A framework for investigating collaborative learning

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Abstract: There are limited studies in engineering education that empirically investigate whether collaborative learning actually materializes as highlighted in the theoretical literature and from educators’ anecdotal evidence. To collect such evidence, it is important to understand how students learn and, more importantly, what actually happens in such learning environments. For example, it is inevitable that the achievement of learning outcomes (positive or negative) will be dependent on the quality of the interactions among the students. By investigating the processes within these interactions, a better understanding of what elements enable the learning outcomes can be achieved. If some kinds of interactions produce effective collaboration, learning and teaching strategies can be adapted to promote such behaviour or interactions. The purpose of this paper is to present a research framework for exploring collaborative learning in engineering education.

The issues identified are: collaborative construction of knowledge, collaborative cognitive processes and design strategies, processes and group interactions/communication that deliver the learning outcomes. The main challenge in investigating these issues is the methodologies employed and this paper concludes by proposing a methodological framework. The research discussion session will provide an opportunity to critique the framework and discuss how practitioners could be encouraged to take this framework further to develop specific research questions for empirical investigation. It provides theoretical grounding for rigorous research in engineering education.

Introduction

The aim of this research is to develop a better understanding of how students learn in a collaborative learning environment in the context of engineering education. The rationale is to help educators design learning environments that promote positive outcomes, as highlighted in theoretical literature. This paper sets the ground work for investigating collaborative learning in engineering education.

Design projects or capstone design projects, problem-based learning and project-based learning have all become an integral part of the engineering curriculum due to pressures both from engineering professional bodies and higher education institutions which want to deliver a high-quality experiential engineering education. Students often work in a team of four or five and the final output is termed as a group project i.e. collaborative output. The pedagogical approaches adopted provide students with both experiential and situated learning opportunities where a real professional environment is simulated, sometimes with an industry partner. Students are able to integrate their conceptual knowledge and factual knowledge resulting in deeper understanding of the engineering discipline.

To summarise, the aim of this research is to develop a better understanding of how students learn in a
collaborative learning environment in the context of engineering education. The ultimate goal is to help educators design learning environments that promote positive outcomes, as highlighted in the theoretical literature. This paper lays out the theoretical and empirical foundations for studying such a learning environment.

**Potential significance of the work**

Theoretical literature on collaborative learning claims a number of positive learning outcomes compared to traditional modes of learning. Those include higher achievement, greater retention of what is being learnt, more frequent use of high-order reasoning and meta-cognitive thoughts, better problem-solving abilities, better capability to tackle open-ended tasks, higher intrinsic motivation, greater ability to transfer knowledge from one situation to another and greater total effort spent on the task (Johnson and Johnson 1989). Design projects develop a sense of community among the group members and this may play a key role in instilling such high positive emotional states as highlighted in this section (Dillenbourg et al 1996, Joiner et al. 2000).

There are limited studies in engineering education that empirically investigate whether collaborative learning actually materializes. To collect, analyse and present such evidence, it is important to understand how students learn, and more importantly, what actually happens in collaborative learning environments. For example, it is inevitable that the achievement of learning outcomes (positive or negative) will depend on the quality of the interactions among the students. By investigating the processes within these interactions, a better understanding can be gained of what elements enable the outcomes. If some kinds of interactions produce effective collaboration, learning and teaching strategies can be adapted to promote such behavior or interactions. Therefore a framework that will assist in qualifying these key characteristics will influence how educators develop their instructional strategies to promote these positive outcomes.

Anecdotal evidence from engineering educators (e.g. Fruchter 2001) suggests that those who create a collaborative learning experience often rely on their ability to innovate and their intuition that such an environment is beneficial to students. Educators often take the students through experiential learning cycles of innovation (Kolb 1984) often with little theoretical and empirical background on collaborative learning. A theoretical background can be combined with empirical data to provide an evidence base support for collaborative learning. Empirical evidence that confirms benefits and raises challenges in collaborative learning can be used to develop educators’ practices. Where necessary, it can be used to make a case for the investment of resources. Often it is assumed that resources required for collaborative learning are not significantly more compared to traditional modes of teaching.

This paper is founded on theoretical and methodological literature, ensuring that any subsequent empirical studies are sound and rigorous.

**Collaborative vs cooperative learning**

_Collaborative_ and _cooperative_ learning are often used synonymously. However, some researchers distinguish the two terms. Dillenbourg (1999) defined collaborative learning as “a situation in which two or more people learn or attempt to learn something together” (p. 1). He characterized collaborative learning with three elements: symmetry of action, symmetry of knowledge, and symmetry of status. Therefore, collaborative learning occurs when the students within the group (1) are equally allowed to engage in a range of actions, (2) possess the same amount and level of knowledge, and (3) share relatively equal status within the group. On the other hand, Johnson and Johnson (2008) gave a definition of cooperative learning as “students working together to maximize their own and each other’s learning (i.e. achieve shared learning goals)” (p. 404). Johnson and Johnson (2008) distinguished cooperative learning from collaborative learning with five essential elements: positive interdependence, individual and group accountability, promotive interaction, appropriate use of social skills, and group processing. These five elements make the term cooperative learning more structured than _collaborative learning_ in ensuring the effectiveness of group work to maximise the learning outcomes. Cooperative learning emphasizes the equality in contributions, obligations, and respect of the group members. Another distinction between collaborative and cooperative learning is that the former focuses more on the philosophy of group working and relationships among the group members, while the latter addresses the practical applications and techniques of group work. In addition to this distinction, the vagueness of the definition of collaborative learning implies that collaborative learning is a less structured form of learning (Johnson & Johnson, 2008).
There is a criticism that collaborative learning is too unstructured. In response to this, researchers and practitioners have incorporated the principles and techniques of cooperative learning into collaborative learning. The line between the two terms has become blurred and they are now often used interchangeably.

**Theoretical perspectives**

There are a number of different theoretical dimensions under which collaborative learning can be defined (Dillenbourg, et al 1996). It is argued that it is socially based learning which in turn is built upon constructivism (Jonassen, 1991), or more specifically, Vygotsky's (1978) sociocultural constructivism. Vygotsky (1978) contended that an individual's cognitive development and knowledge base cannot be understood in isolation since daily experiences significantly comprise social interactions of all forms. Separating how an individual internally processes a cognitive task from the social knowledge and cultural practices that society imposes upon the person is not feasible. Cognitive development of an individual is a function of social, cultural, and historical factors, as well as a result of interacting with other individuals within the environment. Social negotiation takes place (Savery and Duffy 1996) during an individual's knowledge construction process through a number of iterations which involve evaluation of understandings against the collective social agreement. This is backed up by Jonassen et al (1996) who point out that knowledge is socially constructed through interactions with others in everyday life. During the process of interacting, individuals exchange their interpretations of events or entities with others back and forth in order to establish a collective agreement toward a reality.

Vygotsky's (1978) zone of proximal development (ZPD) is the “distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem solving under adult guidance or in collaboration with more capable peers”. The assumption is that competencies and knowledge in a collaborative learning environment are distributed among the group members. Therefore, by working with other students in a group setting, the students who are more competent in some aspects of the learning tasks could provide modeling opportunities for less competent students to improve their learning. This will raise the less competent individual's both actual development level and potential development level.

The socio-cultural perspective is focused on individual development in the context of social interaction, the basic unit of analysis being the social activity from which an individual develops their understanding. The individual's cognition and development of knowledge are as a result of interacting with the environment surrounding him or her.

From a pragmatic perspective (Johnson et al. 1998) cooperative learning occurs if certain conditions are met in the learning environment: positive interdependence, individual's accountability, face to face promotive interactions, appropriate use of collaborative skills, and group processing. Positive interdependence is where all the members are dependent upon each other through mutual goals, joint rewards and shared resources. Individual accountability is where individuals in the group have recognized accountability for the mutual goals. Face to face promotive interactions are when some work is done as a team and is not divided or allocated to individuals in the group. Appropriate use of collaborative skills is about using communication skills, decision making skills, conflict management skills and teamworking skills. Finally group processing is about the group regularly reflecting on: how well they are working together, what is working and what is not working in their teams and whether they should make changes to allow the team to work more effectively.

Learning in collaborative environments can also be interpreted through metaphors of learning as highlighted by Liponen et al (2004). Learning can be interpreted as acquisition, participation and knowledge construction. Acquisition focuses on internalization (i.e. individual knowledge gain), participation stresses interactions (i.e. shared expertise/distributed expertise), and knowledge construction concentrates on transformation (i.e. continuous advancement of shared knowledge).

However, when a group of individuals gather together to achieve a common goal, the effect of learning may be accelerated and amplified. This is because in a collaborative learning environment often there is a clearly defined goal, members have motivation to achieve the goal and there are opportunities within the group to provide scaffolding in individuals' learning processes. These three characteristics justify the implementation of problem/project-based learning as an instructional method that could enhance students' learning experiences (Ormrod, 2008; Roschelle & Teasley, 1995).
Research on collaborative learning and engineering education

Initial empirical research on collaborative learning has focused on circumstances where this form of learning was effective by controlling the independent variables i.e. size, composition of the group and nature of the task (Dillenbourg 1996). The conclusion was that these variables interacted with each other. It is not feasible to draw a causal link between the variables and the effectiveness of the collaboration. Therefore there is a shift in research towards what roles these variables play in mediating interactions.

Roschelle and Teasley’s (1995) study of how learners achieve new conceptual understanding found that learners showed an iterative cycle of displaying, confirming and repairing situated actions. There were three distinctive features that are relevant to collaborative learning research: learning is a visible account of social practice, learning is a process by which meaning is constructed and learning is mediated by communication, language and gestures.

A number of studies found a positive impact on the academic achievement of students (Johnson et al. 1998, Johnson et al. 2000, Felder and Brent 2003, Slavin 1995, Smith et al. 2005). For example, students taught using cooperative learning methods scored above the 70th percentile of students compared to students taught in traditional methods. In addition to quantifiable academic achievements there are some qualitative changes in students: deeper understanding of the material, more critical thinking abilities and higher level of reasoning skills. Evidence also suggests that this type of learning also improves students’ collaborative skills (e.g. team working and communication) and research skills.

The remainder of this section explores what research in collaborative learning means in engineering education.

Collaborative learning in engineering education has become increasingly more commonplace in engineering programs, but how effective is this approach? Two meta-analyses of collaborative learning suggest overall that collaboration is an effective pedagogical tool and method (Prince, 2004; Springer, Stanne, & Donovan, 1999). Specifics of the effectiveness of collaborative learning may be narrowed down to two themes: cognition and soft skills. Although these are the two themes presented, they are not exhaustive or mutually exclusive.

The first theme in collaborative learning is cognition. There are multiple subthemes within this theme: academic achievement, meta-cognitive skills, near/far transfer of knowledge, systems thinking, design thinking and higher order thinking. Collaborative learning impacts on all these aspects (Hmelo-Silver, 2004; Springer et al. 1999). The two reviews from Springer et al (1999) and Prince (2004) show that academic achievement improves with collaborative learning. Under-represented groups had mixed results with collaborative learning. While there was no significant effect on gender, Blacks and Latinos reported significant positive effects in academic achievement with collaborative learning. Collaborative learning may take on various forms and settings, such as interdisciplinary teams, capstone projects, and problem-based learning. However, the amount of time spent in collaboration followed the “law of diminishing returns.” Student achievement improved with increasing collaboration, but reached an apex when the amount of teaming became over-saturated and interfered with individual achievement. However, these meta-cognitive skills are not typically assessed adequately through standardized tests or in pre/post-test methodologies.

The second theme in collaborative learning is team working skills and other soft skills. Team working includes affective skills such as interpersonal relationships, communication, and team member cooperation. The soft skills include motivation, self-esteem, self-efficacy and attitude towards the material or content. The teaming and non-teaming soft skills had a positive effect through collaborative learning. One exception was motivation. This might be due to the brevity in which this aspect is measured. Most studies do not exceed the semester duration, yet some affective traits such as motivation are stable over time. Therefore, measurable changes are not easily identified. Furthermore, interactions between different traits are possible. Purzer et al. (2008) found an interaction effect between student achievement in collaborative groups and self-efficacy. Although the literature supports soft skill enhancement through collaborative learning through attitude change actual gains are not easily measured.

Newestetter and Hmelo (1996) investigated two key questions: first the use that students make of collaborative activity; and second whether students utilize the opportunity to distribute expertise across the group and learn from each other. In the first case study students used a ‘divide and conquer’ strategy. Initially the team identified an individual’s particular areas of expertise and strength that
would be relevant to the project. The task was then divided into individual sub-tasks and assigned to individuals with the appropriate skills. Immediately before the due date these individual components were then assembled. One person made sure that sub-components interfaced well together. Students did not seek opportunities as a group to use their different expertise to enhance an individual’s component or to consider ways to integrate the pieces into a unified whole. The research also found that opportunities did arise for students to exchange their sets of skills these were not utilized. For example, there was an expert on train systems who could have explained gearing to other students. This is a concept most students find difficult to understand. In the study the student built the mechanism alone. The conclusion the authors drew was that it is a disciplinary issue. Engineers are used to thinking in terms of sub-systems and assembling the parts together and as a team that is exactly how they work as well. Another conclusion is that students are under severe time constraints and in order to deliver a finished product within the deadline, this was the most efficient way. One way to counteract this is if special class time for specific kinds of interactions is set aside, a greater exchange of expertise might have occurred. The authors argue that if the focus of the course shifts from realizing a product to exploiting ways to develop group understanding, the shared cognition may be achieved. Other conclusions drawn by the authors are that students do not recognize that other team members have expertise that they can gain from and therefore they fail to avail themselves of those opportunities.

In another study, in an attempt to engage students on a number of cooperative learning, tasks were designed for a material science course (Zemke; et al 2004). The cooperative learning tasks were designed based on Johnson et al (1991) conditions for an effective cooperative learning environment. The results show that students are able to master the difficult materials effectively. This manifested in the form of students: thinking deeply about the subject material, sparking their curiosity and holding most of their attention. This was compared with learning activities that did not involve cooperative learning such as lectures, individual reading, homework and in-class examples.

In a collaborative learning environment, groups use dialogues to solve an engineering problem. Therefore analysis of conversation allows researchers to investigate what types of roles individuals play within the group, how groups share knowledge, or even how they achieve the joint actions. Haller et al (2000) carried out conversation analysis of ‘in situ’ dialogues from four student groups enrolled in an introductory chemical engineering course. The analysis was carried out with the assumption that cooperative learning involves gaining, exchanging of expertise among students. Therefore there is an expectation that students would take teacher and student roles depending upon the distribution of knowledge within the group. In other words the study explored the interactional dynamics of teaching and learning in groups and how group members' different approaches to the management of teaching sequences enhanced and/or detracted from the group learning process. The results show that students generally engaged in two qualitatively different types of teaching sequence: transfer-of-knowledge sequence (TKs) and collaborative sequence (Cs). In the first sequence students took distinct teacher-pupil roles and in the second they worked with no clear role differentiation. They concluded that both modes of group learning can assist students in understanding and applying engineering concept.

Ahern (2007) studied the perceptions and attitudes of lecturers in civil engineering departments. The study found that many lecturers use collaborative learning to develop students’ ‘soft skills’ but are not comfortable with assessment of such work. There is a general lack of awareness of how collaborative learning can be structured. Linking to assessment is perceived to be a major challenge and therefore the link is not made. This is due to perceived uncertainty of the fairness to the highest achievers. In addition there is also the challenge of the type of evidence the lecturers require to see if the ‘soft skills’ they think students are developing are being acquired. Therefore investigating how group learning occurs is an important avenue to explore.

From methodological research, a mixed method observation instrument was developed (Kern, Moore and Akillioğlu 2007) to capture instances of cooperative learning among engineering students based on Johnson and Johnson’s(1989)five conditions of cooperative learning. The instrument is able to measure group directed activity and frequency of the activity at five minute intervals.

**A framework for studying collaborative learning in engineering education**

This section identifies issues that are important to understand from an engineering educators’ point of view, and which can impact teaching practice.
Collaborative construction of knowledge/acquisition of knowledge or skills

This includes the issue of how students collaboratively acquire and apply knowledge and skills to achieve the objectives of the design project or problem set by the tutor. This aspect of the framework will concentrate on how the collective knowledge is transformed within the group. How is collaborative knowledge/expertise shared or how do students learn from each other? This can also include links between a group’s previous knowledge and the knowledge required for the project, and how the group’s knowledge is developed over a period of time.

Collaborative cognitive processes and design strategies

Cognitive design processes and strategies have been the focus of various studies within engineering and science education (Atman et al., 2007; Hmelo-Silver, Holton, & Kolodner, 2000). The processes generally describe what the students cognitively do while strategies may describe how students set about designing and planning. The cognitive processes and strategies may be viewed and analyzed through existing engineering design models and processes, or from a qualitative point of view where themes and phenomena emerge through ongoing analysis (Borrego, Douglas, & Amelink, 2009).

For example some design strategies that have been researched empirically in an engineering context include:

- problem scoping – identification of need, problem definition, gathering information
- developing alternatives – generating ideas, modeling, feasibility analysis, evaluation
- project realization – decision, communication, implementation

These terms from previous research give an indication of the type of processes and strategies to look for in a collaborative learning context.

Group interaction and communication

Group processes

As discussed earlier, collaboration benefits student learning in many ways. However, collaborative learning, or speaking more precisely, effective and productive collaborative learning does not come naturally for many students. Achilles and Hoover (1996) reported a concern in their implementation of PBL in grades 6-12 that students had difficulty working in groups. In fact, the difficulties in collaborating and cooperating in group work did not only occur with K-12 students, but also with medical students. In simplistically assigning a number of students to a group does not automatically produce positive learning outcomes. Rather, certain essential learning processes have to be activated during the collaboration (Barron, 2003). Barron (2003) studied 6th graders working in groups whose tasks were to construct problem spaces and propose solutions to problems presented to them. Based on the results, she concluded that the quality of team interactions was highly related to the quality of the team performance. Barron’s finding could be explained by Wilkerson’s (1995) contention that productive collaborative relationships produce positive collaborative behaviors during the interactions among the students. Consequently, the positive interactions among the team members are one of the keys that make the activation of the critical learning processes possible and result in effective learning and productive group work. The interactions in collaborative problem/project-learning processes could take place in a number of forms, including students engaging in the group activities, exchanging ideas, sharing responsibilities, determining the direction of solving the problems encountered, establishing divisions of labor, completing assigned tasks, and integrating the solutions to the problems as well as learning outcomes. Each of these types of interaction serves different functions that contribute to the quality of group work, and as a result, to advance the group learning and group/team cognitive growth.

Shared Reference

Another key issue in effective group learning and team performance is a shared frame of mental reference. The team member interactions could occur at various times and stages with different emphases in the process of completing collaborative projects. As Cooke, et al (2000) suggested, “team tasks often call for the team to detect and recognize pertinent cues, make decisions, solve problems, remember relevant information, plan, acquire knowledge, and design solutions or products as an integrated unit” (p.152). All tasks have to be built upon a shared intellectual, cognitive, and social frame of mental reference in order for the team to work effectively. Some researchers further argued that this shared frame of mental reference is a premise upon which a team synthesizes different perspectives brought by its members (and result in better problem solving performance) (Bromme,
2000; Johnson & Johnson, 1994). Therefore, to help students productively contribute to their group work, the students’ interactions should be first guided toward the construction of a shared frame of reference.

**Group communications**

To achieve positive and productive interactions, effective communications within the group are a necessity. Group members’ interactions cannot happen without communication. All types of interactions occurring within a group rely on some form of communication. Communications among the members of a team can be in various forms during different stages of collaborative problem solving, such as brainstorming, discussing, debating, negotiating, supporting, or compromising. To study group interactions, according to Cooke, Gorman, and Winner (2007), the most direct channel is through discourse. The discourse among the group members during various stages of problem solving, as well as different types of problem solving tasks and learning, serves as an interchanged platform upon which the members exchange their personal contribution to solving the problem, such as their own prior knowledge about the subject, understanding of the problem, or solutions. Furthermore, these discourses also reveal both individual as well as the group’s reasoning (cognitive) processes. Therefore, the group discourse provides not only “a window” to, but also direct access to, team cognition (Cooke, Gorman, & Winner, 2007, p. 428). This access opens a direct channel for collecting and analyzing individual members’ cognitive processes as well as the evolution and growth of the group’s collective cognition.

**Methodological framework**

This section combines the concepts discussed above into a methodological framework for researching collaborative learning. The emphasis is on the situational nature of collaborative learning where the unit of analysis is a group, not individuals within the group.

<table>
<thead>
<tr>
<th>Issue</th>
<th>Sub-issues</th>
<th>Research questions</th>
<th>Method</th>
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<tbody>
<tr>
<td>Collaborative Construction of Knowledge/Acquisition of Knowledge or Skills</td>
<td>Knowledge construction process Previous knowledge relevant to current goal</td>
<td>How do students collaboratively learn from each other? Is there evidence when students finds out that their knowledge and understanding is different from the others?</td>
<td>protocol analysis and interviews</td>
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<tr>
<td>Collaborative Cognitive Processes and Design Strategies</td>
<td>Analyzing Communicating Computing Creating Defining problem(s) Designing Experimenting Interpreting data Managing Measuring Modeling Models/prototypes Observing Predicting Questions/hypotheses Testing Visualizing</td>
<td>What are the group cognitive processes? To what extent are these performed collaboratively? To what extent are group members on-task or off task?</td>
<td>protocol analysis</td>
</tr>
<tr>
<td>Group interaction and communication</td>
<td>Group processes/interaction</td>
<td>To what extent is there positive and negative interdependence?</td>
<td>observational study, interviews, network analysis (Scott, 1991;</td>
</tr>
<tr>
<td>How do individuals interact? To what extent are there promotive interactions, oppositional interactions, no interactions? What types of interactions foster/attenuate participation, process and help to deliver learning outcomes? Are there definite roles played by individuals within a group (leader/leaderless group, teacher-pupil). Do group members have certain expectations of each other?</td>
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<td>Wasserman &amp; Faust, 1992), interaction analysis (Johnson, D.W., Johnson, R.T., and Smith, K 2007)</td>
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<tr>
<td>Shared reference</td>
<td>What evidence is there that students use another student’s perspective to develop an idea or concept. Does the group have common/mutual understanding of the goal? Are there any social factors that contribute to “air-time” taken by an individual? What amount of time in the groups do individuals participate in the collaborative activity?</td>
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<td>Observational study, interview</td>
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<td>Group communication</td>
<td>How does the group interact and communicate collectively to achieve the goal of the design project/PBL</td>
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<tr>
<td>Conversational analysis/discourse analysis/micro-ethnography/“human interaction analysis” (Jordan &amp; Henderson, 1995)</td>
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**Figure 1: Methodological framework for studying collaborative learning**

As can be seen from the above framework issues of collaborative learning are multi-dimensional. In order to study collaborative learning a whole array of theoretical frameworks and methodological tools are required.

**Expected impact on teaching and learning in engineering education**

Empirical research using the framework outlined above will have implications for teaching and learning in number of ways. First, these relate to the design of the collaborative learning task. The task needs to be challenging enough that it combines the expertise of group members to complete it. The task itself must lend itself so students are engaged and purposely afforded the opportunity to collaborate to achieve the objectives. The accomplishment of each individual’s goals should be the result of actions by others (Johnson, D.W., Johnson, R.T., and Smith, K 2007). The scope for no interdependence
should be avoided where members can reach their goals irrespective of whether others achieve the goals or not. There is positive interdependence when individuals promote each other’s effort and the individuals’ goals are integrated to group goals.

Working in a collaborative learning environment is a challenging cognitive activity. Evidence based research will enable educators to provide appropriate guidance to students on effective learning strategies. For example Haller et al (2000) has found that there are two types of teaching and learning interactions: transfer of knowledge sequence and collaborative sequence. They hypothesize that introducing students to different modes of interactions can empower them in their learning.

In order to benefit from knowledge possessed by collaborators it is important to reason and negotiate understanding. Effective collaboration occurs when there is a shared understanding of the tasks and goals.

In conclusion this paper lays the groundwork for further empirical research on collaborative learning in engineering education so expected benefits reported in the literature can be achieved.

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