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LEARNING DESIGN OF EXPERIMENTS THROUGH PROJECT-BASED LEARNING

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Abstract

Design of Experiments (DOE) is a very versatile tool with broad applicability across disciplines. Fields such as research and engineering can greatly benefit from its systematic approach. For this reason, learning DOE is fundamental for engineering students. Due to its relevance, the use of project-based approaches to learning DOE was chosen for evaluation. Students chose from various project alternatives, designing and conducting a factorial experiment and subsequently analysing the results. Learning outcomes were assessed by reviewing the academic papers submitted as a final project deliverable. Overall, the submitted deliverables demonstrate a satisfactory understanding of DOE principles. However, several areas for improvement were identified. There is a need to reinforce the use of prior research to contextualise the specific focus of each project. Furthermore, as visual resources are commonplace in technical communication, many reports could have been substantially improved by integrating photographs and schematics to support the findings. In addition, the interpretation of numerical results was not consistently clear in terms of the response variables, and the connection to decision-making was sometimes weak. These aspects merit further attention in future implementations.

Keywords: design of experiments; learning; project-based learning; DOE.

1. Introduction

1.1. Design of Experiments in Engineering Education

Design of experiments (DOE) "is a body of knowledge and techniques that enables an investigator to conduct better experiments, analyse data efficiently, and make the connections between the conclusions from the analysis and the original objectives of the investigation" [1]. The experiments referred to, as well as the act of investigation, should be understood in a broad sense: experimentation may take place either in the laboratory or on the shop floor, and investigation refers to the pursuit of a deeper understanding of a phenomenon, system, or process. This set of tools has a wide range of applications, from design[2] to quality assurance [3].

Given its relevance to industrial settings, learning DOE is essential for engineering students. The Accreditation Board for Engineering and Technology (ABET) includes, as a student outcome in its Criteria for Accrediting Engineering Programs, "an ability to develop and conduct appropriate experimentation, analyse and interpret data, and use engineering judgment to draw conclusions" [4]. Moreover, in the context of professional practice, DOE is recognised in the United States as part of the knowledge base required for obtaining Professional Engineer certification in Industrial and Systems Engineering[5], as well as for the Fundamentals of Engineering examination in Chemical Engineering[6] and Industrial and Systems Engineering [7]. Although the reference is to the United States, it is intended merely as an illustrative example of how DOE is integrated into professional certification frameworks.

In view of DOE's relevance to engineering education and practice, it is essential to identify appropriate tools to ensure its effective learning by engineering students. Current pedagogical approaches advocate for student-centred methods that promote skill development, respond to contextual needs, and foster cognitive, procedural, and attitudinal dimensions. One method that has emerged as a viable option to meet these demands is project-based learning (PBL).

1.2. Project-Based Learning

Work with projects in education is often traced back to William Kilpatrick's 1918 article *The Project Method* [8]; however, Knoll suggests that the use of projects in educational contexts began "in the early eighteenth century" [9]. According to Knoll, the project method has its origin in the professionalization... of architecture" and later "it did not long remain the privilege of architects". Since then, the idea of "learning by projects" has evolved and become a key concept in education. *Project-based learning* (PBL), as a specific term, emerged much later. In the Web of Science (WOS) database, this term first appeared in a 1976 article [10]. Nevertheless, it is not possible to say that it was not being used earlier or referred to by an equivalent expression.

Given this historical trajectory, a unified definition of the term is quite difficult to achieve, though it is possible to examine several proposals. In [11], the author synthesises the concept of PBL drawing on [12] and [13], defining it as "an inquiry-based instructional method that engages learners in knowledge construction by having them accomplish meaningful projects and develop real-world products". Kokotsaki et al. [14] reference Cocco [15], who characterises project-based learning as a student-centred methodology and highlights that it "is based on three constructivist principles: learning is context-specific, learners are involved actively in the learning process, and they achieve their goals through social interactions and the sharing of knowledge and understanding". On the other hand, [16] emphasises "the development of higher-order thinking skills such as analysis, synthesis, and evaluation. Just as definitions differ, it must be acknowledged that implementations of PBL are highly varied, "depending on the context, resources, and curriculum design" [17].

The extensive historical trajectory of the concept does not preclude its continued relevance; throughout its development, it has been adapted to various fields and has acquired distinctive nuances. Nevertheless, certain elements remain central: the involvement and centrality of the learner, meaningful learning, interaction, and context-specific learning, among others. Accordingly, it has been recognised as an appropriate pedagogical strategy for facilitating learning in DOE environments.

1.3. Project-Based Learning and Design of Experiments

Previous studies have reported successful implementations of PBL in the teaching of DOE [18], [19]. An important key to success in using a tool lies in its suitability to the task at hand, in [19], the authors declared that PBL methodology was selected because it "enables learners to apply theoretical concepts to a controlled real-world environment and to make decisions based on practical experience". In contrast, reference [18] seeks to test the hypothesis that "a structured PBL curriculum with targeted learning outcomes provides an efficient and engaging learning strategy that addresses the interface between engineering analysis and practice". Nevertheless, both cases are aligned with the core elements of PBL previously discussed.

It is appropriate to highlight some general conclusions drawn from both studies. According to [19], PBL has enabled the acquisition of theoretical knowledge in a practical manner and has facilitated the development of a set of transversal competences, several of which fall within the domain of what are commonly referred to as soft skills. This study also highlights the potential of PBL as a tool for interdisciplinary education, since the project is reportedly developed within the framework of all the semester's subjects. The authors of [18] conclude that the transition from seminar-based course to a project-base course improved the students' engineering judgement "and demonstrated to students the value of engineering analysis and mathematical models in practical engineering design".

The studies mentioned, which were identified for their explicit reference to "project-based learning" and to "design of experiments", reinforce what was previously stated: that PBL can be a highly useful tool for learning DOE.

1.4. Statement of Purpose

In line with the foregoing, this study aims to evaluate the application of PBL in the learning of DOE by identifying opportunities for improvement in various elements of DOE. In this case, the elements of DOE are considered to be reflected in the article submitted by students as one of the deliverables of their project. This objective guides the subsequent analysis, which seeks to assess how effectively PBL supports the learning of DOE through the examination of the student-submitted article.

2. Methodology

The project was proposed as part of the module Design and Analysis of Experiments. Students, organised into teams, defined projects within the thematic areas provided: urban and home gardening, domestic space cooling, by-product utilisation, manufacturing processes, food processing, and physical activity. The provision of multiple topics fulfilled two functions: (1) to provide a basis for idea generation and (2) to stimulate engagement in areas in which students had a greater interest.

Each project was required to use a factorial experimental design comprising at least two factors at two levels (2^2), with four replicates per treatment ($n = 4$); resulting in 16 runs. Other designs could also be used, provided that the minimum number of runs was met.

During the term, formative and summative assessments were conducted to encourage progress and provide feedback. However, this study focuses solely on the final deliverable, namely a paper, as it marks the end of the process and remains a highly valued format within academia.

The typical IMRaD structure (Introduction, Methods, Results and Discussion) was proposed for the article. Key aspects to be evaluated in each section were outlined and are presented in Table 1. These aspects were used in this study to identify opportunities for improvement through a qualitative evaluation of the student submissions. The key aspects mentioned in Table 1 align with the recommended guidelines for article writing.

Paper Section	Key aspects	Description
Introduction	Context	Contextual framework is provided, and it is appropriate to the specific project being developed.
	Key concepts	Relevant concepts are presented, and they are appropriate to the project's experimental approach.
	Previous research	Relevant prior work is cited.
	Aim	Aim is explicit and pertinent to the specific project being developed.
Methods	Equipment and materials	The information on the materials and equipment used is presented.
	Experimental procedure	The experimental procedure is described in such a way that replication would be possible.
	Experimental design	The experimental design provides evidence of both the understanding and application of DOE concepts.
	Variables	The factors and the response variable(s) are identified and described clearly, if necessary.
	Measuring	The method used to measure the response variable is clearly described.
Results and Discussion	Visual aids	Appropriate visual aids (such as graphs, diagrams, images, etc.) are used.
	Qualitative analysis	A qualitative analysis of the results is presented.
	Data analysis	A complete analysis of the collected data is presented, including assumption checking and mean comparison, if appropriate.
	Interpretation	The numerical results are interpreted in a way that informs decision-making.

Table 1. Key elements of each section

The aspects listed do not exhaust the possibilities for evaluating the application of PBL in learning DOE; however, they are considered to provide valuable information for implementing improvements. The evaluation is not limited to DOE understood as mere calculation but rather seeks to highlight its use as a problem-solving tool, as expected in the application of PBL.

3. Results and Discussion

The results of the evaluation are presented below, grouped according to the key aspects mentioned previously. Sixteen projects were evaluated.

3.1 Context

Most of the projects were contextualised as responses to specific needs; however, in one case, the contextualisation was rather superficial. In another, no context was provided for the experiment. Although an experiment was conducted in this instance, which led to data collection and subsequent analysis, it must be noted that DOE is intended to address problems that arise within a specific context.

The opportunity for improvement lies in emphasising that projects involving DOE respond to concrete realities and must be properly situated. It should be noted that, in most cases, PBL has facilitated context-specific learning.

3.2 Key Concepts

The identification of key concepts is an aspect that could be improved in the vast majority of the projects. Given that these are experimental processes, the use of terminology is expected to go beyond general vocabulary. In most cases, it would be necessary to provide definitions that demonstrate a deeper engagement with the subject matter. The recommendation for this aspect is that key concepts relevant to the problem being addressed should be identified, either independently or with the support of experts.

3.3 Previous Research

In nearly all projects, previous research was consulted. Improvements that could be expected in future work include an increase in the number of sources reviewed and a deeper engagement with what those sources express, applied to the case under study as concretely as possible. One case was found in which no references to research articles were made, and another in which citations were not indicated in the text. From a teaching perspective, emphasis should be placed on the importance of contextualising the work in relation to existing research on the topic.

3.4 Aim

Only one case did not explicitly present an aim. Although most projects met expectations in this regard, given the centrality of this element, it is recommended that it be highlighted in the project guidelines, preferably as a separate component. It should also be noted that, in article format, the aim is typically presented at the end of the introduction.

3.5 Equipment and Materials

This aspect can, in general terms, be considered satisfactory. A key consideration is the need to provide sufficient procedural detail to allow replication of the conditions under which the experiment was conducted.

3.6 Experimental Procedure

As with the previous aspect, the observed area for improvement concerns highlighting the importance of replicating experimental conditions. There were projects in which insufficient information was provided regarding the experimental procedure, or where the inclusion of images or diagrams could have enhanced the presentation.

3.7 Experimental Design

The descriptions of the experimental designs are acceptable when evaluated against the minimum requirements established for the project, as outlined in the methodology. Randomisation, a key element in DOE, is mentioned and its implementation is explained in several deliverables.

It is noteworthy that students employed designs that went beyond the minimum requirements. Fractional factorial designs and factorial designs with blocks were implemented. This highlights the development of higher-order thinking skills as described in [16]: "analysis, synthesis, and evaluation". The student, within a specific context [15] — or what [19] refers to as a "controlled real-world environment" — engages in analysis, evaluation, and decision-making [19]. Based on observations, two levels of performance emerged spontaneously: those that meet expectations and those that are outstanding. The evidence associated with each performance level is presented in Table 2.

Level	Design used

Meet expectations	- Full factorial design
	  o Factors: 2
	  o Levels: 2

Outstanding	- Full factorial design
	  o Factors: 3
	  o Levels: 2
	- Full factorial design
	  o Factors:3
	  o Levels:2
	  o Blocks: 1
	- Fractional factorial design
	  o Factors: 5
	  o Fraction: 1/2
	  o Levels: 2
	  o Blocks: 1

Table 2. Levels of performance in design selection

3.9 Measuring

The complexity of measuring the response variable varies depending on the project. Measurement instruments range from a simple measuring tape to specialised laboratory equipment. A concrete area for improvement would be to ensure greater support for projects requiring more complex measurement procedures. Additionally, this again highlights the importance of describing experimental conditions in sufficient detail to allow replication. One practical way to achieve this is using illustrations, as noted in the previous aspect.

3.10 Visual Aids

Graphical outputs specific to DOE are the standard visual resource used to accompany results. However, images, photographs, diagrams, and similar resources can enhance the interpretation of findings. In many cases, visual analysis is a valuable tool for explaining what the data reveal. This is particularly important when emphasising that numerical results—such as those presented in an ANOVA—require interpretation and explanation. One recommended improvement is to draw on examples in which visual elements form part of the evaluative process used to assess the quality of a given item.

Although this aspect was not explicitly included as an evaluation criterion in the methodology, its importance in supporting explanation and replicability was previously acknowledged. Moreover, it was already anticipated that this aspect is related to the qualitative analysis.

3.11 Qualitative Analysis

There is virtually no evidence of any qualitative analysis of the results produced by the experiments. That is, no observations were documented—for example, through photographs—that would allow for additional assessments beyond those provided by the response variable measurements. Given that conducting experiments involves the use of resources (whether financial or otherwise), it is important to make use of any additional information that their execution may yield. Furthermore, as previously noted, the observation of qualitative aspects can provide valuable input for explaining numerical results (Table 3).

Level	Examples
Defects detection	- Slag in plasma cutting - Delamination in 3D printed part. - Insufficient bonding within the briquette material
Cause identification	- Pest occurring in a home garden - Poor bed adhesion in 3D printing
Abnormality detection	- Inappropriate microbial growth in sourdough starter

Table 4. Examples of the uses of qualitative analysis

3.12 Data Analysis

The minimum expectations for a basic analysis of factorial design results—namely, ANOVA and assumption checking—have been met. However, the examination of effects was not addressed in all projects. It would be advisable to reinforce what is meant by "effect" and how effects are to be interpreted. Similarly, mean comparisons were not consistently included.

With regard to data analysis, it should also be noted that several students went beyond the elements that were merely introduced in class, such as the use of non-parametric tests or analytical procedures for verifying assumptions. This was facilitated by access to data analysis software and training in its use. In terms of software, students employed various tools according to their preferences, namely RStudio, Excel, and Minitab. Similarly to the experimental design (3.7), two levels of performance can be identified here: meets expectations and outstanding. The evidence associated with each performance level is presented in Table 4.

Level	Elements

Meet expectations	- ANOVA
	- Model adequacy checking: graphical tools
	    o Normal probability plot
	    o Plot of residuals in time sequence
	    o Plot of residuals versus fitted values

Outstanding	- ANOVA
	- Model adequacy checking: graphical tools
	    o Normal probability plot
	    o Plot of residuals in time sequence
	    o Plot of residuals versus fitted values
	- Model adequacy checking: analytical tests
	    o Normality: Shapiro-Wilk test
	    o Homoscedasticity: Levene test

Table 4. Levels of performance in model adequacy checking

These practices are consistent with recommendations found in recent literature, such as [20], where DOE has been applied to evaluate a full-scale energy consumption project. This example illustrates the broader applicability of DOE in engineering contexts and reinforces the relevance of the skills developed through project-based learning.

3.13 Interpretation

Numerical results are interpreted in all cases; however, in some instances, the interpretation lacks sufficient clarity and assertiveness, particularly with regard to decision-making orientation. This final point may be the most appropriate to reinforce: the results of a DOE are intended to inform decision-making.

One specific issue that stood out is the need to appropriately interpret when the analysis indicates that a source of variation is not significant. In this regard, it is important to recall the fundamental premise of factorial models: the comparison of treatments—that is, determining whether a treatment differs significantly or not.

3.14 Additional Remarks

In several projects, the limitations of the study were explicitly stated; this is a feature that could be revisited in future deliverables. Furthermore, in one of the papers, the development of the methodology was explained with reference to other authors. This idea may be integrated as a recommendation in future implementations of the PBL methodology.

In some cases, the conclusions are not entirely clear in terms of the response variables; this is also a point worth emphasising, as it connects directly with the decision-making dimension.

Using graphs to present the raw data before performing an ANOVA could help students to become familiar with the data and identify possible patterns. However, there is a risk that they will accept these trends as valid without considering the numerical analysis.

4. Conclusions

A qualitative evaluation of the implementation of project-based learning (PBL) in the teaching of Design of Experiments (DOE) has been conducted, based on a deliverable in the form of an academic paper containing thirteen key aspects expected in this format. The conclusions reached are presented below.

First of all, the principles underlying PBL appear to be well suited to the learning of DOE—particularly when it is understood that DOE refers not only to data analysis but also to experimental design.

The principles underlying PBL appear well suited to learning DOE, particularly when DOE is understood to encompass not only data analysis but also experimental design. This was observed in the qualitative evaluation, as most deliverables met the key aspects assessed.

Several areas for improvement were identified. There is a need to reinforce the use of prior research to contextualise the specific focus of each project. Furthermore, as visual resources are commonplace in technical communication, many reports could have been substantially improved by integrating photographs and schematics to support the findings. In addition, the interpretation of numerical results was not consistently clear in terms of the response variables, and the connection to decision-making was sometimes weak. These aspects merit further attention in future implementations.

Addressing these areas for improvement would require data analysis that not only describes the observations but also moves closer to explaining the phenomena analysed and guides decision-making, in a manner consistent with several aspirations of the PBL methodology.

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