. 1, no. 2, pp. 83–106, 2015.

[11] P. Sengers, K. Boehner, S. David, and J. Kaye, "Reflective design," in *Proceedings of the 4th decennial conference on Critical computing: between sense and sensibility*, 2005, pp. 49–58.

[12] J. A. Leydens, K. E. Johnson, and B. M. Moskal, "Engineering student perceptions of social justice in a feedback control systems course," *J. Eng. Educ.*, vol. 110, no. 3, pp. 718–749, 2021.

[13] J. Blacklock, K. Johnson, R. Cook, N. A. Plata, and S. Claussen, "Faculty Interpretations of Sociotechnical Thinking in their Classrooms: Techniques for Integration," in *2021 ASEE Virtual Annual Conference Content Access*, 2021.

[14] K. Johnson, J. Leydens, J. Walter, A. Boll, S. Claussen, and B. Moskal, "Sociotechnical habits of mind: Initial survey results and their formative impact on sociotechnical teaching and learning," in *Proceedings of the 2019 ASEE Annual Conference and Exposition*, 2019.

[15] S. Claussen, J. Tsai, K. Johnson, J. Blacklock, and J. Leydens, "Exploring the Nexus Between Students' Perceptions of Sociotechnical Thinking and Construction of their Engineering Identities," in *ASEE Annual Conference Proceedings*, 2021.

[16] S. Claussen, J. Tsai, A. Boll, J. Blacklock, and K. Johnson, "Pain and gain: Barriers and opportunities for integrating sociotechnical thinking into diverse engineering courses," in *Proceedings of the 2019 ASEE Annual Conference and Exposition*, 2019.

[17] A. Fajardo, J. S. Cicek, K. Zacharias, and R. B. Rodrigues, "Evidence of Sociotechnical Thinking in Engineering Students," *Proc. Can. Eng. Educ. Assoc.*, 2022.

[18] G. E. Burleson, S. V. S. Herrera, K. Toyama, and K. H. Sienko, "INITIAL CHARACTERIZATION OF NOVICE ENGINEERING DESIGNERS'CONSIDERATION OF CONTEXTUAL FACTORS," *Proc. Des. Soc.*, vol. 1, pp. 1857–1866, 2021.

[19] G. Burleson, S. V. S. Herrera, K. Toyama, and K. H. Sienko, "Incorporating Contextual Factors Into Engineering Design Processes: An Analysis of Novice Practice," *J. Mech. Des.*, vol. 145, no. 2, Oct. 2022.

[20] M. Stettler Kleine, K. Zacharias, and D. S. Ozkan, "Contextualization as Virtue in Engineering Education," in *American Society for Engineering Education Annual*

Conference, 2021.

[21] J. M. Smith, J. Lucena, A. Rivera, T. Phelan, K. Smits, and R. Bullock, "Developing Global Sociotechnical Competency Through Humanitarian Engineering: A Comparison of In-Person and Virtual International Project Experiences," *J. Int. Eng. Educ.*, vol. 3, no. 1, p. 5, 2021.

[22] P. M. King and K. S. Kitchener, *Developing Reflective Judgment: Understanding and Promoting Intellectual Growth and Critical Thinking in Adolescents and Adults. Jossey-Bass Higher and Adult Education Series and Jossey-Bass Social and Behavioral Science Series.* ERIC, 1994.

[23] L. Kohlberg, "Stages of moral development," *Moral Educ.*, vol. 1, no. 51, pp. 23–92, 1971.

[24] S. Vosniadou, "Capturing and modeling the process of conceptual change," *Learn. Instr.*, vol. 4, no. 1, pp. 45–69, 1994.

[25] M. B. B. Magolda, "The activity of meaning making: A holistic perspective on college student development," *J. Coll. Stud. Dev.*, vol. 50, no. 6, pp. 621–639, 2009.

[26] M. B. B. Magolda, *Knowing and reasoning in college: Gender-related patterns in students' intellectual development.* Jossey-Bass, 1992.

[27] W. G. Perry Jr, *Forms of Intellectual and Ethical Development in the College Years: A Scheme. Jossey-Bass Higher and Adult Education Series.* ERIC, 1999.

[28] P. Freire, *Pedagogy of the oppressed*. Bloomsbury Publishing, 2000.

[29] E. Von Glasersfeld, *Radical Constructivism: A Way of Knowing and Learning. Studies in Mathematics Education Series: 6*. ERIC, 1995.

[30] M. B. B. TAYLOR, *The development of the measure of epistemological reflection*. The Ohio State University, 1983.