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Sustainability of Project-Based Learning by Incorporating Transdisciplinary Design in Fabrication of Hydraulic Robot Arm

Taha Farid , Sara Ali , Muhammad Sajid *  and Khalid Akhtar

School of Mechanical and Manufacturing Engineering (SMME), National University of Sciences and Technology (NUST), Islamabad 44000, Pakistan; taha.farid@outlook.com (T.F.); sarababer@smme.nust.edu.pk (S.A.); drkhalidakhtar@smme.nust.edu.pk (K.A.)

* Correspondence: m.sajid@smme.nust.edu.pk

Abstract: Wider acceptance of project-based learning (PjBL) in the tertiary education industry has been obstructed by its resource-intensive nature. This paper introduces a transdisciplinary variant of PjBL for undergraduate engineering students through a multidisciplinary complex engineering problem requiring the design and fabrication of a hydraulic robot arm. The robotics-inspired transdisciplinary PjBL variant was first evaluated through student feedback using the Chi-square hypothesis test, which, at Chi-square (4, $N = 101$) = 129.12; $p < 0.05$, revealed a statistically significant difference in the proportion of the student feedback in favor of the PjBL for sustainability of transdisciplinary project-based learning. Furthermore, the students' PjBL and PbBL scores were subjected to the Mann–Whitney U test which concluded the effectiveness of PjBL against PbBL with statistical significance, $U(N = 101) = 192.00$, $z = -11.826$, $p < 0.05$. The results indicate that the novel transdisciplinary project-based learning (PjBL) approach develops students' practical engineering knowledge spanning multiple disciplines, thereby resulting in a sustainable concept of project-based learning.

Keywords: project-based learning; robotics education; transdisciplinary perspective; complex engineering problem; problem-based learning



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1. Introduction

Project-based learning (PjBL) is a vanguard for inculcating 21st century skills. These skills are otherwise hard to measure through standardized testing, yet they are crucial for grooming student into productive members of the global community: proactive and adaptive learners who self-direct their performance improvement in a collaborative context to foster creativity in effectively tackling advanced problems on an interdisciplinary forefront [1]. Thus, engineering education calls for a special emphasis on PjBL that imparts practical thinking in students without sacrificing fundamental engineering knowledge as opposed to the problem-based learning (PbBL). It has been demonstrated that both industry and academia demand a propensity towards project-oriented professional practice as compared to a problem-based approach [2]. Therefore, it is imperative that university engineering programs incorporate PjBL as a vital component of their curricula [3,4]. PjBL is essentially a dynamic learning model that is based on active student planning for collaboratively or independently executing projects, relevant to the domain of learning, such that the resulting project outcome in the form of a product is ultimately evaluated by the instructor [5]. Contrary to the instructor-driven role in the conventional model of learning, project-based learning employs a student-centered learning methodology in which the student integrates theory and knowledge into hands-on skills by using the vehicle of inquiry to transition from ideation to the execution of a viable product under the facilitation of the instructor [6,7]. The application of this technique is a four-phase process: the first phase requires the instructor to define the problem; the second

phase involves research and ideation by students to identify the product requirements to address the defined problem; the third phase revolves around determining and, therefore, developing a viable product solution which is, finally, evaluated by the instructor to gauge the learning of the students [1]. By engaging the students in solving complex engineering problems resembling real-world scenarios [8,9], PjBL enhances the learning of students in an interdisciplinary context using complex engineering problems, which not only ingrains relevant knowledge and skills but also instills practical skills, namely communication, team management, self-regulation, and addressing multidisciplinary issues [10]. Subsequently, this innovative teaching model equips students with multi-faceted professional qualities [9]: deep and well-synthesized understanding of the area of interest, teamwork, independent yet responsible learning, and multidisciplinary learning caliber.

Since the successful completion of any real-world project is pivoted on the integration of all fundamental domains of undergraduate engineering curriculum, this underpins the need to couple PjBL with a transdisciplinary perspective which is defined by Ertas et al. [11] as “the integrated use of tools, techniques, and methods from various disciplines” existing “simultaneously between disciplines, across different disciplines, and beyond all disciplines”. This concept is highlighted in a multitude of sophisticated products ranging from automobiles to computing centers to the state of the art of domains of Internet of Things (IoT) and artificial intelligence where the success is hinged upon a shared understanding of the engineering design process by a collaborative team of experts belonging to diverse engineering domains amalgamating their efforts in transdisciplinary terms [12,13]. Such advanced problem-solving performance is achieved only when the professionals are equipped with a synergistic combination of technical skills and cognitive capabilities [14,15]. It has also been demonstrated by numerous empirical studies [16,17] that even though engineers belonging to different engineering domains tackle a particular complex engineering problem differently, the fundamental design stages supplemented by the core cognitive processes employed by them share common ground. Hence, it can be concluded that current engineering design practices especially at an industrial level are transdisciplinary by nature [18,19]. Thus, this transdisciplinary nature should be a characteristic feature of the complex engineering problem employed in PjBL at the tertiary level of education.

It is evident that the growing link between numerous academic disciplines has transcended the boundaries imposed by the disciplines constituting any particular transdisciplinary context. Therefore, transdisciplinary education is nothing but a product of interdisciplinary and multidisciplinary domains [11]. In this regard, educational robotics has emerged as an effective application of a transdisciplinary educational tool for PjBL that consolidates computational thinking and engineering skills within a single complex engineering project [20]. In particular, the incorporation of robotics in engineering projects not only hones the skills of students at a multidisciplinary forefront but also imparts valuable skills that allow the students to integrate engineering fundamental for employing technology to address practical problems [21]. In doing so, students learn to develop collaborative yet critical problem-solving skills to translate their theoretical knowledge of engineering fundamentals into a tangible outcome.

Keeping this in perspective, this paper presents a potent application of PjBL in a trans-disciplinary context in which educational robotics was coupled with interdisciplinary domains of mechanical engineering dynamics and fluid mechanics to impart undergraduate engineering education through a complex engineering problem of the design and fabrication of hydraulic robot arm. This was achieved through a four-module process by the researchers: management involving defining the project rubric, implementation by students under instructor supervision, assessment to gauge student performance as well as to collect student feedback, and evaluation which involved employing statistical analysis. The main contribution of this article is that it introduces a transdisciplinary variant of PjBL through a multidisciplinary complex engineering problem requiring the design and fabrication of a hydraulic robot arm. This approach focused on coupling two different courses

(Fluid Mechanics and Engineering Dynamics) with robotics-inspired transdisciplinary PjBL compared to the conventional PbBL approach. This also improved the sustainability and increased the PjBL outcomes by reducing the resources, both material and human, required to conduct and evaluate projects for multiple courses.

The research findings of this paper are organized into seven sections. Following the introduction outlined in Section 1, Section 2 presents a literature review that briefly outlines the most notable research endeavors that explore the applications and implications of robotics inspired transdisciplinary PjBL in order to underline the novelty of this investigation. Accordingly, Section 3 explicates the research methodology employed in this study by discussing its salient features comprising the details of the participants and mapping of the associated learning outcomes into measurable attributes evaluated in student feedback forms. The four steps undertaken to execute this investigation, namely management, implementation, assessment, and evaluation, are also explained in Section 3. The results of the investigation are then evaluated and discussed in Section 4.

Finally, Section 5 summarizes the findings of this paper.

2. Literature Review

The review of engineering education in several countries revealed that the engineering disciplines being offered require considerable accreditation criteria [3,4] owing to the orthodox modes of teaching. In this scenario, it has been shown that PjBL is the way forward for the effective transfer of engineering skills, especially for poorly structured, interdisciplinary domains [22]. Hence, numerous studies have been conducted for the effective implementation of this new learning mode, especially in engineering education.

For example, PjBL has been implemented in undergraduate courses by the faculty of mechanical engineering at the Technion [9] where empirical data were collected to capture the student response to the PjBL approach in term of emotions, thoughts, behavior, and difficulties. It was observed that students not only self-evaluated their performance but observed that PBL inculcated in them the responsibility for their own learning through persistence and diligence. However, this study was limited to an introductory course in mechanical engineering that incorporated very basic engineering knowledge at freshman level. Overall, it can be concluded that the teaching modes should be adapted to the student's style of learning so that the under-performing students have the opportunity to hone their skills while those with higher grades can add practical value to their skills [23].

Similar endeavors to integrate PjBL in engineering education were successfully carried out at Aalborg University [24], Tampere University of Technology [25], and University of Malaysia [26]. However, these studies lacked any direct student survey to obtain student feedback to assess the quality of their learning experience. It is worth noting that teaching in a PjBL environment is replete with several challenges, as outlined in [27], amongst which the major challenge is the assessment of student performance. In this regard, an integrated yet unidirectional approach for the teaching of pipe network analysis to undergraduate mechanical engineering students in PjBL track was carried out at our institution [28]. Based on an extensive evaluation of this scheme, the mechanical engineering faculty at our institution further contributed to the advancement of project-based learning, especially in undergraduate engineering, by developing a comprehensive approach [29] to assess student performance in the context of PjBL by mapping the student feedback questionnaire with robotics-inspired transdisciplinary education learning outcomes through fifteen vital attributes. Some initiatives [30,31] went further in the application of PjBL by employing it to design the curriculum. Furthermore, some investigations [32,33] added value to the PjBL approach by incorporating a multitude of mini-projects to pronounce the effectiveness of the PjBL assessment. Accordingly, one such outstanding endeavor [34] employed a PjBL approach in an engineering context by developing an approach to design project-based curricula of the electronic systems. The efficacy of the curricula was evaluated for four academic years using analysis of the academic results as well as the student survey responses. However, the student survey lacked comprehension in linking the

student responses to an extensive range of student learning outcomes so as to capture wider frame of implications of the approach. Recently, a new dimension to project-based learning was also introduced by coupling it with multidisciplinary domains. For instance, researchers from Montana Tech of the University of Montana [35] elicited positive outcomes in implementing multi-course PjBL in the computer science department which involved the development of computer software.

Likewise, a recent study [36] at Nanjing Institute of Technology emphasized the effectiveness of delivering interdisciplinary lessons in project form to engineering students.

Along similar lines, another variant of multidisciplinary PjBL spanning over several semesters was executed by Virginia Military Institute which dawned the deficiencies in the traditional, uni-directional curricula [37]. Nevertheless, it is worth noting that these initiatives to apply PjBL in a multi-domain environment lacked details pertaining to the design and implementation of the project as well as a statistical approach to determine the utility value of this approach. In this regard, an innovative addition to the PjBL approach was made by Amith et al. [38] by implementing PjBL in a multi-course context in undergraduate electrical engineering. The study incorporated both the student surveys and statistical analysis to gauge the effectiveness of a multi-course project especially for education targeting sustainable development. However, in particular, the study was aimed at gauging the student performances only in engineering soft skills and project management skills mapped by student learning outcomes. Overall, the study established the viability of any future initiative to implement PjBL in an interdisciplinary perspective.

Moreover, numerous universities have employed an interdisciplinary approach in their educational programs [39,40]. In this regard, a recent study [16] shared empirical results that showed a transdisciplinary approach to engineering design education grounded on Boom's Taxonomy. As a matter of fact, the latest investigation [41] on the effectiveness of interdisciplinary education in a top-tier engineering college, spanning over a period of six semesters or three years, corroborated empirical evidence in favor of an interdisciplinary approach as the way forward for tertiary level of engineering education.

In conjunction with transdisciplinary education, robotics-based education can play a vital role to enhance student skills to turn engineering design thinking into beneficial technology [20,42]. In this regard, a study [21] investigating the challenges and trends facing the robotics movement in education advocated conclusions and proposals for fostering the collaboration of teachers and researchers for an integration of robotics in education to reap maximum benefits in a transdisciplinary perspective.

Accordingly, robotics was employed in a recent PjBL investigation [43] to impart electronic fundamentals to undergraduate students with promising outcomes of such an approach in honing the skills of students in translating engineering fundamentals into technological advancements. In fact, building on the significance of robotics in advancing the objectives of transdisciplinary engineering education, a contemporary research endeavor [44] recommended in its key findings that the most potent educational training programs, incorporating "student support services", in advanced manufacturing using robotics calls for continuous experimentation and evaluation of these practices.

In view of the brief compendium of literature discussed, this study draws its novelty through the implementation of a transdisciplinary variant of project-based learning which is termed in this work, for convenience, as robotics-inspired transdisciplinary PjBL.

Firstly, the study employed PjBL at a tertiary level of education in the interdisciplinary technical/hard domains of mechanical engineering for undergraduate students. Secondly, the PjBL was implemented through a complex engineering problem that required an understanding of robotics thereby taking the PjBL into a transdisciplinary context. Thirdly, the effectiveness of this robotics-inspired transdisciplinary PjBL approach was extensively investigated through the following statistical methods that assessed both the robotics-inspired transdisciplinary facet and the project-based learning facet of this novel PjBL variant:

- Hypothesis testing for the analysis of the student feedback questionnaire [29] in gauging the effectiveness of robotics-inspired transdisciplinary PjBL in achieving the corresponding robotics-inspired transdisciplinary education learning outcomes mapped by the student feedback questionnaire.
- Hypothesis testing for the comparison analysis of the student scores in the complex engineering problem-based project as well as the student scores in solving associated numerical problems in assignments to evaluate the effectiveness of PjBL and PbBL approaches that the project and the numerical problems represent, respectively.

3. Research Methodology

The robotics-inspired transdisciplinary PjBL, comprising robotics and fluid mechanics, was carried out in four phases. The first phase of ‘management’ involved the organization of the complex engineering problem in terms of the project guidelines and project rubric. The second phase of ‘implementation’ entailed the execution of the project by the students under the supervision of the instructor. This was followed by the ‘assessment’ phase in which the student feedback was obtained through a questionnaire [29] that integrated the robotics-inspired transdisciplinary education learning outcomes with PjBL. The final phase of evaluation then investigated the effectiveness of robotics-inspired transdisciplinary PjBL, for both the robotics-inspired transdisciplinary education learning outcomes as well as PjBL against PbBL, through reliable statistical analysis techniques. Figure 1 illustrates the complete architecture of the project explaining the block diagram and research methodology in terms of three stages incorporating the phases of management, implementation, assessment, and evaluation. The sub-blocks in Figure 1a represent the components of each domain, i.e., fluid mechanics, engineering dynamics, and robotics that are integrated using a transdisciplinary approach.

The subjects of this study were a total of 101 undergraduate students for an entire semester (fall 2017–2018), in the department of Mechanical Engineering at our institution. The robotics-inspired transdisciplinary PjBL approach was implemented through the hydraulic robot arm semester project in conjunction with the PbBL approach implemented through conventional numerical problems for the undergraduate course of Fluid Mechanics. The research group consisted of 3 groups comprising of 101 students being evaluated for both PjBL and PbBL approaches.

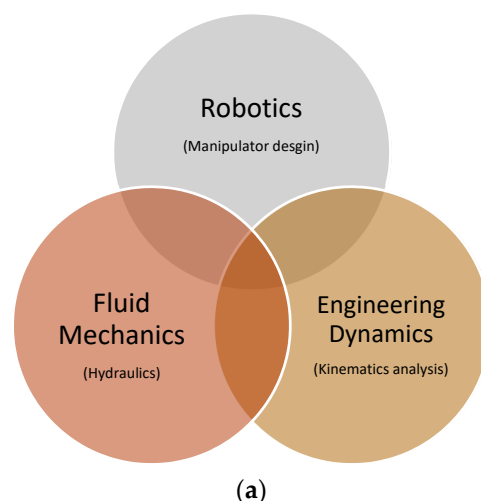


Figure 1. Cont.

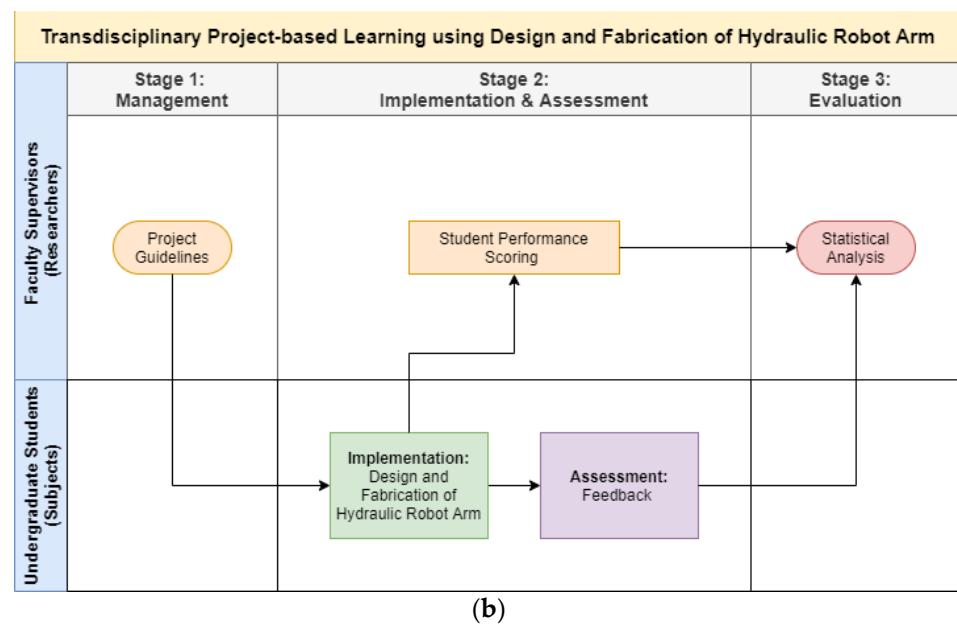


Figure 1. Project architecture: (a) Block diagram of the project, and (b) research methodology: Faculty–student mapping for PjBL.

The effectiveness of the robotics-inspired transdisciplinary learning facet of the robotics-inspired transdisciplinary PjBL approach was evaluated by assessing student performance (via questionnaire feedback) in terms of their success in achieving the four primary robotics-inspired transdisciplinary education learning outcomes, as illustrated in Figure 2. The mapping of the constituent feedback question statements onto these learning outcomes through sixteen attributes is based on the scheme established by Sara et al. [29]:

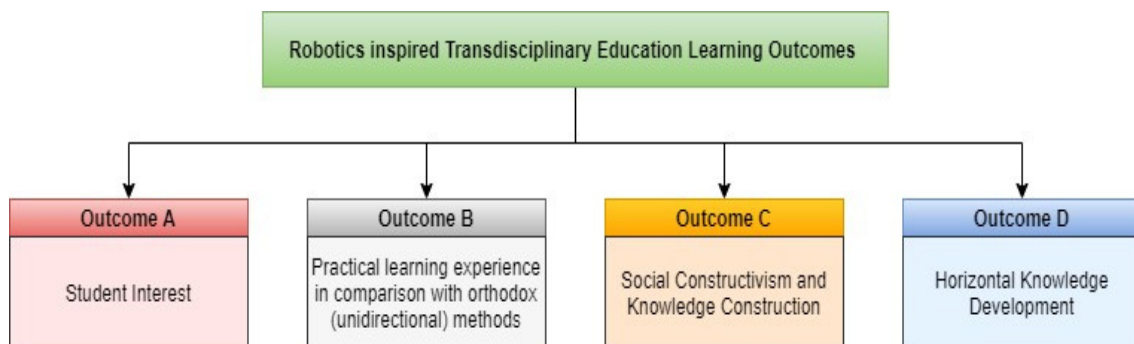


Figure 2. The four primary robotics inspired transdisciplinary education learning outcomes.

3.1. Management: Complex Engineering Problem

The PjBL was carried out by introducing the students to a semester project based on a complex engineering problem in the industrial context. At the same time, the project also incorporated a robotics-inspired transdisciplinary learning approach by introducing the core concepts of robotics which are crucial for the successful design and implementation of the solution to the complex engineering problem of the project. The robotics module of the project was focused on the development of a kinematic model verified by experimental testing.

Accordingly, the project entailed the design and fabrication of a three degree-of-freedom hydraulic robot arm with a multi-pronged hydraulic gripper operated using the piston and levers. In particular, the robotics module of the project required the development of a kinematic model that related the position of the gripper from the base as a function

of link lengths and angles based on the frame assignments illustrated in Figure 3. It is pertinent to observe that the red axes represent the z-axes, blue axes represent the x-axes, and the green axes represent the y-axes. The axes were assigned so that a joint's rotational motion was always along the z-axis (red), and the link length from one axis to the next in the manipulator chain was mostly along the x-axis (blue) with the exception of L1.

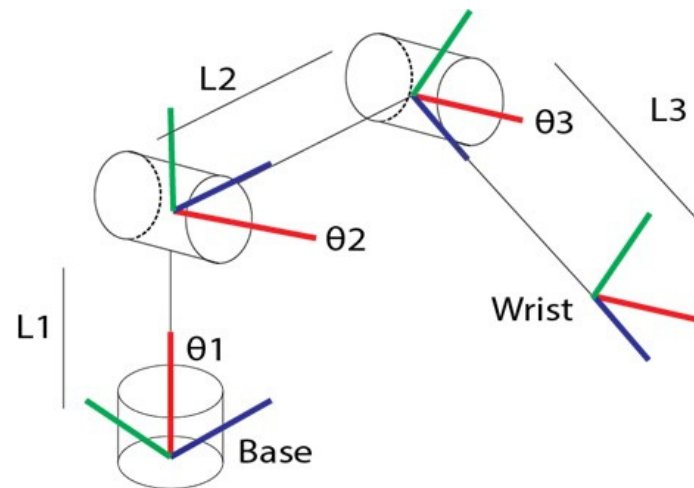


Figure 3. Frame assignments for kinematic model development of a hydraulic arm.

On the other hand, the fluid mechanics (hydraulic) component of the project required the development of a kinematic-hydraulic model that related the position of the gripper wrist from the base as a function of the level of hydraulic fluid in the various tubes. Based on these transdisciplinary design deliverables, the hydraulic robot arm designed by the students was expected to fulfil the following function for its demonstration: pick up and crush the paper cups distributed at random within a region of area 3 inches by 6 inches and place them in a collection bin in the center of the region with the hydraulic robot arm placed close to the center, as shown in Figure 4.

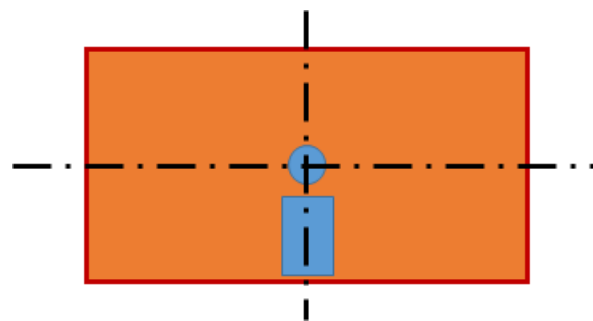


Figure 4. Operation space of the hydraulic robot arm.

In presenting these deliverables through the demonstration and the design report, the students were expected to present a comprehensive engineering analysis for addressing the core design problem statements outlined as follows:

1. What is the (derived) mathematical relationship between the joint angles and the corresponding position of the wrist with regard to the base frame?
2. What are the joint angle values that produce the maximum extension in the manipulator? What is the length of the hydraulic column corresponding to that maximum extension?
3. What are the maximum joint angle limitations of your fabricated manipulator? What is the length of the hydraulic column corresponding to that maximum extension?
4. Be able to calculate how far the wrist moves from the base to reach a goal point.

3.2. Implementation: Project Development by the Students

The students were given the time of approximately two months from the issuance of project guidelines for the submission of project deliverables. During this period, the student progress was appraised on bi-monthly basis to ensure timely project completion without compromising quality.

The student performance in the PjBL facet of robotics-inspired transdisciplinary PjBL was assessed through three key project activities as outlined in the project rubric shown in Figure 5.

1. Presentation and demonstration (45% of total score): To assess the students' practical knowledge along with the teamwork and presentation skills pertaining to the project design and development.
2. Assignment/project Submission (5% of total score): To gauge the student vigilance and timely preparedness in meeting project deadlines.
3. Report (50% of total score): To evaluate the academic/professional communication skills for technical report writing.

Project Activities	Presentation and demonstration (45%)	Assignment/Project submission (05%)	Report (50%)
Performance Assessment	Do the students know the project?	Was the report submitted on time?	Background Search / Literature Review / Application
	Did the presenter exhibit good presentation skills?		Analytical solution
	Did the students exhibit good team work during demonstration?		Problem Solving in Computational tools (e.g. Matlab)
	Did the presentation/demonstration fill the allotted time?		Data presentation
			Conclusion and Recommendations
			References

Figure 5. Project rubric with score distribution.

Based on the student performance in each of the above activities, the students were awarded scores by the evaluation committee of faculty members such that the aggregate student score of 100 points was calculated using the weightages of the three key project activities indicated in the project rubric (Figure 5).

In conjunction with the semester project, the students were also engaged in the conventional PbBL tasks which involved solving graded numerical problems. Accordingly, the student performance in terms of aggregate score out of a total of 100 points was calculated for comparison against the students' project scores in PjBL context.

3.3. Assessment: Student Grades and Feedback Questionnaire

At the end of the semester, two datasets were collected, namely the students' grades for PjBL as well as PbBL, and the student feedback via questionnaire for the evaluation of the robotics-inspired transdisciplinary education learning outcomes for the overall assessment of robotics inspired transdisciplinary PjBL approach.

The first dataset, i.e., the student grades, was collected by noting the students grades out of a total aggregate of 100 marks for both the PbBL and for PjBL via the project rubric (Figure 5). The comparison of the student grades for both these contexts served to investigate the effectiveness of project-based learning.

The second dataset, i.e., the student feedback questionnaire, was collected to specifically investigate the degree of efficacy of the robotics-inspired transdisciplinary learning approach encompassing the fields of robotics and fluid mechanics (hydraulics) for effec-

tively imparting engineering knowledge through the complex engineering problem of the semester project. The questionnaire was tailored based on [29]. It employed the Likert scale [45] for each question statement to determine the student perspective on achieving the robotics-inspired transdisciplinary education learning outcomes through the robotics and hydraulics based engineering design problem of the project:

‘Strongly Agree’ = Likert score of 5

‘Agree’ = Likert score of 4

‘Neutral’ = Likert score of 3

‘Strongly Disagree’ = Likert score of 1

During the conduction of the survey, student anonymity was ensured so that the merits of the survey data were not compromised. Table 1 outlines the question statements that constituted the questionnaire to collect the student feedback.

Table 1. Transdisciplinary learning assessment questionnaire.

Question Statements	
1	The project provided me with motivation to learn about hydraulics and robotics.
2	The project provided me with opportunities for independent learning and knowledge construction.
3	The project allowed me to explore and make decisions in order to reach a solution.
4	Inclusion of the project increased my interest in the course as a whole.
5	The project helped me explore meaningful questions related to hydraulics and kinematics.
6	The project encouraged me to do independent, out-of-the-box research utilizing all resources (Internet, library, seniors, faculty, et cetera) available to me.
7	The project has helped me in becoming a better engineer.
8	I am confident in solving kinematic problems.
9	The project provided me with sufficient skills to design a simple hydraulic arm in the future.
10	Knowledge acquired through the project will help me if/when I am to work in an industry.
11	The project helped me with horizontal knowledge development (i.e., skills not strictly a part of the course, including soft skills).
12	The project helped me with team working skills.
13	The project helped me with time management.
14	The project gave me insights into handling projects professionally.
15	The project made me an active learner.
16	I prefer project-based learning over lecture-based learning.
17	Working on a project improved my grade for this course.
18	My understanding of hydrostatics is better than my understanding of the other topics of fluid mechanics.
19	Had the project not been a part of the course, I would not have learned as much.

3.4. Evaluation: Statistical Analysis

The effectiveness of the transdisciplinary perspective of the hydraulic robot arm project was gauged through a graphical analysis of the student feedback questionnaire.

In particular, the analysis aimed to determine the extent to which the project successfully achieved the four robotics-inspired transdisciplinary education learning outcomes (refer to Figure 2).

The overall student responses to each of the robotics-inspired transdisciplinary education learning outcomes was analyzed by categorizing the responses to the feedback questionnaire in five Likert-type categories: ‘excellent rating’ corresponding to a Likert score of 5, ‘good rating’ corresponding to a Likert score of 4, ‘neutral rating’ corresponding to a Likert score of 3, ‘satisfactory rating’ corresponding to a Likert score of 2, and ‘poor rating’ corresponding to a Likert score of 1. It is important to consider that the feedback questionnaire’s question statements (refer to Section 3.3) were designed in such a way that they were conducive to this Likert-type categorization of responses.

In order to establish the viability of the classification of the student responses into Likert-type categories, the Chi-square test was employed to measure the comparison of expected data to actual data pertaining to Likert-type categories of responses. This is because the Chi-square analysis [46] is an effective means for evaluation of survey results that lead to different expected results [47]. Accordingly, the null hypothesis of the test states that “there is no difference in the proportion of student feedback for different Likert-type categories of responses” whereas the alternative hypothesis of the test states that “there is a significant difference in the proportion of student feedback for different Likert-type categories of responses”. The type of data used in the Chi-square test fulfilled the prerequisites of the Chi-square test by being raw, drawn from independent variables, obtained from a large sample, and mutually exclusive. The formulae [46] of the Chi-square (χ_c^2) statistic is (refer to Equation (1)):

$$\chi_c^2 = \sum \frac{(O_i - E_i)^2}{E_i} \quad (1)$$

The learning performance of 101 students, in each of the PjBL and PbBL contexts, was measured through scores out of a total of 100 points. The effect of PjBL on student learning performance compared to the PbBL was analyzed based on the normality analysis of the data. This is because the normality test determines whether the data should be subjected to the parametric testing analysis or non-parametric testing analysis. Therefore, in particular, the normality test employed for this study was the Shapiro–Wilk test [48] for each of the PjBL and PbBL score data since it is the most effective normality test for large enough data samples [49]. Accordingly, for PjBL score data, the Shapiro–Wilk test showed a significant departure from normality, $W(101) = 0.97$, $p = 0.017$ ($p < 0.05$). On the other hand, for PbBL score data, the Shapiro–Wilk test also showed a significant departure from normality, $W(101) = 0.95$, $p = 0.001$ ($p < 0.05$). Thus, the Mann–Whitney U test [50], termed as the non-parametric equivalent of the Student’s t -test for independent samples [51], was employed. In fact, for various data scenarios including large sample size, the Mann–Whitney U test is more powerful than Student’s t -test [52].

For conducting the Mann–Whitney U test, the null hypothesis states that “there is no difference between the scores for PjBL and PbBL” whereas the alternate hypothesis states that “there is a significant difference between the scores for PjBL and PbBL”. In addition to its non-normal distribution, the score data fulfilled the requisites of the Mann–Whitney U Test by being continuous, comprising two categorical, independent groups namely PjBL and PbBL, and being obtained from independence of observations. The large-sample formulae for the Mann–Whitney U test are [53]:

$$\mu_u = \frac{n_1 \cdot n_2}{2}, \sigma_u = \frac{n_1 \cdot n_2 (n_1 + n_2 + 1)}{1}, z = \frac{U - \mu_u}{\sigma_u} \quad (2)$$

where in Equation (2), sample sizes for PjBL and PbBL, n_1 and n_2 , respectively, are large (more than 10); the Mann–Whitney U test statistic is denoted by U value; μ_U denotes the mean of U value; and σ_U denotes the standard deviation of the U value.

This study also investigated the effect of the residential status of students, boarder or day scholar, on their learning performance through scores in the context of PjBL and PbBL. Therefore, the statistical technique for investigating the impact of residential status on students’ PjBL and PbBL was decided based on the normality test. In this regard, the normality test employed was the Shapiro–Wilk test [48] for each of the PjBL and PbBL score data, since it is the most effective normality test for large enough samples [49].

Accordingly, for PjBL score data, the Shapiro–Wilk test showed a significant agreement with normality in case of boarders, $W(76) = 0.98$, $p = 0.131$ ($p > 0.05$), whereas in the case of day scholars, $W(25) = 0.91$, $p = 0.035$ ($p < 0.05$), the test showed a significant departure from normality. On the other hand, for PbBL score data, the Shapiro–Wilk test showed a significant agreement with normality in case of boarders, $W(76) = 0.99$, $p = 0.666$ ($p > 0.05$),

whereas in the case of day scholars, $W(25) = 0.86$, $p = 0.03$ ($p < 0.05$), the test showed significant departure from normality. Since the score data for PjBL and PbBL for both the boarders and day scholars were not normally distributed, as evidenced by the Shapiro–Wilk test, the Mann–Whitney U test [50], termed as the non-parametric equivalent of the Student’s *t*-test for independent samples [51], was employed. This is also because the Mann–Whitney Test is more powerful than Student’s *t*-test in various data scenarios, especially for a large sample size [52].

For conducting the Mann–Whitney U test for both PjBL and PbBL, the null hypothesis states that “there is no difference between the scores for PjBL/PbBL with respect to status of residence, boarder or day scholar,” whereas the alternate hypothesis states that “there is a significant difference between the scores for PjBL/PbBL with respect to status of residence, boarder or day scholar”. In addition to its non-normal distribution, the score data for both PjBL and PbBL fulfilled the requisites of the Mann–Whitney U Test by being continuous, composed of two categorical yet independent groups, namely PjBL and PbBL, and being obtained from independence of observations. The large-sample formulae for Mann–Whitney U test are same as those given in Equation (2).

4. Results and Discussion

Figure 6 shows a sample of the hydraulic arm robot designed and fabricated by the students to address the complex engineering problem explained in Section 3.1. The focus of this research was not on the build complexity, but rather on the design complexity, therefore aiming at concepts such as pressure transfer in the hydraulic system and advance concepts of kinematics. However, for the initial prototype testing, the control of hydraulics was kept simple. As compared to similar work in literature [54,55], the current approach focused on coupling two different courses with robotics, thereby improving the sustainability and increasing the outcomes for multiple courses unlike previous research that focused on a single course only.

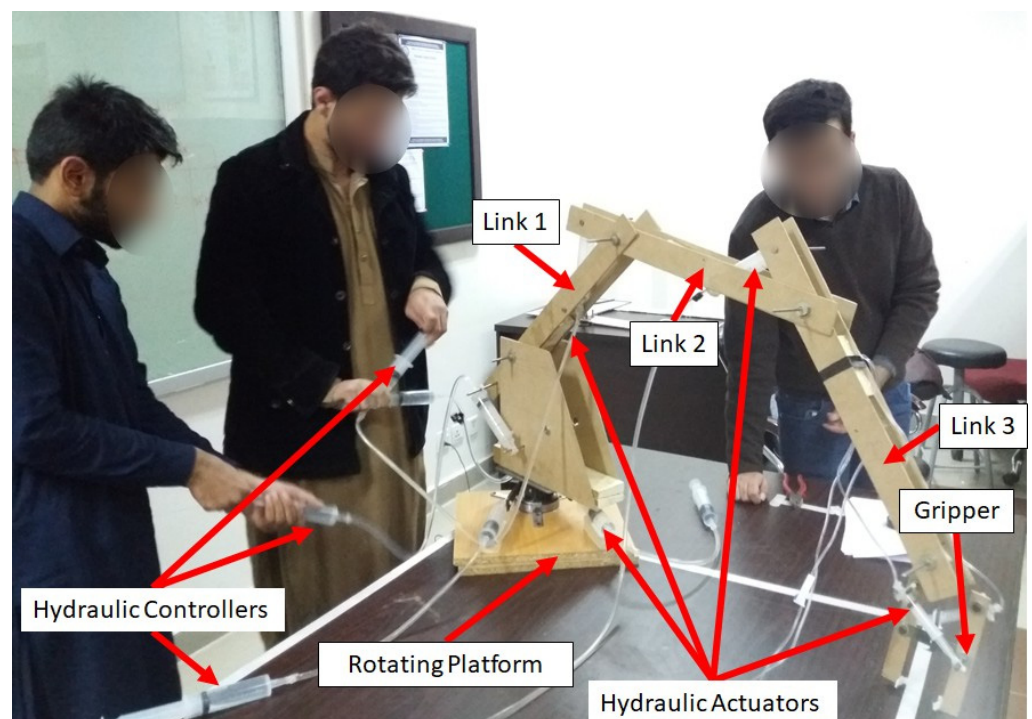


Figure 6. Demonstration of hydraulic robot arm by the students.

The results of each of the analyses are discussed under their following respective heading.

4.1. Statistical Analysis of the Student Feedback Questionnaire

Figure 7 illustrates the comparison of the percentage rating of overall student responses for each of the four robotics-inspired transdisciplinary education learning outcomes complex engineering PjBL project. The results reveal that the percentage rating of student responses for all the outcomes was approximately the same; in particular, the rating for outcome C was the highest. Hence, the results illustrated by Figure 7 establish the viability of robotics-inspired transdisciplinary education as a viable means to advance PjBL for undergraduate engineering education.

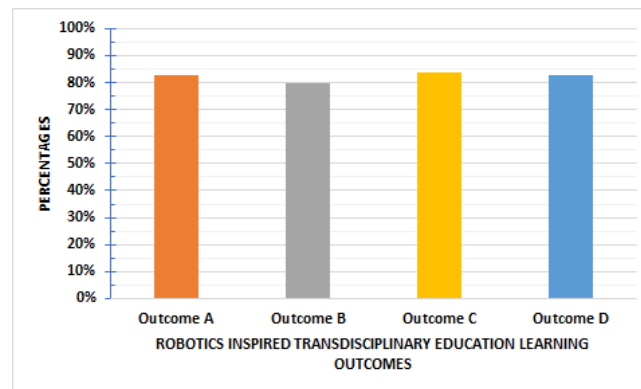


Figure 7. Student feedback questionnaire response evaluation for achieving.

The Chi-square test was conducted at a 95% confidence level for differences in the proportion of student feedback for different categories of responses pertaining to each of the transdisciplinary outcomes. Table 2 outlines the Chi-square test results for each of the robotics-inspired transdisciplinary education learning outcomes.

Table 2. Chi-square hypothesis testing results for robotics-inspired transdisciplinary PjBL.

Variable	χ^2 Value	<i>p</i> -Value
Outcome A	130.83	2.59×10^{-27}
Outcome B	150.73	1.42×10^{-31}
Outcome C	105.19	7.72×10^{-22}
Outcome D	129.74	4.42×10^{-27}

Furthermore, Figures 8–11 establish the effectiveness of PjBL in achieving the robotics inspired transdisciplinary education learning outcomes with an overall student response rating of “good” from “poor”, “satisfactory”, “neutral”, “good”, and “excellent”.

4.2. Statistical Analysis of Project-Based Learning Compared to Problem-Based Learning

The Mann–Whitney U test was conducted at a 95% confidence level for differences in the student scores for PjBL and PbBL. The scores of students for PjBL (median = 86.0) were higher than those for PbBL (median = 65.5). A Mann–Whitney U test indicated that this difference was statistically significant, $U(N_{PjBL} = 101, N_{PbBL} = 101) = 192.00, z = -11.826, p < 0.05$. Hence, the null hypothesis was rejected in favor of the alternate hypothesis. This means that the overall student learning performance in the PjBL was greater than that in PbBL, as indicated in Figure 12.

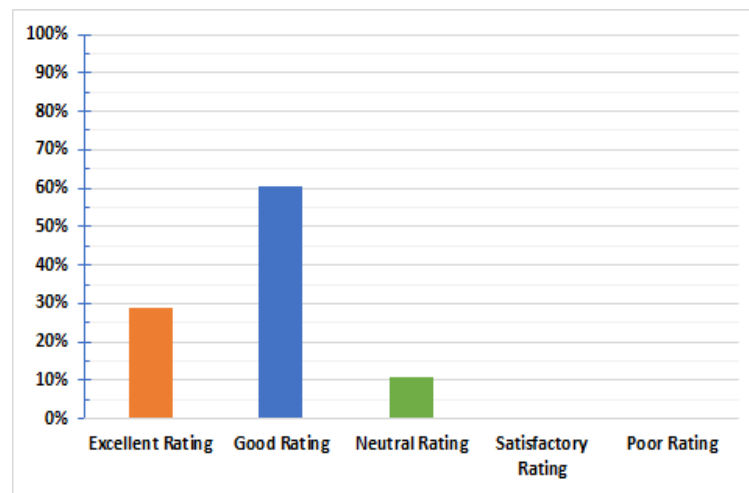


Figure 8. Student feedback for robotics-inspired transdisciplinary education learning outcome A.

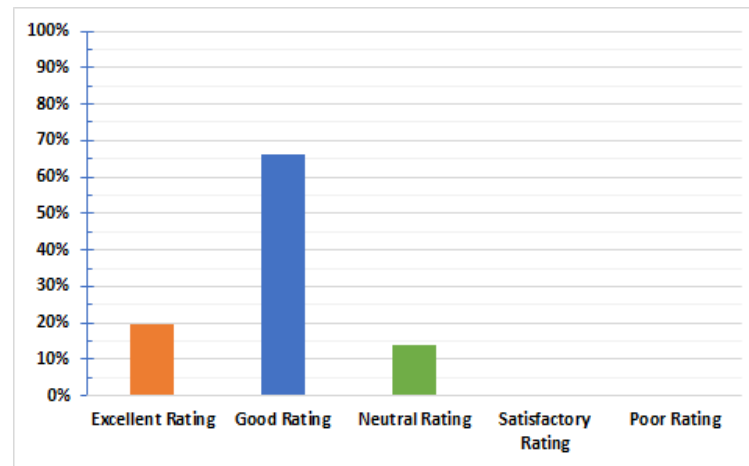


Figure 9. Student feedback for robotics-inspired transdisciplinary education learning outcome B.

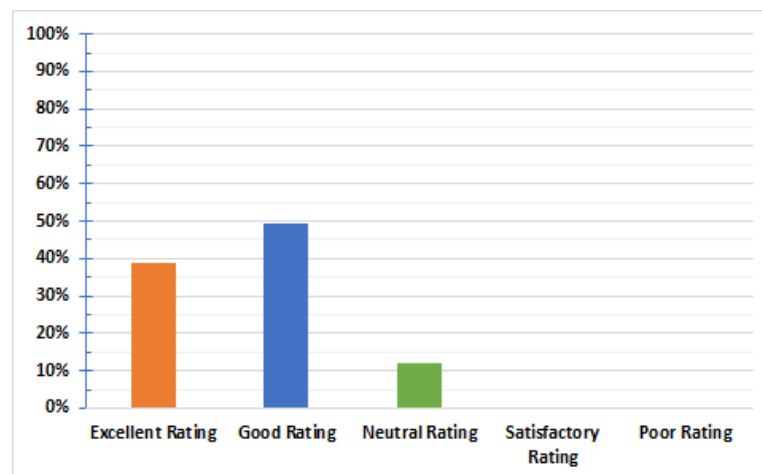


Figure 10. Student feedback for robotics-inspired transdisciplinary education learning outcome C.



Figure 11. Student feedback for robotics-inspired transdisciplinary education learning outcome D.

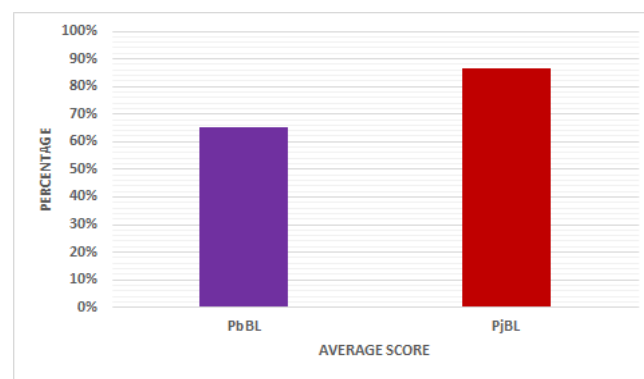


Figure 12. Comparison of average student scores in PjBL and PbBL contexts.

4.3. Statistical Analysis of the Impact of Student Residential Status on Project-Based Learning and Problem-Based Learning

The Mann–Whitney U test was conducted at a 95% confidence level for differences in the student scores based on students' residential status, boarder or day scholar, for both the PjBL and PbBL contexts. The scores of boarder students (median = 86.0) were higher than those for day scholar students (median = 88). A Mann–Whitney U test indicated that this difference was not statistically significant, $U(N_{Boarders} = 76, N_{Day\ Scholars} = 25) = 1133.50$, $z = 1.453$, $p > 0.05$. Hence, the null hypothesis was retained and the alternate hypothesis was rejected. This means that the overall student learning performance in PjBL was not affected by their residential status. For PbBL, the scores of boarder students (median = 65.7) were higher than those for day scholar students (median = 65.5). A Mann–Whitney U test indicated that this difference was not statistically significant, $U(N_{Boarders} = 76, N_{Day\ Scholars} = 25) = 948.5$, $z = -0.12$, $p > 0.05$. Hence, the null hypothesis was retained and the alternate hypothesis was rejected. This means that the overall student learning performance in PbBL was not affected by their residential status.

5. Conclusions

This paper introduced a novel variant of project-based learning called robotics-inspired transdisciplinary project-based learning abbreviated as robotics-inspired transdisciplinary PjBL. The investigation of the effectiveness of this variant in imparting engineering knowledge to a total of 101 undergraduate students was conducted through the complex engineering project problem of the design and fabrication of a hydraulic robot arm along with associated numerical problems for fluid mechanics spanning an entire semester. The robotics-inspired transdisciplinary dimension of robotics-inspired transdisciplinary PjBL was evaluated through the student response to feedback questionnaires mapping the

robotics-inspired transdisciplinary education learning outcomes, which in turn was subject to statistical hypothesis testing at 95% confidence level.

The study reinforced the effectiveness of PjBL as compared to PbBL in terms of student learning performance. It also indicated that students' scores in PbBL and PjBL were independent of their residential status: boarder or day scholar. Furthermore, it established the effectiveness of PjBL in achieving the robotics-inspired transdisciplinary education learning outcomes with an overall student response rating of "good" from "poor", "satisfactory", "neutral", "good", and "excellent".

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