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Development of a proof-of-concept prototype amid limited face-to-face interactions: A case study of an engineering two-student team

Luis Medina Uzcátegui[1], José Mardones Fernández[2], Alex Pailapán Neicuán[3], and Miguel Cárdenas Villegas[4]

Abstract

The COVID-19 crisis has necessitated the exploration of alternative learning methodologies to address the challenges of online education, especially in the context of teamwork. This case study examined the effectiveness of a small student team through a project focused on designing, fabricating, and testing a proof-of-concept prototype, specifically a Level 3 prototype according to the technology readiness level (TRL) scale. The project was predominantly carried out under the restrictions imposed by the pandemic. The student team consisted of two undergraduate engineering students with prior experience in project-based learning (PBL) courses. The effectiveness of this teamwork in the current project was found to be strongly influenced by attributes such as shared goals and values, commitment to team success, constructive feedback, and accountability. However, the students' previous experiences in larger teams indicated

[1]Instituto de Diseño y Métodos Industriales, Facultad de Ciencias de la Ingeniería, Universidad Austral de Chile, Valdivia, Chile
[2]Instituto de Electricidad y Electrónica, Facultad de Ciencias de la Ingeniería, Universidad Austral de Chile, Valdivia, Chile
[3]Escuela de Ingeniería Civil Electrónica, Facultad de Ciencias de la Ingeniería, Universidad Austral de Chile, Valdivia, Chile
[4]Escuela de Ingeniería Civil Mecánica, Facultad de Ciencias de la Ingeniería, Universidad Austral de Chile, Valdivia, Chile

Corresponding author:
Luis Medina Uzcátegui, Instituto de Diseño y Métodos Industriales, Facultad de Ciencias de la Ingeniería, Universidad Austral de Chile, Valdivia, Chile.
Email: luis.medina@uach.cl

that characteristics such as ideal team composition, leadership, and open communication were more prominent in those contexts. While team size may explain these differences, further research is necessary to establish definitive conclusions. The contributions of each student to the teamwork were characterized by independence and self-pacing, which played a crucial role in achieving the desired project outcomes. In conclusion, this case study emphasizes the importance of adapting to remote teamwork scenarios and provides strategies for effective project management. The findings highlight the significance of shared goals, commitment, feedback, and accountability in fostering effective teamwork. Moreover, the contributions of independence and self-pacing were instrumental in navigating the challenges posed by limited face-to-face interactions. Future research should investigate the impact of team size on team dynamics, the development of self-regulation skills in similar contexts, and the dynamics of teamwork when students lack experience in a PBL course. These investigations will contribute to a comprehensive understanding of effective teamwork strategies in diverse educational settings. The insights gained from this study contribute to the ongoing discussion on effective teamwork strategies in remote learning environments.

Keywords

Engineering education, online learning, autonomous learning, project-based learning, digital teamwork

Introduction

The COVID-19 pandemic has brought about a rapid transition to online work, which has significantly impacted the nature of interactions and collaboration in teamwork activities. Researchers have observed that the outbreak has had an effect on the performance of engineering students, although the specific implications for education remain to be fully explored and addressed.[1]

Engineering students have reported that an online learning environment requires a highly self-motivated and self-regulated learners in order to get similar learning outcomes expected under face-to-face conditions.[2] Authors have pointed out that students have felt compelled to motivate themselves when they abruptly had to work virtually.[3] The onset of the pandemic has underscored the importance of providing students with the necessary skills to effectively engage in learning during emergency or crisis situations. Consequently, achieving effectiveness in teamwork may become arduous, and this challenge may be further amplified when faced with the restrictions of face-to-face interactions.

Attributes or factors for effective work in engineering teams have been gathered by several researchers.[4,5] For engineering student teams, Borrego et al.[4] have identified four models to describe team effectiveness. Despite the difference between the number of attributes comprised by each model, and given terms to name them, they point out similar overall characteristics when dealing with how to measure team effectiveness. For instance, a frequent model cited by engineering educators is Adams' team effectiveness model.[6] This model is defined by seven constructs (i.e., characteristics): productive conflict resolution, mature communication, role clarity, accountable interdependence, goal clarification, common purpose, and psychological safety. The description of each of these characteristics is provided by the authors' model. More recently, Chowdhury and Murzi[5] have proposed 11 attributes, that should be measured to characterize effective teamwork, i.e.: (1) shared goal and value, (2) commitment to team success, (3) motivation, (4) interpersonal skills, (5) open/effective communication, (6) constructive feedback, (7) ideal team composition, (8) leadership, (9) accountability, (10) interdependence, and (11) adherence to team process and performance. As was pointed out by Goñi et al.[7] these attributes are related in a complex way; some of them should be present in team members (e.g., motivation and interpersonal skills), whereas others are inherent to the group's development. In general, measuring those attributes allows us to identify the outcomes expected from an engineering student's teamwork.

The student outcomes, based on interaction and teamwork, have been negatively affected by the transition from face-to-face to online instruction mode.[1,8,9] Researchers not only have warned about the consequences of the pandemic in terms of individual work productivity and mental health but also its consequences on the dynamics of the team-based work structures.[10]

In their study, Wildman et al.[10] identified a range of challenges encountered by engineering student teams, including external distractions, forgetfulness, and procrastination. However, their examination of team communication yielded diverse outcomes. While some team members indicated limitations in communication, others reported increased frequency and efficiency in their communication processes. Additionally, the researchers highlighted the need for adjustments in teamwork involving hands-on experiments, such as prototyping, during the crisis. These adjustments may necessitate changes to the expected project outcomes and task allocation within the team.

In contrast to the aforementioned studies, an additional outcome has been reported by Naji et al.[11] when comparing readiness (i.e., how prepared could be the students to face a sudden change to online learning) between students enrolled in project-based learning (PBL) courses and those who were not, to face online learning as a reaction to COVID-19. The reported results were based on four factors, defined to understand the influence on students' readiness to deal with an emergency online environment: (1) initial preparedness and motivation, (2) self-efficacy beliefs about online learning, (3) self-directed learning online, and (4) support-overcoming challenges. Findings derived from an exploratory factor analysis suggest that engineering students with a PBL background report better self-efficacy and motivation, i.e. higher readiness, to deal with an abrupt change to online learning.[11] These findings are aligned with those reported in previous studies, which indicate how interactive and collaborative learning methods, e.g. PBL, prepare the students for better time management and goals in an online learning framework, suggesting that a PBL background is desirable to manage teamwork with limited face-to-face interaction.[12]

The current case study presents a qualitative examination of the effectiveness of a two-student team involved in a project focused on the development of a proof-of-concept prototype. The project took place amidst limited in-person interaction due to the COVID-19 crisis. The study gathers and examines the students' perspectives on the effectiveness of teamwork, assessing it by considering 11 attributes identified in the literature[5] that are closely linked to effective teamwork within the context of engineering education.

Prior to examining the effectiveness of teamwork, this article provides a background of the two students who formed the team. Additionally, an outline of the project in which the teamwork occurred is presented, followed by a detailed description of the methodology employed to assess the students' perceptions of their teamwork performance.

The findings of the present study are subsequently examined and analyzed, incorporating valuable insights from the perspective of the involved advisors. The conclusions are then presented, underscoring the importance of exercising caution when extrapolating the results from this case study and emphasizing the considerations that should be taken into account for future research endeavors.

Student team members' background

The project team comprises two undergraduate engineering students at the Universidad Austral de Chile. One is in the fifth year of their mechanical engineering degree, while the other is in the fourth year of their electronic engineering degree. Both engineering programs are five and a half years in duration. The two students participated in an annually held PBL course that is offered concurrently to five-year mechanical engineering students and four-year electronic engineering students. Each team in this course is composed of students from both disciplines. Five faculty members, three from mechanical engineering and two from electronic engineering, regularly instructed the course.

The assigned projects in the aforementioned course were adapted to focus on technical feasibility due to the pandemic crisis, which made it difficult to conduct real-world testing. This course spans a 17-week semester and entails the completion of assigned projects. Notably, both students enrolled in this course during separate semesters. Hence, it is important to acknowledge that prior to the current project, the two students had not engaged in any collaborative or joint work.

The electronic engineering student took the course in the second semester of 2020 (September through December) and formed a team with two mechanical engineering and three electronic engineering students. Their assigned project involved evaluating the technical feasibility of developing a prototype inertial measurement unit (IMU) for biomechanical applications. The results obtained from that project were subsequently considered for the current project, as described in the following section.

In contrast, the mechanical engineering student participated in the PBL course during the second semester of 2021 (August through December). In that instance, the mechanical student worked in a team consisting of three mechanical engineering and two electronic engineering students, focusing on a project unrelated to the current one. It is worth noting that the mechanical engineering student had already completed all six PBL-oriented courses required by the mechanical engineering program, whereas the electronic engineering student had only taken one PBL-oriented course during their fourth year. The electronic engineering program does not require any additional PBL-oriented courses.

The participation of both students in the current project was voluntary and independent of their regular coursework in both the mechanical engineering and electronic engineering programs.

For the sake of brevity, throughout the subsequent sections of this article, the term "previous experience" will refer to the learning experience gained by both students during the above-mentioned PBL-oriented course. Conversely, the term "current experience" will denote the learning experience acquired during the ongoing project, the methodology of which is summarized in the following section.

The current experience: Developing a wearable IMU prototype

The scheme presented in Figure 1 provides an overview of the methodology followed for the design, fabrication, and validation stages of the prototype. It includes an approximate timeline of the project and incorporates a "heat line visualization" to indicate the extent of face-to-face interaction involved in team collaboration. In this context, the term "face-to-face interactions" refers exclusively to in-person interactions. As such, it does not include the virtual meetings that are described later.

The scheme identifies the key participants in the project: the development team, consisting of the two undergraduate students, and two advisors, who served as mentors for the project. Alongside the project's timeline depicted in Figure 1, a qualitative scale

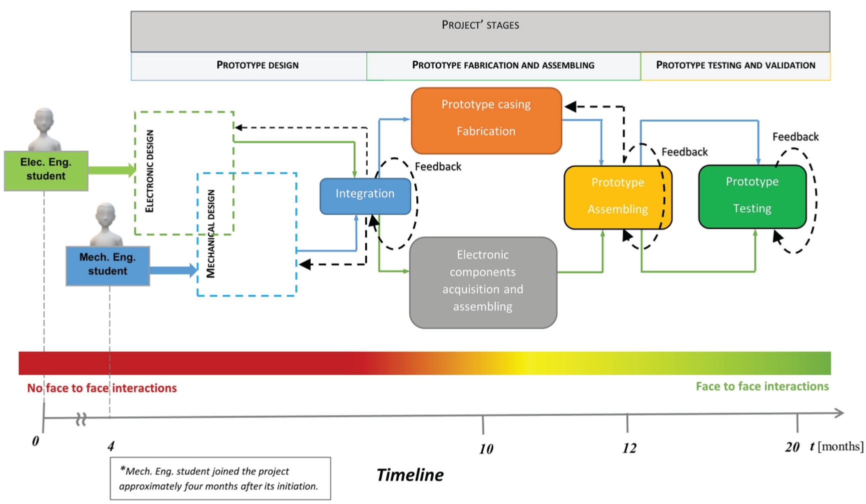

Figure 1. General prototype design methodology.

illustrates how face-to-face interactions, although limited, gradually increased as the project advanced towards the prototyping assembly and testing phases.

The project began in January 2021 and lasted approximately 20 months. Despite facing the challenges of online classes due to the pandemic, the two students effectively managed their time and mentoring was primarily conducted through virtual meetings held every two weeks. The project experienced interruptions during university breaks and testing and validation were completed in January 2023. Limited access to laboratory facilities required the team to find alternative solutions for prototype fabrication. The electronic engineering student led the design of the electronic subsystem, while the mechanical engineering student focused on the mechanical subsystem. Both team members worked independently on their respective designs without face-to-face interaction.

The design stage resulted in the integration of the two subsystems, with feedback mainly impacting the mechanical design phase for dimensioning the prototype's casing. Additive manufacturing was planned for fabricating the casing, while essential electronic components were commercially acquired.

During the fabrication and assembly stage, each team member worked separately using their own tools. The mechanical engineering student utilized a personal 3D printer, and the electronic engineering student employed tools like a multimeter, an electric soldering iron, and a mobile phone with an Android application for wireless communication with the IMU board. Necessary electronic components were obtained from suppliers and delivered to an advisor team member, with limited personal interactions. The integration of subsystems involved exchanging assembled components, such as the casing and IMU boards, to ensure proper integration of the designed prototype.

Figure 2 presents a sequential depiction of the fabrication and assembly process of the IMU prototype, with images labeled from ***a*** to ***d***. The upper-left image (***a***) shows the development board, while image ***b*** displays the assembled prototype, including essential components such as the battery, casing, and switches. The lower-left image (***c***) showcases the fabricated casing for the prototype. Additionally, image ***d*** provides a closer look at the assembly details.

After the complete assembly of the prototype, the electronic engineering student tested its functionality using an open-source electronic platform to process the acquired measurements. The validation stage included comparing these measurements with those obtained from a commercial wearable IMU device. Although in-person interactions were possible during this final stage, the testing was primarily carried out by a single team member.

Once the prototype was fully assembled, its functionality was tested by the electronic engineering student, who utilized an open-source electronic platform to process the acquired measurements. The validation stage also involved comparing the measurements with those obtained from a commercial wearable IMU device. While in-person interactions were feasible during the final stage, the majority of the testing was conducted by a single team member.

In terms of the technology readiness level (TRL) scale,[13] this prototype can be classified as level 3 (TRL3), representing a proof of concept that has been experimentally

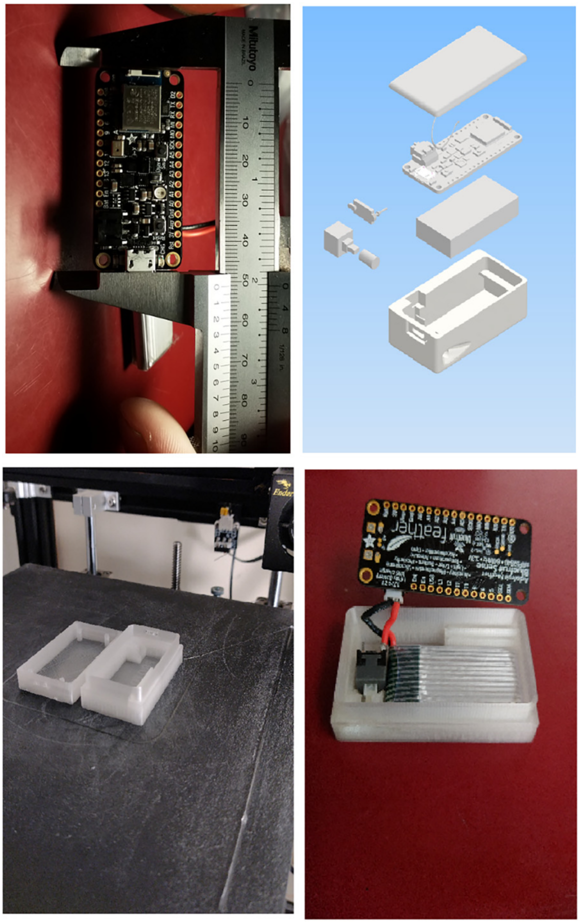

Figure 2. IMU prototype development.
IMU: inertial measurement unit.

demonstrated. The subsequent section will discuss how the students perceived this experience in relation to the teamwork involved, focusing on a set of team attributes that assess the effectiveness of their collaborative efforts.

Assessing student's perceptions of teamwork performance

In this qualitative investigation, the two team members were requested to evaluate and assess their teamwork experience. A questionnaire was developed as an instrument to collect their perceptions. The design of this instrument was based on eleven attributes, reported by the literature, and identified in effective teamwork in engineering education. Table 1 gathered those attributes, with a concise definition for each one. The attributes

Table 1. Expected attributes in an effective teamwork in engineering education[5]

Team attributes in an engineering education context	
Shared goal and values	Establishing shared team goals and values to promote unity, consistency and flexibility within the group.
Commitment to team success	Commitment to team success and recognition as a result of achievement.
Motivation	Motivated and satisfied with team tasks, driven to succeed through positive perception.
Interpersonal skills	Respect, care, and a high level of mutual trust among team members lead to productive interactions and enhanced task performance.
Open/effective communication	Open dialog, timely communication and active listening skills to facilitate effective presentation of work among team members.
Constructive feedback	Foster a team spirit of constructive criticism where team members provide and accept positive feedback from each other in a nonprotective manner.
Ideal team composition	Team function involves diversity, member roles, ideas, subject knowledge, etc.
Leadership	Leadership skills within the group include taking a leadership role through consensus, acting as a facilitator, monitoring tasks, managing conflicts and achieving objectives.
Accountability	Individuals are accountable for their own work and take personal responsibility for team tasks and assigned actions.
Interdependence	Helping and promoting individual contribution within the group, learning together and providing social support to each other.
Adherence to team process performance	Developing creative and feasible strategies, decisions, and solutions to effectively solve problems and enhance the work process.

have been collected by Chowdhury and Murzi,[5] who provided a more detailed description of each attribute.

Given the students' prior experience with teamwork in a PBL course, the objective of the questionnaire was to compare their perceptions of teamwork in the current project with their previous experience, as outlined in the preceding section. The focus of the questionnaire was to assess the efficiency of teamwork, regardless of the specific outcomes of each experience (i.e., feasibility report and prototype). To evaluate teamwork efficiency, the questionnaire included the teamwork attributes presented in Table 1 and provided concise definitions for each attribute before the assessment. The students rated each attribute for both experiences using a Likert-based scale. The scale ranged from "very effective" (5) to "very ineffective" (−5). Additionally, the scale included a level for "not perceived," (0), allowing participants to indicate when a certain attribute was not observed in the corresponding teamwork experience. The subsequent section will discuss the findings obtained from the administered questionnaire.

Findings and discussion

Figures 3 to 8 display the evaluation of each team member's perception regarding the prevalence of the attributes in the previous and current learning experiences. The labels EES and MES represent the perceptions provided by the electronic and mechanical engineering students, respectively. The term "Previous" refers to the experience gained as a team member in the projects developed during the PBL course mentioned in the above section. In contrast, the label "Current" refers to the teamwork developed in the ongoing project.

Figure 3 illustrates the effectiveness of teamwork in the shared goal and values and commitment to team success attributes for both experiences. The team members hold varying perceptions, but it is important to highlight that both students acknowledge the current experience as being more effective than the previous one in terms of shared goals and commitment to team success.

In contrast, different perceptions are provided when dealing with motivation and interpersonal skills, as it is illustrated in Figure 4.

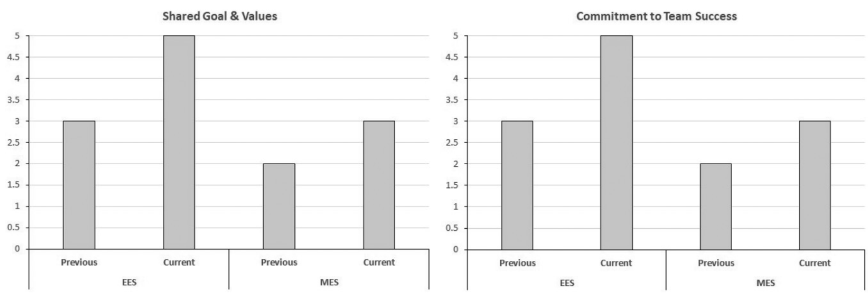

Figure 3. Team members' perceptions of shared goal and values and commitment to team success in previous and current experiences.

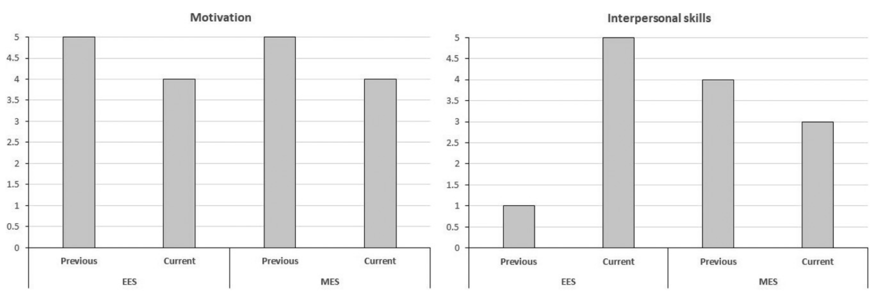

Figure 4. Team members' perceptions on motivation and interpersonal skills in previous and current experiences.

Although both team members reported greater motivation in their previous teamwork experience compared to their current one, their perceptions differed when evaluating attributes such as mutual respect, care, and trust among team members, which relate to interpersonal skills. The electronic engineering student believed that these attributes were more effective in the current experience, whereas the other teammate considered that students were more effective in the previous experience. It is hypothesized that these differences may be associated with their personal experiences.

Results show interesting differences in the perceptions of team members regarding the effectiveness of communication and constructive feedback in their previous and current teamwork experiences (Figure 5). While both team members acknowledge that the current experience was better in terms of constructive feedback, the students also recognize that communication was more effective in the previous experience. These perceptions suggest that in the previous experience, although open dialog was present, it did not necessarily result in constructive feedback.

Though both team members agreed that the current experience was more effective in fostering a team culture of constructive criticism and nondefensive positive feedback, contrasting results emerged when evaluating ideal team composition and leadership. As illustrated in Figure 6, both students indicated that the previous experience was more effective in terms of these attributes. It is worth noting that the definitions of these attributes (refer to Table 1) suggest that perception may be associated with team size. The current experience was carried out with a team of two members, whereas the previous experience involved student teams consisting of five members. This observation implies that larger teams are expected to have greater diversity in terms of member roles and ideas, as well as a more developed distribution of leadership skills within the student group.

In contrast, it might be inferred that in a small team, accountability seems to be more effective, according to the perception provided by the students, as it is illustrated in the left graph in Figure 7.

It should be noted that both students recognize the current experience as more effective in terms of this attribute when compared with the previous one. Earlier studies have claimed that larger team sizes do not negatively impact team performance.[14,15] However, some researchers suggest that the way in which team members perceive accountability may be linked to students' perception of the quality of their team experience.[16,17]

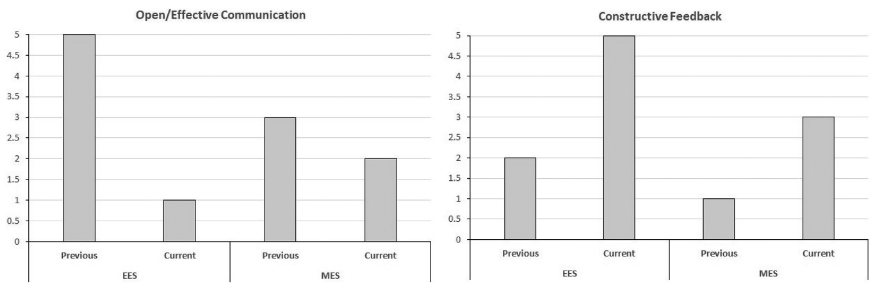

Figure 5. Team members' perceptions on open/effective communication and constructive feedback in previous and current experiences.

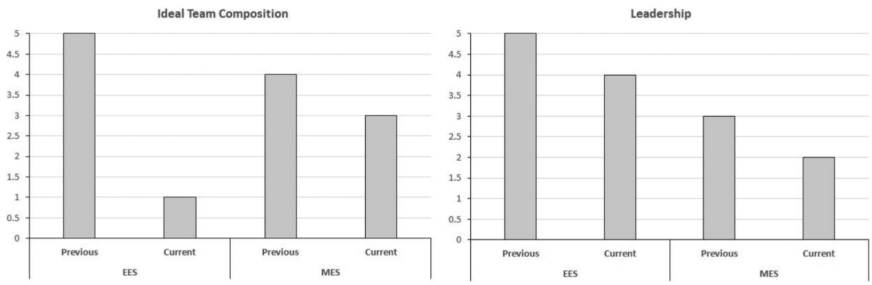

Figure 6. Team members' perceptions on ideal team composition and leadership in previous and current experiences.

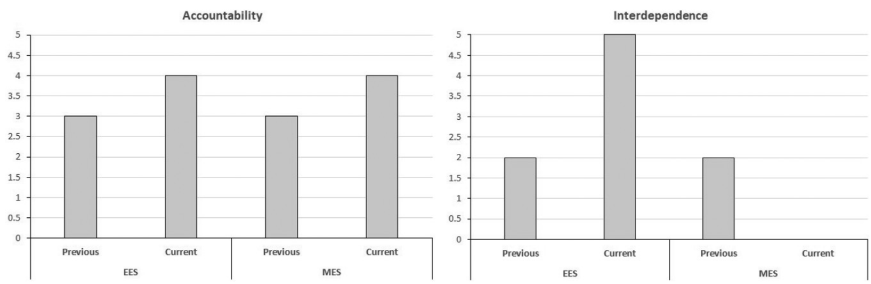

Figure 7. Team members' perceptions on accountability and interdependence in previous and current experiences.

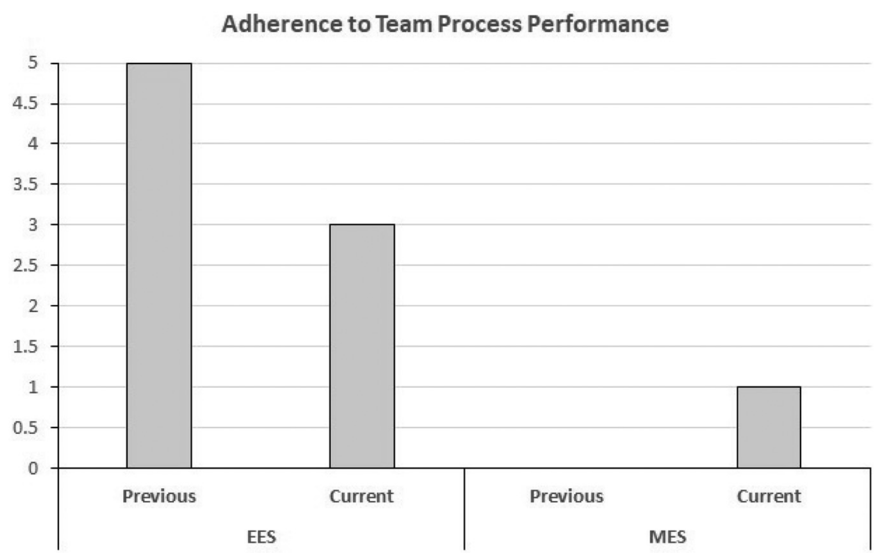

Figure 8. Team members' perception of adherence to team performance in previous and current experiences.

On the other hand, the perception of interdependence is remarkably different between both team members, as the right graph in Figure 7 depicts. While the electronic engineering student opinion suggests that a high grade of interdependence was more evident in the current experience, the mechanical engineering did not perceive this attribute in the current experience. It is posited that the latter observation can be elucidated by the sequential methodology employed in developing the prototype. Specifically, the mechanical design of the casing was developed subsequent to the assembly of the electronic subsystem, leading to reduced interactions among team members during this phase.

Figure 8 displays the perceptions of the team members regarding adherence to team process performance. Interestingly, the two students have differing opinions on this attribute. The electronic engineering student recognizes a greater emphasis on adherence to team process performance during the previous experience, whereas the mechanical engineering student holds the opposite view. In fact, the latter individual did not perceive this attribute to be present during the previous experience.

In summary, based on the perspective of the two students involved in this case study, certain attributes were more prominent in the current experience compared to the previous one. It is hypothesized that the students' perception of teamwork is largely influenced by the team size. According to the students, the efficiency of teamwork in the current project appears to be closely associated with attributes such as shared goals and values, commitment to team success, constructive feedback, and accountability. On the other hand, drawing from their previous experiences in larger teams, both students agree that characteristics such as ideal team composition, leadership, and open/effective communication were more prominent in the previous experience. It should be noted that both experiences took place amidst limited face-to-face interactions, but the specific impact of this factor on their perceptions is not yet fully understood. However, as indicated by other researchers, the absence of face-to-face interactions does not necessarily have a negative impact on teamwork. In fact, some students have reported that virtual team meetings can be more effective in certain contexts.[10]

From the perspective of the advisors, it is apparent that the students' prior experience played a crucial role in effectively managing teamwork despite the constraints imposed by limited in-person interactions. The students' previous engagement in a PBL course, conducted in a virtual format, contributed to their preparedness for the current project. This finding aligns with previous research that has reported quantitative analysis results highlighting the positive impact of prior experience on students' readiness in similar contexts.[11] Additionally, traits such as independence and self-pacing were observed in how each student approached the current project. Furthermore, considering the nature of the project and the students' backgrounds, the workload was evenly distributed among team members.

Conclusions

This case study investigates the effectiveness of a two-member team consisting of a mechanical engineering student and an electronic engineering student, both with prior experience in project-based learning (PBL) courses. The study examines, qualitatively, the efficacy of their collaborative work.

The team successfully designed, fabricated, and tested a TRL 3 prototype, despite facing limited opportunities for face-to-face interactions. Both students have prior experience working in larger student teams through their participation in PBL-oriented courses and project development. A qualitative exploration of the students' perceptions regarding the effectiveness of teamwork is presented. While it is important to exercise caution in generalizing the results of this case study, the following key points can be emphasized:

1. The effectiveness of teamwork in the current project appears to be strongly influenced by attributes such as shared goals and values, commitment to team success, constructive feedback, and accountability. However, the students' previous experiences in larger teams indicate that characteristics such as ideal team composition, leadership, and open/effective communication were more pronounced in those contexts. It is hypothesized that these differences may be attributed to variations in team size, although further research is necessary to draw definitive conclusions in this regard.
2. The contributions of each student to the teamwork were characterized by independence and self-pacing. These qualities played a crucial role in achieving the desired outcomes of the current project, particularly given the limitations imposed by the reduced face-to-face interactions and on-campus hands-on activities. Additionally, the successful execution of the project was facilitated by the level of technological maturity expected for the fabricated prototype.

The project advisors' observations suggest that the two students' experience with PBL contributed significantly to their ability to mitigate the effects of the limitations the two students encountered in developing the project. This finding is consistent with the results of other research on the benefits of PBL.[11] Nevertheless, this qualitative approach needs to be complemented with future studies to explore the impact of team size on teamwork dynamics, investigate the development of self-regulation skills in similar contexts, and examine the dynamics of teamwork when students do not have experience in a PLB course. In addition, it is worth noting that the design and implementation of interviews to complement the information derived from the survey results could be explored in future research. These investigations will contribute to a comprehensive understanding of effective teamwork strategies in diverse educational settings.

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ORCID iD

Luis Medina Uzcátegui https://orcid.org/0000-0001-9681-0590

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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