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Discovery-based approach combined with active learning to improve student learning experiences for STEM students

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Abstract

A combination of discovery-based learning (as a novel instructional approach) and Pro-Con Grids (as an active learning activity) is used to improve long-term retention among STEM students. Students in a required Construction Management course were provided with a course lecture prior to in-class sessions. A quiz was used for each lecture to gain insight into students' understanding and to evaluate the effectiveness of the learning method. During the in-class sessions, a blank sheet of paper was handed out to students to make a list of the pros and cons/advantages and disadvantages of the topics covered in the lecture. Once the pro-con grid was complete, the students were directed to share their documents with the instructor. This was followed by a summary of key concepts and then a review of the correct answers. Data was collected for this study in two forms; through a student survey and grades. The results showed that discovery-based learning could convince students to find and use information rather than memorizing and repeating concepts and facilitate effective group work. In addition, the grade comparisons for three semesters indicated that the higher the use of discovery learning during the course the higher the course grades were found to be.

Keywords: *Discovery-Based Learning, Pro-Con Grids, STEM, Construction Management, Problem Solving*

A. Introduction

The National Academies of Sciences, Engineering, and Medicine, also known as NASEM or the National Academies are private, nonprofit institutions in the United States that provide independently researched information on vital matters in science and health policy. A recent National Academies report notes that more than 50 percent of students who complete a science, technology, engineering, and math (STEM) bachelor's degree switch to jobs or graduate programs outside of STEM (NASEM 2021). Such STEM students frequently decide to major in non-STEM programs after STEM introductory courses, perhaps in response to the teaching methods and atmosphere they encountered in STEM classes. Many students abandon their goal of earning a STEM degree due to how STEM courses are taught, compounded by the struggle to find the additional support for tutoring they need. STEM students are expected to learn a large amount of information and concepts, but long-term retention of this information is a substantial challenge. For example, understanding the composition and production of materials can be challenging for many construction management students because it is difficult to predict the properties of construction materials based on the jobsite condition (temperature, volume,

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delivery method, etc.). Thus, students studying Construction Management try to use rote memorization tools that worked for them in secondary school, but there is too much information for memorization to effectively be a learning tool. Such methods are associated with poor long-term recall and poor performance on design questions and field activities (Torres et al. 2019). Recall is deemed the lowest order of Bloom's Taxonomy for cognitive process thus doing a disservice to the students (Jensen et al. 2014). A combination of discovery-based learning (as a novel instructional approach) and Pro-Con Grids (as an active learning activity) would promote long-term retention of knowledge of concrete design and production.

Thibaut et al. (2018) reviewed relevant studies describing learning and teaching in secondary education and found nine categories of discovery based instructional practices to be more effective learning tools. These are the integration of STEM content, focus on problems, inquiry, design, teamwork, student-centered, hands-on, assessment and 21st century skills. Strategies focusing on discovery based and active learning instructional practices result in greater student success. STEM students who exchange information when solving the problems (Anazifa & Djukri 2017) have control of learning through hands-on exploration (Jambunathan et al. 2021) and have the opportunity to learn in groups through the use of social interactions (Purmawanti et al. 2020), result in significant improvement in learning and retention of knowledge (Biggs & Tang 2011). Incorporating active learning strategies into class sessions can potentially improve long-term retention. Working in groups is just one example of many active learning strategies that help students make meaningful connections to course concepts (Gasiewski et al. 2012). In the construction industry working in groups to complete projects is the norm and it is obvious that group learning is superior to individual learning (Gunderson & Moore 2008). Arguably, the main advantage is that students can apply concepts, solve problems, and generally engage cognitively with course content with the support of peers.

A review of discovery-based learning in STEM education, to be discussed in the next section, indicates numerous benefits students notice while applying discovery learning. However, current literature contains few examples or studies where an entire subject has been taught using discovery learning techniques. Even with the many benefits, studies in literature explain how discovery-based learning is not perfect. A few drawbacks associated with discovery-based learning are student confusion, particularly with unguided learning, lack of measurable performance, and insufficient scaffolding. Unlike in the real world, students in higher education are first provided with instruction and then a problem. Undoubtedly, direct instructions such as readings and lectures can prepare students for the real world. The problem occurs when students become accustomed to learning, working with thorough instruction, and relying on their teachers (Hurst 2015). The research question guiding this study is "how discovery-based learning can improve students' problem-solving skills compared to the conventional lecture/lab model. After reviewing relevant literature in the following section, the experimental section provides details of the methods and procedures used to answer this research question.

B. Literature Review

Inquiry-based learning is an educational strategy where students construct their own knowledge through exploration, investigation, and collaboration with their peers (Pedaste et al. 2015). Lai (2018) used an inquiry-based teaching model to explore college students' academic performances in STEM courses and observed that the students created excellent works and achieved good results in a professional competition. Deak et al. (2021) analyzed the recently developed novel pedagogy models with inquiry-based learning and post-pandemic scenarios and identified some discoveries in the learning of subjects. Inquiry-based learning can be either information- or discovery-focused, whether on discovery or information acquisition. Discovery learning hinges on the assumption that students do not necessarily acquire knowledge passively; instead, they build new knowledge by exploring new information into their pre-existing knowledge.

Discovery-based learning is typically associated with teachers' passive or facilitator role but with students' active participation in their learning with the aid of hands-on activities (student-centered participation with inquiry-based activities). Dorier and Garcia (2013) identified favorable conditions and limiting constraints for implementing discovery-based learning in the educational systems: a) teacher engagement by providing guidance and direction for achieving learning objectives but building upon students' reasoning and connecting to their experiences. b) Classroom culture where there is a shared sense of purpose between teacher and students, type of materials available for the class that supports discovery-based learning where it is missing, or to highlight and reinforce already-existing material. c) Students are encouraged to ask questions, inquire through exploration, and collaborate with teachers and peers.

The discovery learning model boosts students' mathematical problem-solving ability when they find and develop their own concept of understanding the material (Herdiana et al. 2017). Discovery-focused inquiries arguably create a better learning environment relevant to innovation rather than information-focused inquiries because they emphasize generating new ideas and creating something original rather than exploring and acquiring existing knowledge (Acar & Tuncdogan 2019). Discovery-based learning means having an experience where the students are actively engaged in their learning process by exploring solutions or performing experiments to solve problems. Purwaningsih et al. (2020) investigated the effect of discovery learning on students' problem-solving abilities in STEM. The results showed a significant difference in students' problem-solving ability scores in the experimental class, where students studied with discovery learning and the comparison class. Kansas State University (KSU) created a summer program aimed at under-represented minority community college students enrolled in STEM fields to recruit them into research opportunities (Betz et al. 2021). Hands-on, discovery-based activities were used to help students develop a strong self-identity in STEM and strengthen their self-efficacy. The KSU survey results showed that the program was successful at improving STEM identity and academic self-concepts. Qualitative feedback suggested that the program could increase interest and self-confidence in STEM majors.

A drawback of the discovery-based learning pedagogies is that there is no strong focus on how a student's learning can or would impact others in the classroom or beyond (Pearson et al. 2019). Once the students have limited amounts of existing knowledge to integrate additional information, the use of this novel instructional approach can lead to minimal learning. Lechelt (2020) suggested designing situated prompts to provide students with guidance for what to explore in a discovery task and also use explicit strategies to step out of an immersive, hands-on activity to reflect on what they are learning. Gutiérrez et al. (2022) argued that discovery-based learning could be very effective in science education when guided instruction is delivered with various instructional techniques and scaffolding support is given to the students, e.g., by showing how to complete the task by an instructor throughout the learning process. "Pro and Con Grids" can also be used with discovery-based learning to allow students to review an issue, create a list of the advantages and disadvantages of an identified problem, and make the appropriate choice by considering the pros and cons. A student example of a pro and con grid is shown in Figure 1 for the lecture explaining the various types of Portland cement.

Type III – High Early Strength Portland Cement	
Pros	Cons
Early compressive strength gains are greater.	Increased quality control is needed
Forms can be removed sooner	Ultimate strength is not higher than ordinary cement
Good for cold weather to reduce the controlled curing period.	Difficult to find in small quantities

Figure 1. A student sample of a pro and con grid

C. Methods

This study focuses on student perceptions of active learning in the classes they take and instructor perceptions in the classes they teach. A survey is administered to all STEM instructor in a teaching-based University in the south United States to understand the challenges they face in STEM education and the frequency and importance of curriculum development and instructional strategies to promote content understanding, and retention among all students. The focus is on the college of science and engineering technology within the university that consists of eight departments (see Table 2 for more details about the respondents and their department). The survey is divided into the following sub-questions: (1) Challenges in STEM Education, (2) Curriculum Development and Instructional strategies, and (3) Shifts from Science to Equity to Justice. Note that only the second sub-question is used for the present study. The insights gained from the survey led to the development of active learning instructional strategies for a required course in Construction Management.

Table 1. Demographic makeup of the respondents to the survey

Department	% Respondents (n= 32)	Department	% Respondents (n= 32)
Agricultural Science	4/23 = 17%	Biological Science	2/26 = 7%
Chemistry	5/17 = 29%	Computer Science	1/17 = 6%
Engineering Technology	8/24 = 33%	Environ. & Geosciences	4/15 = 27%
Mathematics & Statistics	7/35 = 20%	Physics & Astronomy	1/10 = 10%

The class involved in this study is a required course for Bachelor of Science (BS) students in Construction Management. The Construction Management program represents around half of the total enrolment of the department that has an enrolment of more than 550 students. The university is a teaching-based public institution with a student population of over 21,000. The class selected for this study is Concrete/Masonry Construction with an average 23 students (with an average of two females (9%) and 21 males (91%)). The class is a lecture/lab course with a 1-hour lecture and 3-hour labs per week. Figure 2 shows the concrete lab area that allows exposure to the machines and hands-on practices typically found in industry.

Figure 2. The concrete lab facility for the selected class

The labs rely on structured groups that engage in specific concrete and masonry activities. The hands-on lab component of the selected class provides a unique opportunity to apply pedagogical strategies such as discovery-based and hands-on learning, where students can be assigned specific roles that operate throughout the semester. The author taught this course twice in the Spring of 2020 and Fall of 2021, and active learning pedagogies were incorporated into the Spring of 2022 class. Most of the students tended to memorize information based on repetition. Although they could quickly recall basic facts, it did not allow for a deeper understanding of subjects. It was also noticed that there was no connection between new and previous knowledge, although students enjoyed the opportunity to do a hands-on project. More learner-centered pedagogical practices were used to make the most of the students' time for face-to-face classroom interactions to make stronger connections between old and new knowledge. The goal was to encourage students to think creatively when solving problems as well as increase their confidence when solving problems.

The university emphasizes hands-on learning in the classroom, allowing students to engage in real-world activities that are similar to the activities that construction manager professionals are often faced with. The author's effort has focused on applying active learning methods as an alternative to "cookbook" procedures. Traditionally, students in Concrete/Masonry Construction were supposed to perform the exact sequence of steps specified by the instructor or the textbook. From the authors' observations, it could be seen that students did not learn when and how to apply these same procedures outside of the classroom. A deeper understanding of concrete construction is needed. Most students were conditioned to wait for the instructor to give them the answer and did not take collaborative inquiry seriously. Based on the body of literature, we compiled a list of recommendations and strategies for improving engagement and fulfilling educational purposes.

Discovery-based learning method provides structures for completing work or products by dividing work among group members. This cooperative instructional approach was chosen for the Concrete/Masonry Construction class because concrete projects can be tackled and completed by groups working collectively. For this study, the students were provided with a course lecture that discussed key characteristics of concrete in a PowerPoint file and an instructional video prior to the active-learning in-class sessions. A short quiz was used for each lecture to gain insight into students' understanding and evaluate the learning method's effectiveness. During the in-class session, a blank sheet of paper was handed out to students to list the pros and cons/advantages and disadvantages of the concrete issues covered in the lecture. The questions are primarily focused on solving a problem, e.g., how to determine the water/cement ratio). Second, each in-class activity would allow students to communicate, collaborate, and think critically. The students were informed about the number of items they expected to list and whether they should use words, phrases, or sentences in their list of pro and con arguments. Once the pro-con grid was complete, students were directed to share their documents with the instructor. This was followed by a summary of key concepts and then a review of the correct answers. The students were encouraged to collaborate with their teammates to create a list of pros and cons.

Data was collected for this study in two forms: through a student survey and grades. All students were given a pre-survey at the beginning of the semester when the study began, and the same survey was given at the end of the semester or the conclusion of the study. The results of the surveys and the students' grades are statistically analyzed to see any statistically significant difference between pre-study and post-study results for the students in the experimental group. The survey was administered via an individual online survey link using the Qualtrics platform. The students enrolled in Spring 2020 and Fall 2021 were taught with the traditional lecture/lab method. The grades for these control groups were also used to measure the instructional approaches' strength by comparing control (Fall 2021 and Spring 2020) and experimental (Spring 2022) groups. Figure 3 shows an example of the concrete project given to the student. For this example, the students were asked to make concrete pavers used in landscaping. They had one week to search for five interlocking concrete pavers available in-home improvement retail stores. In the first 5 minutes of the class session, the students were asked to share their findings with the instructor and then see what they discovered by themselves. Next, students were asked to consider the advantages and disadvantages of using flowing concrete to cast the pavers. It was notified that mistakes were inevitable, so timely feedback was provided to correct them quickly.

Figure 3. An example of the concrete activity for making concrete pavers

D. Findings and Discussion

A total of 32 (19%) educators from the College of Science and Engineering technology responded to the survey. Survey data were downloaded from Qualtrics to Excel and partial responses were removed. Table 2 shows the results of the survey for Curriculum Development and Instructional strategies sub-questions. The participants were asked to use a scale of 1-Not at all important, 2-Low importance, 3-Neutral, 4-Important, 5-Very Important (or Essential) to rate the importance of different aspects of STEM education and a scale of 1-Never, 2-Rarely, 3-Sometimes, 4-Often, 5-Always to rate their frequency in STEM education.

Table 2. Survey results for the STEM educators

Question (Importance)	1	2	3	4	5
Q1- Allow teacher flexibility in modifying curriculum.	6%	13%	19%	44%	19%

Question (Importance)	**1**	**2**	**3**	**4**	**5**
Q2- Allow students to collaboratively apply knowledge within the disciplines of STEM as they develop questions and plan inquiries.	3%	13%	9%	47%	28%
Q3- Recruit students from culturally diverse or underrepresented groups.	16%	19%	28%	22%	16%
Q4- Engage student knowledge through individual testing and group collaboration.	0%	0%	3%	47%	50%
Q5- Use of STEM units of study that promotes real- world applications.	0%	6%	16%	44%	34%
Q6- Exchange of expertise between high school STEM educators and research faculty.	9%	22%	19%	31%	19%
Question (Frequency)	1	2	3	4	5
Q1- Modifying curriculum	13%	16%	25%	28%	19%
Q2- Recruit students from culturally diverse or underrepresented groups.	13%	16%	28%	28%	16%
Q3- How often the learners are provided with opportunities to collaboratively apply knowledge within the disciplines of STEM as they develop questions and plan inquiries.	6%	10%	15%	41%	28%
Q4- How often collaborative projects are arranged for students with working professionals.	19%	22%	28%	22%	9%
Q5- The use of complex real-world problems.	9%	16%	28%	22%	25%
Q6- Participation of high school STEM educators in active research.	16%	28%	28%	16%	13%

Figure 4 better demonstrates the difference between the pre-and post-study surveys. Only one data point is presented for each question. As seen in the questionnaire, we used a Likert scale to quantify the strength/intensity of students' attitudes. Each of the five responses has a numerical value to measure the attitude under investigation. The values are used to create an aggregated or average score for each question to gauge the perspective of the experimental group.

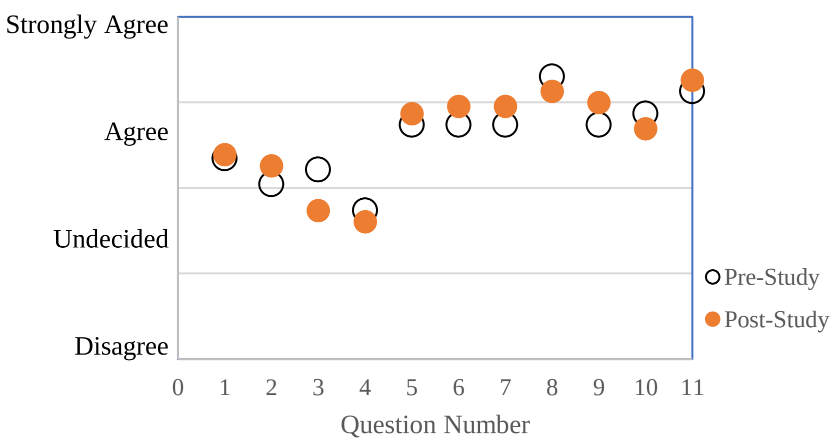

Figure 3. An example of the concrete activity for making concrete pavers

The data supports the national trends in the use of active learning among STEM teachers as in different disciplines they incorporate large amounts of active learning into their instruction.

The other group of surveys was used for the students in the Concrete class. Table 3 shows the results of the pre-and post-study surveys. The first four questions focus on an individual student's ability to solve problems. In questions 5-6, we wanted to see whether students' confidence increases while their dependence on instructors for problem-solving decreases by having them discover ideas and solutions. The last five questions focus on group problem-solving and the effects of various communication behaviors on group problem-solving. As seen in the questionnaire, we used a Likert scale to quantify the strength/intensity of students' attitudes. Each of the five responses has a numerical value to measure the attitude under investigation. The values are used to create an aggregated or average score for each question to gauge the perspective of the experimental group.

Table 3. Survey results for the experimental group (use of discovery-based learning)

Question		**Strongly Agree 5**	**Agree 4**	**Undecided 3**	**Disagree 2**	**Strongly Disagree 1**
1- I feel confident finding the correct type of cement/mix of concrete on my own.	Pre-study	13%	38%	38%	6%	6%
	Post-study	*17%*	*30%*	*35%*	*9%*	*9%*
2- It is easy for me to find a solution to a concrete problem.	Pre-study	6%	38%	38%	13%	6%
	Post-study	*17%*	*30%*	*26%*	*13%*	*13%*
3- I memorize and repeat concepts instead of finding and use information.	Pre-study	6%	44%	31%	13%	5%
	Post-study	*4%*	*26%*	*30%*	*17%*	*22%*
4- I see myself as a problem solver rather than a hands-on person	Pre-study	6%	13%	38%	38%	6%
	Post-study	*4%*	*4%*	*43%*	*43%*	*4%*
5- Finding information about my work/project is an important part of learning	Pre-study	19%	69%	6%	0%	6%
	Post-study	*26%*	*57%*	*4%*	*4%*	*9%*
6- Problem solving is a subject that I am good at.	Pre-study	19%	69%	6%	0%	6%
	Post-study	*35%*	*43%*	*4%*	*17%*	*0%*
7- Working in groups helps me better understand concrete.	Pre-study	19%	69%	6%	0%	6%
	Post-study	*22%*	*65%*	*4%*	*4%*	*4%*
8- I feel like I can help my group plan for a concrete assignment.	Pre-study	44%	50%	0%	0%	6%
	Post-study	*30%*	*57%*	*9%*	*4%*	*0%*
9- If I am struggling with an assignment, it helps to have a classmate explain it to me.	Pre-study	13%	56%	25%	0%	6%
	Post-study	*31%*	*38%*	*31%*	*0%*	*0%*
10- I feel like my opinions and ideas are used in my group.	Pre-study	13%	75%	6%	0%	6%
	Post-study	*17%*	*57%*	*9%*	*13%*	*4%*
11- Creative thinking is necessary for solving/doing a concrete problem/project.	Pre-study	48%	35%	4%	8%	4%
	Post-study	*43%*	*39%*	*17%*	*0%*	*0%*

The survey results before and after using discovery-based learning can be compared to determining whether there are differences and, if so, how significant the difference is. The differences in the collected Likert scale data were considered statistically significant if the p-value for a paired t-test statistic associated with the pair of means is smaller than 0.05. The T-test is conducted for all thirteen questions; the results are shown in Table 4.

Table 4. Paired t-test results for the pre- and post- survey results

Question	Mean		Std. deviation		t	Sig. (2-tailed)
	Pre-Study	Post-Study	Pre-Study	Post-Study		
1- I feel confident finding the correct type of cement/mix of concrete on my own.	3.35	3.39	1.11	1.16	-1.000	0.328
2- It is easy for me to find a solution to a concrete problem.	3.04	3.26	1.11	1.29	-2.472	0.022**
3- I memorize and repeat concepts instead of finding and use information.	3.21	2.74	1.04	1.21	-4.491	<0.001*
4- I see myself as a problem solver rather than a hands-on person	2.74	2.61	0.92	0.84	1.817	0.083**
5- Finding information about my work/project is an important part of learning	3.74	3.89	1.29	1.14	-1.367	0.186
6- Problem solving is a subject that I am good at.	3.74	3.96	1.29	1.06	-1.311	0.203
7- Working in groups helps me better understand concrete.	3.74	3.96	1.29	0.93	1.738	0.096**
8- I feel like I can help my group plan for a concrete assignment.	4.30	4.13	0.88	0.76	-1.699	0.103
9- If I am struggling with an assignment, it helps to have a classmate explain it to me.	3.74	4.00	0.86	0.95	-2.787	0.011*
10- I feel like my opinions and ideas are used in my group.	3.87	3.70	0.89	1.06	1.447	0.162
11- Creative thinking is necessary for solving/doing a concrete problem/project.	4.13	4.26	1.14	0.75	-1.141	0.266

* Significant at P < 0.05
** Significant at P < 0.1

The null hypothesis states, "there is no difference in the mean score of students' opinion when discovery-based learning is used." Based on the significance (2-tailed) value for the first four questions, we can conclude that there is less than 5% (or 10% for Q2 and Q4) probability that there is no difference in individual students' ability to solve problems with and without using discovery-based learning. From the students' perspective, there is a significant mean difference between their confidence level in solving concrete problems when they learned through discovery compared to traditional lecture-based teaching. Furthermore, the students found it easier to find a solution to a concrete problem when they worked in groups (Q7) and when they had a classmate explain the problem to them (Q9).

Another essential metric to measure the strength of discovery-based learning is the student's grades before and after using this learning method and the comparison between the grades for the students in control and experimental groups. The control groups were given similar quizzes.

Although students' grades are not necessarily an indicator of students' problem-solving skills, they can reflect the knowledge possessed by the students and thus show the effectiveness of the proposed method. Therefore, we use the paired t-test to compare the students' grades before (from the beginning to the middle of the semester) and after using discovery-based learning (from the middle of the semester to the end of the semester) and the grades between the experimental group (Spring 2022) and the control groups (Fall 2021 and Spring 2020). To exclude and understand the changes in the grades for the second half of the semester, the paired t-test is also used for the control group, and the results are shown in Table 5.

Table 5. Paired t-test results for the students grades in control and experimental groups

Group	Mean	Std. deviation	t	Sig. (2-tailed)
Control (Traditional Learning – Spring 2020)	7.73	1.34	-7.339	<0.001*
Experimental (Discover-based Learning – Spring 2022)	9.27	1.19		
Control (Traditional Learning – Fall 201)	8.16	1.28	-6.342	<0.001*
Experimental (Discover-based Learning – Spring 2022)	9.27	1.19		

* Significant at P < 0.05

The average difference in the student's grades for the students learning through discovery-based learning and those with traditional learning is statistically significant (p=<0.001). The experimental group students earned higher average grades than the control group students. There is unlikely that the use of discovery-based learning does not improve the students' grades.

E. Conclusion

A good way to encourage students to engage in active and independent learning is to use discovery An excellent way to encourage students to engage in active and independent learning is to use discovery learning methods. This means shifting roles from a teacher or a resource for the students to a facilitator who helps students develop their skills and knowledge and encourages them to solve problems. Teachers reap benefits when they see how excited their students are about applying their ability to solve a problem. The author implemented the discovery learning method in one of his STEM classes; the students did not receive all the materials at the beginning of the class. Instead, they were encouraged to participate in the learning process, share their knowledge, share information, and cooperate in the group. Our conclusion is that discovery learning was successful when students had prerequisite knowledge on the subject and were guided through structured experiences. It is important to review standard models of discovery learning to adopt the model that best fits the classroom and the subject. These models include but are not limited to collaborative discovery learning, guided discovery learning, learning by exploring, case-based learning, problem-based learning, and inquiry-based learning.

After reviewing the discovery-based models of learning methods and prior observation in an introductory STEM class, a combination of problem-based and inquiry-based learning was used for a required course in the BS program in Construction Management. Data was collected for this study in two forms; through a student survey and grades. The survey results show a significant mean difference between students' confidence level in solving problems when they learned through discovery compared to traditional teaching. The students found it easier to find a solution to a problem when they worked in groups and had a classmate explain the problem to them. The comparison between the students' grades with and without discovery-based learning shows significant improvement. Discovery learning as a learning model can potentially increase the students' scores.

Our observation showed that discovery-based learning could develop a sense of independence and autonomy among the students, convince them to find and use information rather than memorize and repeat concepts, and facilitate effective group work. The learning method successfully provided the students with the opportunity to experiment and discover something for themselves, mainly because it was tied to problem-solving. However, when the subject was relatively new, and no initial prior knowledge was available, the students were not able to develop lifelong learning skills or personalize their learning experience. While unguided or minimally guided learning approaches are becoming popular and intuitively appealing, the conclusion from this study reveals that learning models with strong efforts on the guidance of the student learning process are more effective. The emphasis of this study was on the practical application due to the course content, and it was observed that knowledge could best be learned through experience based on the discipline's procedures.

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