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An Investigation of the Effectiveness of Project Based Learning on Students' Skills in Engineering Modeling and Design Courses

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Abstract

Ability to model and design engineering systems is an important outcome of engineering education. Within the undergraduate engineering curriculum, the students pursue project-based learning (PBL) especially in courses involving modeling and design of engineering systems. The students undertake various stages of engineering system design including problem definition, background research, requirement specifications, brainstorming to choose a solution, prototyping, design review, and communicating outcomes. Students also get a chance to work in diverse teams and learn to work across gender and other boundaries. To measure effectiveness of the PBL approach, there is a need to identify critical skills that should be focused during the modeling and design education. We have collected data from undergraduate junior-standing engineering modeling and design students at our university through a longitudinal study spanning the last three years. The statistical analysis has helped us identify important factors that can influence success of students in their future engineering careers. These include problem solving, communication, and logical thinking skills, perception of self-efficacy to develop students' self-belief, and their course grades. The purpose of present work is to examine the effect of PBL activities on engineering students' grades and self-efficacy. Furthermore, we investigate whether there is a difference between students' course grades based on their gender after engaging in PBL activities. Finally, we also examine the relationship between students' course grades and their problem solving, communication and logical thinking skills after engaging in PBL activities. The results indicate that PBL approach significantly improves the self-efficacy and course grades of students. The PBL methodology was equally effective in improving student learning outcomes of both male and female engineering students. Significant improvement was observed in self-efficacy and course grades of both male and female students when the PBL strategy was employed. We also observed statistically significant difference between students' problem solving, communication and logical thinking skills before and after engaging in PBL activities.

Introduction

The practice of modern engineering profession is built on constantly dealing with decision making based on inadequate data from unreliable sources, ambiguity and continuous shifting of the project objectives, and challenging demands from all stake holders including government agencies, interest groups and general public. Many research studies have been based on data collected from industries to determinethe hands-on technical and inter-personal skills required of engineers(e.g. [1], [2]). Analysis of data has highlighted some key shortcomings of engineering students with respect to requirements of professional careers. Areas for improvement include communication and teamwork skills, awareness of ethical, social, environmental and economic issues, and application of fundamental engineering knowledge to model and design complex engineering systems. These findings have had a major impact on the revision of national accreditation criteria for engineering programs [3]. The engineering education paradigm has shifted to not being "what is taught" to "what is being learnt"through program educational objectives and student learning outcomes [4]. These developments in industry needs and accreditation criteria have necessitated the need of changing the focus of delivery of engineering education to more hands-on student-centered teaching and learning methodologies in contrast with mostly static and one-way lecture-based teaching.

Engineering Design and Project Based Learning

The primary goal of engineering curriculum is to prepare future engineers for modeling, designing, constructing, and maintaining engineering systems to meet the growing demands of society. Engineering education is focused on developing a thorough understanding of fundamental principles of engineering design: need analysis, specification development, modeling and simulation, prototyping, testing and validation, and design review and updating. In the face of these challenges, however, the principal model of engineering education is still based on decades old practice of one-way communication through lecture-based teaching, the so called "chalk and talk" [5]. The early year engineering classes are also typically large and single-discipline and, therefore, students lack personal attention from the faculty.The student-centered pedagogical approaches such as PBL, problem based learning and experiential learning have been adopted by education based disciplines (such as K-12 teacher training). However, these have had relatively low impact on changing the traditional model of engineering education.

ABET has amply highlighted the goals of engineering education with respect to preparedness of future engineers through student learning outcomes specified under Criterion 3 [3]. The key competencies for future engineers emerging from ABET learning outcomes include complex engineering problem solving, engineering design, communication skills, teamwork, data analysis, and application of new knowledge. To develop these competencies in future engineers, engineering curriculum needs to develop hands-on skills. These skills play a very important role in their success to meet the technological challenges in their engineering careers to solve complex engineering challenges and undertake engineering design related activities.

Many of the activities undertaken by engineers in their professional work are related to projects that involve working for a client within the constraints of strict specifications, varying complexity, and controlled time lines. The projects can be multidisciplinary involving teams of specialists from diverse backgrounds. To successfully achieve the goals of a project, engineers need to integrate knowledge and skills gained from the engineering curriculum. The project experience during undergraduate curriculum provides engineering students an opportunity to go over tasks that are similar to professional reality. Project work also involves application of new and existing knowledge, time and resource management, and self-direction. The PBL can be part of individual courses where it can be combined with more traditional teaching methods [6].

There has been growing need to understand and measure effectiveness of existing teaching approaches in engineering education and resulting student learning. Traditional assessment methods of engineering education include exams, quizzes, and homework assignments. These are aimed at measuring development of skills in students through more traditional methods of content delivery. However, important elements of success for future engineers are their self-belief and resolve to utilize the skills they learn during courses, laboratories, and projects through the curriculum. An important element of measuring effectiveness of engineering education, therefore, is to assess the impact of content delivery methodologies on the resolve and self-belief of the students as they progress through various courses during the curriculum [7].

A very important subject in undergraduate engineering curriculum is engineering modeling and design. Success in engineering career largely depends on thorough understanding of engineering design process from problem definition to prototype development, dissemination of results, and design review.The engineering modeling and design curriculum, therefore, needs to include hands-on PBL activities for students that provide solid grounding in engineering fundamentals. Going through the curriculum, students also gain experience of working collaboratively as a team to undertake and solve complex engineering problems.

To measure the effectiveness of engineering modeling and design curriculum, it is important to determine the self-efficacy of students. The aim is to enable students to go through hands-on PBL activities during the curriculum to develop self-belief and optimism in their competence to accomplish tasks and produce expected results. In an earlier work on this subject, authors have proposed an instrument to measure student's perception of self-efficacy in engineering modeling and design courses [8-10]. The developed instrument was used to conduct pre and post course surveys of students in engineering modeling and design courses at our school to collect data for analysis. The analysis helped authors to draw conclusions to improve pedagogy in the course.

Self-Efficacy Construct

The self-efficacy construct referred to in this paper is based on Bandura's Social Cognitive Theory [11-13]. Bandura defines self-efficacy as “the belief in one’s capabilities to organize and execute the courses of action required to produce given attainments” [12]. These beliefs affect the way people make choices, the efforts they put into completing assigned tasks, their will and resolve when difficulties arise, and their skills to cope with difficult situations. An important argument in Bandura’s construct is that self-efficacy is not about the number of skills people possess but what they can accomplish with those skills under different situations. Bandura also identified cognitive, motivational, affective and selection processes that contribute to the development of self-efficacy beliefs [13]. The self-efficacy construct is very important in the context of PBL based engineering modeling and design courses. As the students successfully go through the experience of following engineering design process, they acquire necessary skills and competencies and develop a self-belief to perform with the acquired skills [14].

Preferred Learning Styles

The concept of learning style describes differences in learning based on student’s preference for employing different phases of the learning cycle. According to Gardner multiple intelligences theory (2011), students have different preferred learning styles and they have different approaches or ways of learning. Students’ preferred learning styles was defined in the literature as the way individuals seek to extract, process, and memorize information [15]. The educational literature identified types of learning styles as visual learners, auditory learners, kinesthetic learners, and tactile/kinesthetic learners. According to prior studies, different students have different perceptual learning styles or different sensor preferences for processing information.

Several studies examined the relationships between learning styles, motivation, teaching techniques, delivery modes and online learning environments [16, 17]. For example, many studies examined the relationship between students’ learning styles and academic work. Terrell and Dringus [18] investigated graduate students in information science major in an online course using the Kolb Learning Style Inventory [19]. The study found that most students can succeed in an online learning environment regardless of their learning style. Simpson and Du [20] used the Kolb learning style inventory to examine the effect of students' learning styles on their online participation and the level of satisfaction in distributed learning environments. The results indicated that learning style had a significant impact on the students' participation and students' satisfaction level. Based on these and similar findings, many researchers have noted that it is important to identify student learning styles and adopt course design to accommodate these styles. For example, Michalski [21] addresses students' learning styles in online learning environment and how to develop materials to accommodate different learning styles. The results suggested that before develop learning materials; instructors must know who their students learn and their learning styles. Other studies investigated the relationship between learning style and preference for delivery mode such as learning through classroom, computer, video, print, or audio-based delivery modes. For example, Buch and Bartley [22] examined learning style and delivery mode and found stronger preference for computer-based delivery and assimilators as well as an overall preference for classroom-based delivery, regardless of their learning style.

Purpose of the Study

The purpose of this study is to investigate the effectiveness of PBL methodology on students' skills in Engineering Modeling and Design with focus on understanding and analyzing the impact of PBL approach on their self-confidence and resolve to apply the skills that they learn during the course and their academic grades. Furthermore, this study investigates whether there is a difference between students' course scores based on their gender after engaging in PBL activities. Finally, we examine the relationship between students' course grade and their problem solving, communication and logical thinking skills after engaging in PBL activities during engineering modeling and design course.

Our study employed a within-subjects design to assess the impact of PBL on students in engineering modeling and design courses with respect to their course grades, self-efficacy, and other essential skills. The participants were 95 undergraduate third year engineering students enrolled in Engineering Modeling and Design Course during 2017- 2019 academic years. This is the first course focused on engineering modeling and design within the engineering curriculum and is offered in the first semester of the third year. This course is followed by a two-credit course on engineering design during the second semester of junior year. The students then undertake a senior design project during their senior year. The course covers topics on reduction of engineering systems to mathematical models; methods of analysis using MATLAB and Simulink; interpretation of numerical results; optimization of design variables, three-dimensional Computer-Aided Design (CAD), and engineering system modeling and design projects. The course is fully hands-on and students'model, simulate, and design complex engineering systems. The students are also divided in groups to undertake projects based on real-world and industry-proposed engineering problems. The examples of engineering systems for the course are drawn from various engineering disciplines. The student learning outcomes for this course corresponding to ABET criterion 3 are given below:

1. Analyze engineering systems through simulation using MATLAB as programming language.
2. Construct an engineering system model through analysis of data.
3. Demonstrate competency in advanced plotting of engineering system responses in two and three dimensions.
4. Evaluate engineering systems through statistical analysis of the data and apply probability and interpolation techniques during the analysis.
5. Demonstrate proficiency in solving system models in differential equation form and related calculus problems using numerical analysis techniques.
6. Construct engineering system models and simulate their response with Simulink.
7. Design and construct basic engineering systems using CAD software.

The topics covered during the course are designed with a goal to achieve the student learning outcomes. Essential elements of engineering design process are emphasized during the course through hands-on learning activities and projects.

Research Questions and Methodology

Given the prior research regarding the use of project-based learning as a teaching strategy, this study will be guided by the following questions:

1. Is there a correlation between students' course grade and their self-efficacy after they engage in PBL activities in engineering modeling and design courses?
2. Do PBL activities affect students' course grades differently based on their gender?
3. What is the impact ofPBL activities in engineering modeling and design courses on students' problem-solving, communication and logical thinking skills?

The present study employed a within-subject design with students enrolled in engineering modeling and design courses. It has four variables, including three independent variables. The dependent variable is students' self-efficacy. The independent variables arelogical thinking, communication, and problem-solving skills. The learning materials used in this experiment were project-based class activities designed to engage students in engineering modeling and designprocess. The instrumentations consisted of surveys to determine students' demographics and perception of their self-efficacy.

- The demographic survey was used to collect information about the participants such as gender, age range, years in college, major, ethnicity, learning style preference, comfort with computer, confidence in use of technology, and GPA range. The learning style preferences included Lectures/Discussions, Books/Related Written Material, Video/Movies/Media, Hands-on activities, Collaborative Group Work, and a Mixed method between some or all of the above

- The study survey consists of 20-questions about students' self-efficacy about their ability to perform a specific task at a designated level [12]. This survey was used twice during the semester (first week and the last week). The instrument was designed in accordance with Bandura's guidelines for constructing self-efficacy scales. As the self-efficacy is concerned with "perceived capability", the items contained in the instrument are phrased in terms of "can do" rather than "will do". The questions ask students how confident they are in their belief that they had developed certain ability and can be answered using an 11-point Likert scale to achieve greater variance in the collected data. The scale ranges between "Cannot do at all" at zero to "Highly certain can do" at 10. The questions are primarily directed at three higher order factors: (a) Logical thinking skills (e.g., develop a statistical model of an engineering process, analyze data with a modeling and simulation software); (b) Communication skills (e.g., effectively communicate to wider audience through verbal, and written communication about engineering design process) and (c) Problem Solving skills (e.g., work well with hands, think practically to find a solution to an engineering problem).

Students complete demographic and self-efficacy surveys at the beginning of the semester. Students then attend 14-weeks class activities in engineering modeling and design such as transforming an analytical model into working code to run on a simulation software, building statistical model of an engineering process, develop test methods to check if a prototype meets the specifications, and operate engineering tools and common workshop machinery. At the end of the semester, students complete a self-efficacy survey again.

For analysis, the collected data was screened for univariate outliers or missing values. Four missing values were identified due to dropping the course after few weeks and recoded as missing data. The minimum amount of data for factor analysis was satisfied, with a final sample size of 83 (using list wise deletion), providing a ratio of over 27 cases per variable following the rule of 10, where it should be at least a minimum of 10 cases for each item in the instrument being used [23-28]. The demographic descriptive statistics are given in Table I. Data from self-efficacy survey was analyzed using Statistical Package for the Social Sciences (SPSS).

Table I: Demographics Descriptive Statistics

Descriptive Statistics				
	N	Sum	Mean	Std. Deviation
Gender	95	104	1.09	.294
Age	95	154	1.62	.913
Years in College	95	309	3.25	.505
Major	96	188	1.96	1.297
Race	96	453	4.72	1.093
Learning Styles	92	395	4.29	1.580
Computer	92	320	3.48	.654
Technology	91	311	3.42	.700
GPA	96	472	4.92	2.081
Course Grade	89	6712	75.42	14.022

Data Analysis and Results

Question 1:

Is there a correlation between students' course grade and their self-efficacy after they engage in PBL activities in engineering modeling and design courses?

To answer this question, we conducted a Pearson correlation coefficient (PCC) to assess the relationship between students' course grades and their self-efficacy after engaging in PBL activities. The PCC measures association between variables of interest and is based on the method of covariance. The calculation of PCC gives numerical results that describe magnitude of the association, or correlation, as well as the direction of the relationship.The analysis shows that there was a strong and positive relationship between students' course grade (M = 75.42 SD = 14.02) and their self-efficacy (M = 1611.46, SD = 232.352), r = .336, p = < .001, n = 89. The PBL improved their self-efficacy as well as there was marked improvement in their course grades. Tables II and III summarize the correlation results.

Table II: Descriptive Statistics

Descriptive Statistics			
	Mean	Std. Deviation	N
Course Grade	75.42	14.022	89
Self-efficacy	1611.46	232.352	89

Table III: Pearson Correlation - Results

Correlations			
		Course Grade	Self-efficacy
Course Grade	Pearson Correlation	1	.336**
	Sig. (2-tailed)		.001
	Sum of Squares and Cross-products	17301.618	96305.955
	Covariance	196.609	1094.386
	N	89	89
Self-efficacy	Pearson Correlation	.336**	1
	Sig. (2-tailed)	.001	
	Sum of Squares and Cross-products	96305.955	4750910.112
	Covariance	1094.386	53987.615
	N	89	89
**. Correlation is significant at the 0.01 level (2-tailed).			

Question 2:

Do PBL activities affect students' course grades differently based on their gender?

To answer this question, we conducted a one-way between subjects' Analysis of Variance (ANOVA) to compare the effect of PBL activities on students' course grades based on difference in their gender. We selected one-way ANOVA to compare two means from two independent (unrelated) groups (male and female) using the F-distribution. This is based on null hypothesis that the two means are equal. A significant result indicates that the two means are unequal. Our analysis showed that there was no difference between male and female course grades after they engaged in PBL. The statistical analysis resulted in a confidence level of $p<.05$ between male and female [F (1, 86) = 2.983, p = 0.05]. Taken together, these results suggest that students' course grades improved for both male and female students equally when they engaged in PBL. Tables IV to VI summarize the one-way between subject's ANOVA.

Table IV: Descriptive Statistics – One-Way ANOVA

Descriptive										
Course Grade										
						95% Confidence Interval for Mean				
		N	Mean	Std. Deviation	Std. Error	Lower Bound	Upper Bound	Minimum	Maximum	Between-Component Variance
Male		81	76.38	13.941	1.549	73.30	79.47	48	100	
Female		7	67.00	11.576	4.375	56.29	77.71	53	85	
Total		88	75.64	13.946	1.487	72.68	78.59	48	100	
Model	Fixed Effects			13.790	1.470	72.71	78.56			
	Random Effects				5.209	9.45	141.83			29.262

Table V: Test of Homogeneity - Results

Test of Homogeneity of Variances			
Course Grade			
Levene Statistic	df1	df2	Sig.
.592	1	86	.444

Table VI: One-Way ANOVA - Results

ANOVA							
Course Grades							
			Sum of Squares	df	Mean Square	F	Sig.
Between Groups	(Combined)		567.228	1	567.228	2.983	.088
	Linear Term	Unweighted	567.228	1	567.228	2.983	.088
		Weighted	567.228	1	567.228	2.983	.088
Within Groups			16353.136	86	190.153		
Total			16920.364	87			

Question 3

What is the impact of PBL activities in engineering modeling and design courses on students' problem-solving, communication and logical thinking skills?

To answer this question, we conducted paired samples t-test to compare students' mean of self-efficacy before and after they engaged in PBL activities. The focus of analysis was on students' problem solving, communication and logical thinking skills. The paired samples t-test was chosen as it compares two means from the same variable. The goal was to determine whether there was statistical evidence to show that the mean difference between paired observations on self-efficacy before and after PBL was significantly different from zero.

Results show that mean self-efficacy before (M = 1303.22, SD = 288.329) and after PBL (M = 1621.95, SD = 224.234) was at the .001 level of significance (t = -13.225, df = 86, n = 89, p < .001, 95% CI, Paired Samples Correlations r = .64). On average, the improvement in the students' self-efficacy was large after they engaged in PBL activities. As displayed in the following Tables, there are statistically significant differences, at the .001 significance level, before and after they engaged in PBL. Tables VII - IX summarize results from paired-samples t-tests performed for the same groups of participants.

Table VII: Paired Samples t-Tests - Statistics

Paired Samples Statistics					
		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	Self-efficacy before	1303.22	87	288.329	30.912
	Self-efficacy after	1621.95	87	224.234	24.040
Pair 2	Logical thinking skills Before	569.54	87	119.231	12.783
	Logical thinking skills After	655.86	87	91.899	9.853
Pair 3	Communication skills Before	429.08	87	152.656	16.366
	Communication skills After	618.85	87	108.900	11.675
Pair 4	Problem solving skills Before	304.16	89	64.523	6.839
	Problem solving skills After	334.38	89	52.396	5.554

Table VIII: Paired Samples Correlations

Paired Samples Correlations				
		N	Correlation	Sig.
Pair 1	Self-efficacy before, Self-efficacy after	87	.641	.000
Pair 2	Logical thinking skills Before and After	87	.517	.000
Pair 3	Communication skills Before and After	87	.516	.000
Pair 4	Problem solving skills Before and After	89	.507	.000

Conclusion

This paper presents our findings from a longitudinal study to investigate the effectiveness of PBL methodology on course grades and self-efficacy of students in engineering modeling and design courses. The data was also used to determine if there was any significant difference in the impact of PBL based on gender of students. The effect of PBL on logical thinking, communication and problem-solving skills of students was also investigated. This subject is very important for engineering students, as thorough understanding of engineering design process is essential for success in engineering career. The study has helped us identify key factors affecting student performance that include logical thinking skills, communication abilities, and problem-solving skills. Statistical analysis was done to answer the research questions. Results indicate that the PBL improved students' course grades and self-efficacy significantly. Analysis also indicates that PBL strategy was equally effective for both male and female students. The problem solving, logical thinking, and communication skills of students also significantly improved as they followed PBL methodology during the course. The data has helped us learn students' preferred learning styles. Majority of the students liked PBL approach which was followed throughout the course. The results have helped us improve the pedagogy of the course to achieve ABET student learning outcomes. We plan to continue this study in the coming semesters to collect more data, and analyze it to identify particular hands-on activities that can significantly impact course grades, self-efficacy, and engineering and professional skills of students.

Table IX: Paired Samples t-Test - Results

Paired Samples Test									
		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	Self-efficacy before, and after	-318.736	224.804	24.101	-366.648	-270.823	-13.225	86	.000
Pair 2	Logical thinking skills before and after	-86.322	106.445	11.412	-109.008	-63.635	-7.564	86	.000
Pair 3	Communication skills before and after	-189.770	134.190	14.387	-218.370	-161.170	-13.191	86	.000
Pair 4	Problem solving skills before and after	-30.225	58.987	6.253	-42.651	-17.799	-4.834	88	.000

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