Integrating cooperative learning principles into the engineering design process: A mixed-methods study at first-year undergraduate engineering

Preethi Baligar
Assistant Professor,
Centre for Engineering Education Research
KLE Technological University
Hubballi, India
preethi.b@kletech.ac.in

Rohit Kandakatla
Associate Professor,
Department of Electronics and Communication
KG Reddy College of Engineering, India
rohit.kandakatla@kgr.ac.in

Gopalkrishna Joshi
Executive Director
Karnataka State Higher Education Council
Bengaluru, India
ghjoshi@kshec.ac.in

Ashok Shettar
Vice-Chancellor
KLE Technological University
Hubballi, India
vc@kletech.ac.in

***Abstract*— This work-in-progress research paper aims to integrate cooperative learning principles into the engineering design process. The context of the study is an interdisciplinary, design-experiences course at first-year undergraduate engineering in India. Under the Indian schooling systems, the incoming first-year engineering students do not have any prior practice in intensive and protracted problem-solving and team-based experiences. Thus, when these students encounter their first design-experiences course, we cannot assume that the students will be able to self-organize their learning, apply new knowledge to the problem-solving contexts and effectively function in teams while meeting the outcomes of design problem-solving.**

The proposed study investigates the research question: How does integrating cooperative learning principles during engineering design phases impact the problem solver's knowledge of teamwork and taskwork, team effectiveness and team performance? The objective of the proposed work is to integrate Cooperative learning principles during the initial tasks of problem-definition and information gathering and investigate its impact on students in terms of their teamwork knowledge, taskwork knowledge, team effectiveness and team performance. The study follows a quasi-experimental research design with an embedded qualitative strand. The core design of Convergent parallel design is embedded in experimental research design. The detailed methodology is described in this work.

Keywords*— *Engineering design, cooperative learning, Mixed-Methods

I. Introduction

Engineers solve different types of workplace problems like design problems, system-analysis problems, troubleshooting problems, and decision-making problems [1]. Therefore, engineering education strives to develop aligned competencies from as early as the first year of undergraduate engineering, commonly through team-based design problems [2]–[4]. First-year engineering students face teamwork related challenges while undergoing team-based design problems, as highlighted in [5][6].

One of the most popular pedagogies that architects team interactions among students is cooperative learning. Engineering Educators' interest in Cooperative Learning is evident since 1981 when Dr Karl Smith introduced it to Engineering Education [7]. Since then, thousands of articles have been published that document the need, scope, objectives, process, and results of applying this student-centred pedagogy. In these studies, cooperative learning is mainly applied for content mastery which [8] refers to as "knowing that" and differentiates it from "knowing how", i.e., problem-solving.

This study aims to develop problem-solving competency by integrating cooperative learning principles into the engineering design process and contextualizing it in an interdisciplinary design course in the first year of undergraduate engineering at a private university in India. While the research, on the whole, targets the entire design process, this study only showcases how this integration was achieved during the first two tasks of information gathering and problem formulation. The following section summarizes the key themes: cooperative learning, engineering design process and frameworks to study team interactions.

II. Literature Review

A. Cooperative learning

Cooperative learning is the use of small groups so that students work together to maximize their own and each other's learning [9]. As summarized in [10], Cooperative learning has five fundamental principles; positive interdependence, face-to-face promotive interaction, individual and group accountability, teamwork skills and group processing. These are operationalized through structures like Jigsaw, Student-Teams Achievement-Divisions, Think-Pair-Share, Group-Investigation, and Three-step interview [11]. These structures are described in-depth in the books titled "Learning to Cooperate, Cooperating to Learn" [12] and Student-Centered Cooperative Learning [13].

Several studies describe the application of cooperative learning for knowledge acquisition in engineering courses like math [14][15], chemistry [16], electrical and electronics [17], and mechanical engineering [18]. However, only a few studies have applied cooperative learning for developing problem-solving competencies. The most scalable model is the Cooperative Problem-Based Learning model, which is applied in several engineering disciplines[19].

B. Engineering design process

The engineering design process consists of the following phases: identification of need, problem definition, gathering information, generating ideas, feasibility analysis, evaluation, decision, communication, and implementation [20]. Each phase in the engineering design process has specific learning goals and is taught using relevant strategies, consolidated by

Crismond & Adams in the Informed Design, Teaching and Learning Matrix [21].

C. The novelty of the proposed work

Worldwide, design courses are being offered at first-year engineering for more than a decade. Despite this, studies have reported that first-year engineering students face team-related issues as they lack experience in both engineering (design) and cooperative components [22], faculty members are not trained to teach teamwork skills [23], and teamwork skills are not developed by merely assigning students to teams [24]. The students are often overwhelmed by the transactional overhead of task division, task distribution, and consolidation of results. Thus, to guide students and faculty members to navigate the process of engineering design and teamwork, the interventions have been designed using the principles of cooperative learning principles to attain the learning outcomes of engineering design problem-solving as outlined in [21].

III. RESEARCH QUESTION

The proposed study investigates the research question: How does integrating cooperative learning principles applied during the engineering design phases impact the students' knowledge of teamwork and taskwork, team effectiveness, and team performance?

The objective of the proposed work is to integrate Cooperative learning principles during the two initial tasks of the engineering design process - problem-definition and information gathering. The authors hypothesize that students who undergo a cooperative problem-solving experience have better teamwork knowledge and task knowledge (engineering design), and their teams are more effective and perform better.

IV. METHODOLOGY

The proposed study follows a mixed-methods experimental (quasi) approach and is developed using the step-by-step guidelines detailed in [25]. First, it investigates the outcomes of the quantitative study and the participants' qualitative experiences while they underwent the interventions.

A. Research context

This study is conducted at a first-year interdisciplinary engineering design course - "Engineering Exploration" [26], which is taught for 16 weeks at a private engineering university in India. The teams are given a set of design problems to choose from and follow the engineering design process to design a mechatronic prototype.

B. Sampling

Sixty-four students belonging to 16 teams were invited to participate in the study, with 42 male and 18 female students. A team of 4 students were formed based on gender and academic performance in the previous exam. Thus nine teams were comprised of two male and two female students; the rest were all-male teams. Based on the scores in previous exams, the sample was divided into four performance groups based on the percentage of marks(aggregate) scored in Physics-Chemistry-Maths. One member of each performance group was assigned to a team. Thus sixteen such teams participated in the experimental and control groups, with eight teams in each group.

Randomization was not possible since students were invited from preassigned divisions. While the entire sample of students participated in the quantitative study, 25% of students were invited for a qualitative study based on maximal variation sampling [25][27], which is a purposeful sampling strategy in which the researcher samples cases (teams) based on specific differentiating traits. The teams were sampled based on gender representation and educational background(urban/rural).

C. Conceptual framework

The conceptual framework for the proposed research is based on the input-mediator-output (IMO) framework and is as shown in fig. 1. The IMO framework is appropriate as it focuses not just on the team interaction processes that are primarily behavioural but also on the mediators, i.e. emergent states of teamwork knowledge and taskwork knowledge [28]. Thus, the framework consists of three elements: inputs, mediators and outputs. The inputs are further categorized as task-level inputs, individual-level inputs and team-level inputs.

The second element is the mediators, which are the emergent states of the mental models developed as a result of solving design problems cooperatively, i.e. teamwork knowledge and taskwork knowledge. Taskwork knowledge refers to the knowledge about tools and equipment and an understanding of work procedures, strategies, and

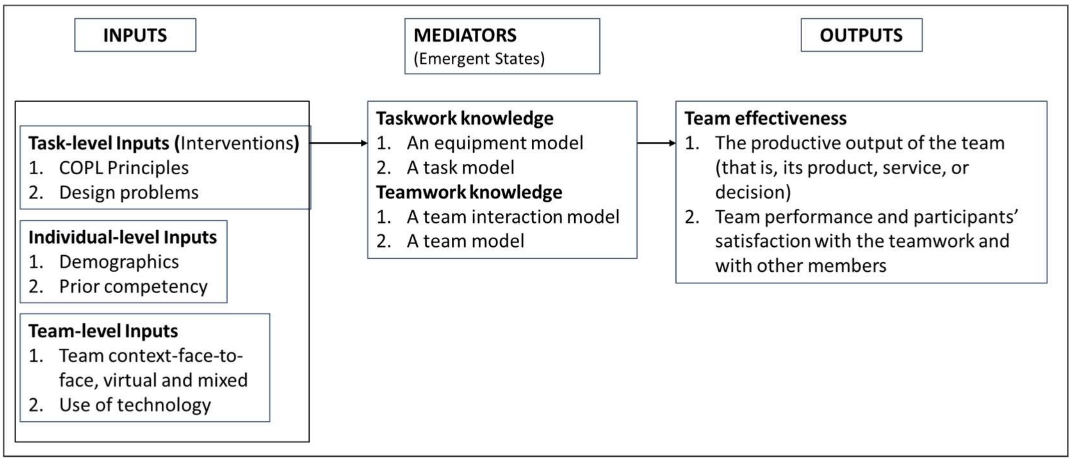

Figure 1 Conceptual framework for the proposed study

contingency plans related to engineering design. Teamwork knowledge refers to an awareness of member responsibilities, role interdependencies, and communication patterns and understanding of teammates' preferences, skills, and habits [33]. Finally, the third element is the outputs, i.e. team effectiveness. The underlying theory for team effectiveness was proposed by Hackman [26] [27], and its variables are also shown in fig. 1.

D. *Intervention 01: Gathering pertinent information*

The first intervention focuses on the task of information gathering. Early designers skip doing initial research about the problem and instead develop solutions immediately [21]. Thus, this intervention aims to help students systematically research and pool their knowledge about the existing products, mechanisms, and systems related to their chosen design problem.

To begin with, every student finds at least three existing products and creates a results table which consists of functions and features of the product, its clients, mechanism and principle of working, and electronic and mechanical components used. This individual information gathering is followed by team presentations in which each student explains his/her results table to the team members.

The diversity of the products is represented by a similarity index based on which individual and team marks are allotted to the student groups.

E. *Intervention 02: Formulating a design problem*

Beginning designers treat a design problem as a well-defined problem and hastily proceed to solve it. The purpose of the intervention is to delay the decision-making process until the team can collectively explore and comprehend the users' requirements [21]. In addition, the intervention aims to inject multiple interpretations of the problem by allowing the students to investigate what different individuals and interest groups require in the solution [1].

To begin with, the teams brainstorm to identify the users/interest groups/parties who need the solution and categorizes them as primary, secondary and tertiary users[31]. The individuals then bring in requirements for all three groups of users and list the objectives, functions, and constraints (OFC) for each user group. Finally, the team reviews the objectives, functions, and constraints, identifies the unique, common and contradictory OFCs and resolve conflicts to develop the final problem definition.

A perspective index represents the inclusiveness of the users based on which individual and team marks are allotted.

F. *Reflection of cooperative learning principles in the interventions*

Cooperative learning is defined by five principles as summarised by Davidson & Major in [10]:- positive interdependence, face-to-face promotive interaction, individual and group accountability, development of teamwork skills, and group processing.
The foremost principles of cooperative learning are positive interdependence which sets the stage for the other principles. Positive interdependence can be structured through group product-goal interdependence, learning goal interdependence, role interdependence, reward interdependence, resource interdependence and task interdependence [9]. It is the instructor's responsibility to design learning experiences with such interdependencies.

In both the interventions, group product-goal interdependence, task interdependence and reward interdependence have been introduced. In the interventions, group product-goal interdependence comes from similarity index and perspectives-index; task interdependence arises from the division of the task and resource-sharing, as the overall task is broken down into subtasks and assigned to individual members. Reward interdependence comes from individual and team scores allotted based on the attainment of group product-goal.

Since the interventions are implemented in the in-person classroom sessions, they set the stage for dialogue between the team members, which leads to face-to-face promotive interaction. Furthermore, individual and team accountability comes from the task interdependence shown as "team task" and "individual task" in the interventions. Finally, office hours were set aside to discuss the current work status, plan to accomplish the next task and any team and teamwork related issues. In this way, all the five principles of cooperative learning were introduced.

G. *Variables of study and instruments for collecting data*

The proposed study evaluates the effectiveness of the interventions using a mixed-methods approach. The qualitative strand comprises semi-structured interviews, and the quantitative strand comprises a team diagnostic survey [32] and paired comparison tests [33].

Data for teamwork knowledge and taskwork knowledge was collected using paired comparison tests. This data collection method presents the participants with a list of stimuli/concepts and asks them to rate the relationship among the concepts using a 7-point Likert scale [34]. A list of stimuli for teamwork and taskwork knowledge for the context of design studies are listed in [34][35]. Paired comparison tests are subjective to the study context, and the stimuli/concepts need to be identified systematically.

The stimuli were identified from previous literature. Instructors who have taught engineering exploration were asked to rank the stimuli based on their applicability to first-year design experience. The paired comparison tests were developed using the top 7 stimuli, which led to 21 combinations of relationships.

Satisfaction with team and teamwork is measured using an existing questionnaire called Team Diagnostic survey [32]. It is used to self-report team performance measures and participants' satisfaction with teamwork and other members. Again, faculty identified the relevant items for the context of engineering exploration, using which the shorter version of the survey containing 50 questions was developed.

H. *Procedural diagram for the proposed study*

Procedural diagrams have been used to convey the complexity of mixed methods design. They incorporate details about specific procedures and their order [25]. The procedural diagram for the proposed study is shown in fig. 2. The flow of control is vertically downwards.

The procedural diagram begins with a demographic survey which will be used to form teams. The mid-part of the diagram shows the four interventions on the left side and the qualitative data collection on the right side. The letters A, B, C and D,

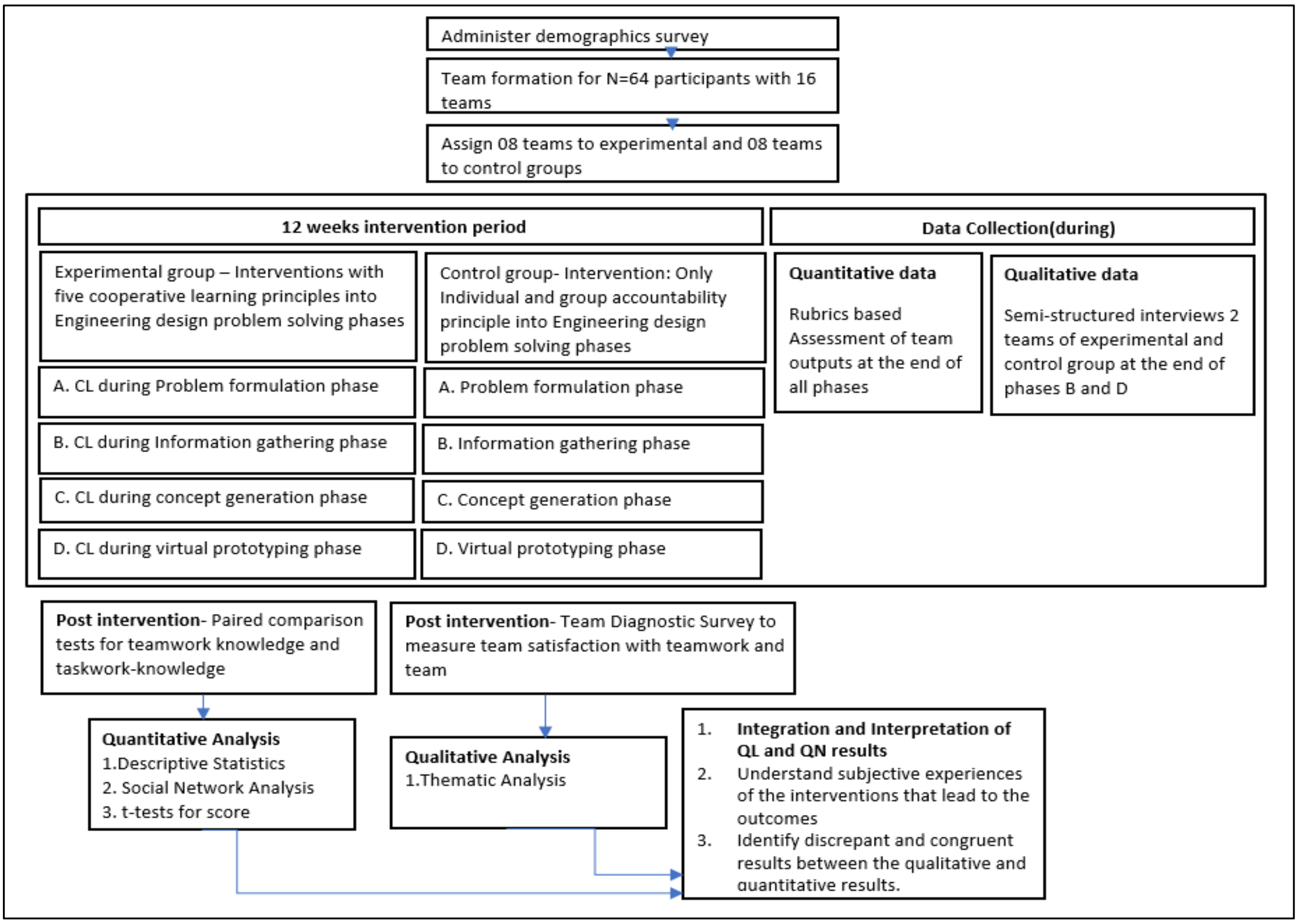

Figure 2 Procedural Diagram for the proposed study

refers to the interventions of problem definition, information gathering, concept generation and virtual prototyping, respectively. This side-by-side representation indicates that data will be collected at the end of phases B and D. While the procedural diagram lists interventions C and D, only interventions A and B are discussed in this study.

The bottom of the diagram shows the quantitative data collection using two questionnaires as indicated in sub-section G. The final block at the bottom right shows how the quantitative and qualitative data will be mixed.

I. Arguments for using qualitative data

In the proposed study, qualitative data is collected for four reasons. Firstly, the focus of the study is not only on the outcomes but also the processes that the participants experienced while attaining the design outcomes. Secondly, although the interventions may be effective, qualitative data helps us understand how the participants experienced the intervention. Thirdly, qualitative data will also be used as a manipulation check [27] to identify whether the participants truly experienced the interventions. Finally, it will be used to help explain the results of the quantitative results.

V. WORK COMPLETED SO FAR

This study was initiated in January 2021 and is currently at the end of the experimental phase. At the time of writing this manuscript, both quantitative and qualitative data has been collected from the students. The data analysis is in progress.

VI. THE IMPLICATION OF THE STUDY

Interest in cooperative learning is not new. It is one of the widely used pedagogies for knowledge acquisition. The point of departure in this work is to integrate the principles of cooperative learning into the engineering design phases to structure student's participation in team-based problem-solving for engineering design problems. The authors reason the need for this integration.

Design thinking is a cognitively overwhelming experience for novice designers, mainly when it focuses on both processes and artefacts. Moreover, the fact that design problems are solved in teams compounds the challenges.

Hence, the authors wonder whether it is adequate to group students together, assign them a design problem[36], communicate expectations of each phase and let them figure out how to distribute the task in a team, pool their knowledge and skills across the design phases. Teamwork skills, leadership development, communication, conflict management and resolution are not always simple to self-discover, so they must be taught and practised [5].

Hence, the authors propose a model that integrates the principles of cooperative learning into the engineering design process that architects every member's participation in the design team. Therefore, it is vital to ensure the students are not only studying teamwork but were also experiencing engineering teamwork[6]. This study can also be used to develop faculty members' proficiency in teaching teamwork skills to students

REFERENCES

[1] D. H. Jonassen and W. Hung, "All problems are not equal: Implications for pbl," *Interdisciplinary Journal of Problem-Based Learning*, vol. 2, no. 2, p. 10, 2008.

[2] F. D. Koch, A. Dirsch-Weigand, M. Awolin, R. J. Pinkelman, and M. J. Hampe, "Motivating first-year university students by interdisciplinary study projects," *European Journal of Engineering Education*, vol. 42, no. 1, pp. 17–31, 2017.

[3] L. Zhao and K. Vernaza, "Teaching first year engineering students engineering design process and problem solving through service learning projects," in *2016 IEEE Frontiers in Education Conference (FIE)*, 2016, pp. 1–7.

[4] L. Francis, D. J. Orser, K. Bazargan, S. Mantell, J. M. Feinberg, and R. J. Holmes, "Engaging First-Year Students with a Hands-On Course using Student-Driven Projects," 2019.

[5] M. Fontenot, K. Canales, and A. N. Quicksall, "Taking care of the team in a first-year design experience course," in *2014 IEEE Frontiers in Education Conference (FIE) Proceedings*, Oct. 2014, pp. 1–5. doi: 10.1109/FIE.2014.7044433.

[6] D. Missingham and R. Matthews, "A democratic and student-centred approach to facilitating teamwork learning among first-year engineering students: a learning and teaching case study," *European Journal of Engineering Education*, vol. 39, no. 4, pp. 412–423, Jul. 2014, doi: 10.1080/03043797.2014.881321.

[7] J. E. Froyd, P. C. Wankat, and K. A. Smith, "Five major shifts in 100 years of engineering education," *Proceedings of the IEEE*, vol. 100, no. Special Centennial Issue, pp. 1344–1360, 2012.

[8] S. Sheppard, K. Macatangay, A. Colby, W. M. Sullivan, and L. S. Shulman, *Educating engineers: Designing for the future of the field*, vol. 9. Jossey-Bass San Francisco, CA, 2009.

[9] K. A. Smith, S. D. Sheppard, D. W. Johnson, and R. T. Johnson, "Pedagogies of engagement: Classroom-based practices," *Journal of engineering education*, vol. 94, no. 1, pp. 87–101, 2005.

[10] N. Davidson and C. H. Major, "Boundary crossings: Cooperative learning, collaborative learning, and problem-based learning.," *Journal on excellence in college teaching*, vol. 25, 2014.

[11] S. Kagan, "The structural approach to cooperative learning," *Educational leadership*, vol. 47, no. 4, pp. 12–15, 1989.

[12] R. Hertz-Lazarowitz, S. Kagan, S. Sharan, R. Slavin, and C. Webb, *Learning to cooperate, cooperating to learn*. Springer Science & Business Media, 2013.

[13] G. M. Jacobs and W. A. Renandya, *Student-centred cooperative learning: Linking concepts in education to promote student learning*. Springer, 2019.

[14] J. M. Morales, B. Olea, M. A. Atencia-Ruiz, and N. Madrid, "Fostering the cooperative learning of mathematics in engineering schools through the" Teacher-Apprentice" group dynamics," 2019.

[15] I. Wardiah, R. F. Cahyani, and F. Sholihin, "Improving The Quality of Learning on Applied Mathematics III Subject Using Stad Cooperative Learning Model for Informatics Engineering Students At State Polytechnic ff Banjarmasin," *First published in March 2016 by:\copyright Faculty of Mathematics and Natural Sciences, Banjarbaru 2016 All rights reserved Compiled by Aprida Siska Lestia and Rani Sasmita Edited by Sasi Gendro Sari*, p. 284, 2016.

[16] S. A. Helmi, S. El Hassani, K. M. Yusof, and F. A. Phang, "Enrichment of problem solving skills among engineering students through cooperative problem based learning," in *2017 7th World Engineering Education Forum (WEEF)*, 2017, pp. 410–414.

[17] M. A. Kousa, A. H. Muqaibel, D. B. Williams, M. T. Alkhodary, and Q. Mayyala, "Developing Electrical Engineering Course in an Active Cooperative Learning (ACL) Platform," in *International Conference on Interactive Collaborative Learning*, 2016, pp. 64–74.

[18] N. Fang, "A project-based active and cooperative learning approach to improving manufacturing engineering education," 2009.

[19] K. Mohd-Yusof, F. A. Phang, and S. A. Helmi, "How to develop engineering students' problem solving skills using cooperative problem based learning (CPBL)," in *Engineering Leaders World Congress on Engineering Education 2013*, 2014, vol. 2014, no. 3, p. 30.

[20] C. L. Dym and P. Little, *Engineering design: A project-based introduction*. John Wiley and sons, 1999.

[21] D. P. Crismond and R. S. Adams, "The Informed Design Teaching and Learning Matrix," *Journal of Engineering Education*, vol. 101, no. 4, pp. 738–797, 2012, doi: 10.1002/j.2168-9830.2012.tb01127.x.

[22] X. Neumeyer and S. C. Santos, "The effect of team conflict on teamwork performance: An engineering education perspective," *The International journal of engineering education*, vol. 36, pp. 502–9, 2020.

[23] T. Chowdhury and H. Murzi, "Literature review: Exploring teamwork in engineering education," in *Proceedings of the Conference: Research in Engineering Education Symposium, Cape Town, South Africa*, 2019, pp. 10–12.

[24] H. G. Murzi, T. M. Chowdhury, J. Karlovšek, and B. R. Ulloa, "Working in large teams: Measuring the impact of a teamwork model to facilitate teamwork development in engineering students working in a real project," *The International journal of engineering education*, vol. 36, no. 1, pp. 274–295, 2020.

[25] J. W. Creswell and V. L. P. Clark, *Designing and conducting mixed methods research*. Sage publications, 2017.

[26] P. Baligar, S. Kavale, M. Kaushik, G. Joshi, and A. Shettar, "Engineering Exploration: A Collaborative Experience of Designing and Evolving a Freshman Course," in *2018 World Engineering Education Forum-Global Engineering Deans Council (WEEF-GEDC)*, 2018, pp. 1–5.

[27] J. W. Creswell, *Educational research: Planning, conducting, and evaluating quantitative*. Prentice Hall Upper Saddle River, NJ, 2002.

[28] E. Salas, R. Rico, and J. Passmore, "The psychology of teamwork and collaborative processes," in *The Wiley Blackwell Handbook of the Psychology of Team Working and Collaborative Processes*, Wiley Online Library, 2017, p. 1.

[29] Hackman, *Handbook of organizational behavior*. Englewood Cliffs, NJ: Prentice-Hall, 1987.

[30] "Hackman. (1987). Handbook of organizational behaviour. Prentice-Hall. - Google Search." https://www.google.com/search?q=Hackman.+(1987).+Handbook+of+organizational+behaviour.+Prentice-Hall.&rlz=1C1CHBD_enIN892IN892&oq=Hackman.+(1987).+Handbook+of+organizational+behaviour.+Prentice-Hall.&aqs=chrome..69i57j69i60l2.240j0j4&sourceid=chrome&ie=UTF-8 (accessed Jun. 23, 2021).

[31] C. Abras, D. Maloney-Krichmar, and J. Preece, "User-centered design," *Bainbridge, W. Encyclopedia of Human-Computer Interaction. Thousand Oaks: Sage Publications*, vol. 37, no. 4, pp. 445–456, 2004.

[32] R. Wageman, J. R. Hackman, and E. Lehman, "Team diagnostic survey: Development of an instrument," *The journal of applied behavioral science*, vol. 41, no. 4, pp. 373–398, 2005.

[33] S. Mohammed, L. Ferzandi, and K. Hamilton, "Metaphor no more: A 15-year review of the team mental model construct," *Journal of management*, vol. 36, no. 4, pp. 876–910, 2010.

[34] B.-C. Lim and K. J. Klein, "Team mental models and team performance: a field study of the effects of team mental model similarity and accuracy," *J. Organiz. Behav.*, vol. 27, no. 4, pp. 403–418, Jun. 2006, doi: 10.1002/job.387.

[35] R. L. Edwards, "Exploring novice engineers' mental models of collaboration and engineering design," PhD Thesis, 2018.

[36] P. Baligar, K. Mallibhat, S. Kavale and G. Joshi, "Evaluating an Engineering Design Problem for Its Complexity," in IEEE Transactions on Education, doi: 10.1109/TE.2021.3093459 .