

Implementation of Project-Based Learning for Design of Experiments Using 3D Printing

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Abstract:

Purpose: This paper aims to present how the project-based learning (PBL) methodology was implemented in the Faculty of Engineering of Mondragon Unibertsitatea, located in The Basque Country, Spain, during the second year of the Engineering in Industrial Organisation degree to help integrate statistical knowledge related to design of experiments (DOE) and the use of advanced technologies, such as additive manufacturing (AM; also known as 3D printing).

Design/methodology/approach: The methodology applied was PBL, which enables learners to apply theoretical concepts to a controlled real-world environment and to make decisions based on practical experience. PBL was applied in a team setting involving 51 students divided into 12 teams.

Findings: The improvement in academic results demonstrates an enhancement in the acquisition and assimilation of technical knowledge related to the use of statistical tools through experimentation in a semi-industrial environment. In addition, the results of the satisfaction surveys show an increase in the motivation and commitment of the students during the project.

Originality/value: The value of this study lies in the integration of advanced technologies (AM or 3D printing) and statistical knowledge in DOE using the PBL methodology in a higher education environment.

Keywords: PBL, project-based learning, wind turbine, design of experiments, DOE, industrial organisation engineering degree, additive manufacturing, 3D printing, ANOVA, classification trees

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1. Introduction

Traditional teaching involves students receiving unidirectional information from a teacher. In this learning model, students do not get the opportunity to apply the acquired theoretical knowledge in a practical manner. In higher education, new training techniques and tools that integrate the theoretical teaching of concepts and their practical application in adequately prepared real-world scenarios are being implemented. Such a teaching environment is ideal

for active learning, wherein knowledge is transferred in a practical manner, allowing students to play a primary role in their learning process (Aldabbus, 2018; Unzueta & Eguren, 2021).

The most commonly used tool in higher education is project-based learning (PBL) (Aldabbus, 2018; Herget, 2020). PBL can be defined as “an instructional learner-centred approach that empowers learners to conduct research, integrate theory and practice, and apply knowledge and skills to develop a viable solution to a defined project” (Guo, Saab, Post & Admiraal, 2020; Kokotsaki, Menzies & Wiggins, 2016). PBL can take place in teams and is based on the application of theoretical knowledge that students assimilate over the course of the academic year; this allows students to assimilate transversal competencies in various ways, such as teamwork, decision making, project management and sharing of responsibilities.

This paper aims to present the application of PBL to the integration of theoretical knowledge in the design of experiments (DOE) approach with additive manufacturing (AM; also known as 3D printing), which is an advanced technology that is changing the way companies operate. Therefore, engineering students find it interesting to learn about these advanced technologies and their potential applications. Additionally, during the PBL, theoretical knowledge, such as the Fourier series, was applied to analyse the vibrations, and classifications trees to analyse experimental data; furthermore, other advanced technologies, such as laser cutting machines, a multimeter and an anemometer, were used.

This study poses the following research questions:

- Do students autonomously reinforce their theoretical knowledge during PBL?
- Does the application of the PBL methodology facilitate the acquisition of technical and transversal competences?
- Does the PBL methodology allow students to learn the application of advanced technologies, such as additive manufacturing, in a semi-autonomous way?

The PBL methodology was implemented during the second year of the Engineering in Industrial Organisations degree in the Faculty of Engineering of Mondragon Unibertsitatea, located in The Basque Country, Spain.

The paper is organised as follows. Sections 2 and 3 briefly describe the literature review on additive manufacturing technologies and explore in detail the technology used in the project and the theoretical framework of design of experiments (DOE). Section 4 describes the methodology used to assess the application of the PBL tool and how the PBL approach was applied. Section 5 presents the results of the application of the PBL approach, and Section 6 presents the conclusions.

2. Additive Manufacturing

AM is an advanced technology that is changing the way companies operate. The term “3D printing” describes the processes of converting a computer-aided design (CAD) 3D model into a stereo lithography (STL) triangular lattice surface model and then creating solid parts (Eguren, Esnaola & Unzueta, 2020). This technology has mainly been used to quickly create prototypes to verify details before commencing the entire production process. However, the possibility of obtaining parts with different materials and better characteristics is currently being studied to compete with traditional parts and processes (Zgodavová, Lengyelová, Bober, Eguren & Moreno, 2021). AM technologies can be classified in various ways, such as according to their baseline technologies and raw material input (Gibson, Rosen & Stucker, 2009). Table 1 summarises the most important AM technologies.

In this project, the students used fused deposition modelling (FDM) technology. FDM is widely used in several industries and is one of the most common 3D printing techniques owing to its simplicity and low cost. FDM involves extruding a thermoplastic filament through a heated nozzle. The material is deposited in a controlled manner, layer by layer, onto a build platform to create the final object. The filament is heated to a temperature where it becomes molten and is then extruded through the nozzle in a controlled manner. Once the material cools and solidifies, it forms a strong bond with the previous layer.

ID	AM Technology	Description	Material used
1	Vat Photopolymerisation Technologies (Stereolithography)	<ul style="list-style-type: none"> Involves the reaction of resins to ultraviolet light to become solid Ultraviolet light cures the resin layer by layer New layers added from bottom to top 	Radiation-curable resins or photopolymers
2	Material Jetting, Fused Deposition Modelling (FDM)	<ul style="list-style-type: none"> Jetting the material onto a build platform by solidifying it and adding the material layer by layer 	Filament of thermoplastic material
3	Binder Jetting	<ul style="list-style-type: none"> Objects created by printing a binder onto a powder bed to produce a part 	Binder adhesive and powder
4	Extrusion-based Systems	<ul style="list-style-type: none"> Used to create objects of a fixed cross-sectional profile in order to create parts by successive deposition of layers of semi-liquid raw material 	Polymeric filament materials
5	Powder Bed Fusion Technologies	<ul style="list-style-type: none"> Involves speeding a material over the build platform and fusing the first layer using an electron beam, a laser or a thermal head New layers of powder are spread and fused 	Metallic material
6	Sheet Lamination, Laminated Object Manufacturing (LOM)	<ul style="list-style-type: none"> Involves layer-by-layer lamination of paper material sheets and cutting them using CO₂ lasers to create the layers 	Paper with pre-applied adhesive
7	Directed Energy Deposition (DED)	<ul style="list-style-type: none"> Involves creating parts by melting materials and depositing them in the form of wire or powder Powder material is melted using a laser, electron beam or plasma arc 	Metallic material

Table 1. Classification of AM technologies (Eguren et al., 2020)

3. Design of Experiments

DOE is an effective statistical tool to understand and optimise processes and products and maximise the information obtained from the resulting experimental data. The most important methods of applying DOE include fractional and full factorial designs, analysis of variance (ANOVA), response surface methodology and the Taguchi method (Allen, 2007; Anderson & Whitcomb, 2015; Krishnaiah & Shahabudeen, 2012). Choosing the most appropriate method depends on the problem to be studied, the knowledge available about the product or process to be studied and the capacity for experimentation (number of experiments that can be performed, time needed to run each experiment, precision required, etc.). The application of a systematised methodology allows for the selection of the most appropriate DOE method. Figure 1 shows the main phases of the DOE application methodology.

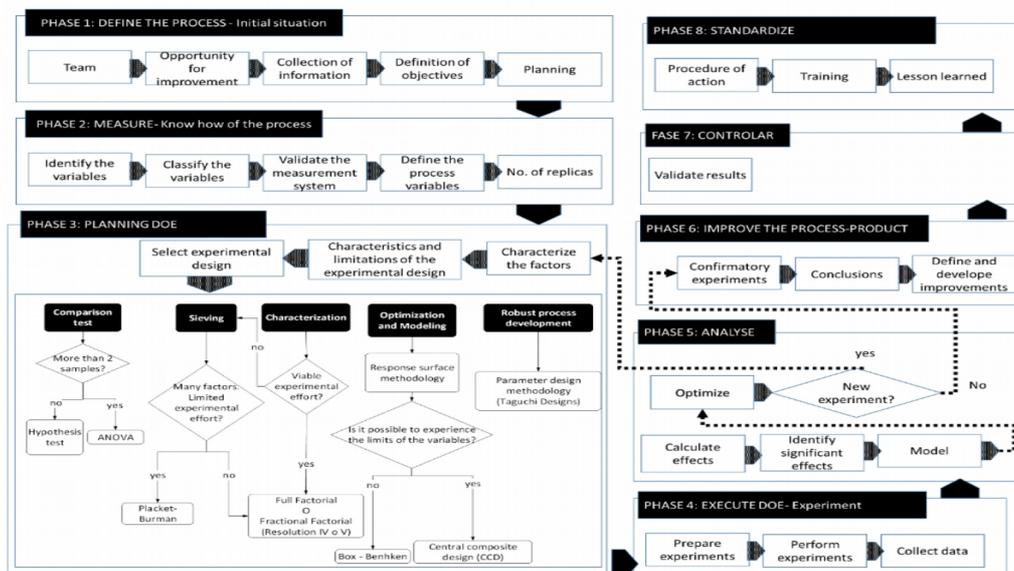


Figure 1. Methodology for the application of DOE (Unzueta, Orue, Esnaola & Eguren, 2019)

4. Methodology

Figure 2 shows the methodology applied in the research as well as the methodology followed for the design, development and evaluation of the PBL applied in this study. PBL was conducted over a period of seven weeks between December 2021 and February 2022. In the first part of the semester, between September and December 2021, the students acquired technical knowledge of the semester subjects, which was applied in practice in the PBL period. During this first part of the semester, the teaching staff defined the case to be analysed in the PBL, designed assessment rubrics for the competencies to be developed during the PBL (both technical and transversal), purchased the necessary material, designed and developed the test bench for experimentation and scheduled the activities to be performed during PBL.

The effectiveness of implementing the PBL methodology was analysed using data collected via participant observations, learner satisfaction surveys, documentation and files generated by each team participating in PBL, in addition to the academic results achieved by students in the PBL period and in ordinary classes. To assess the benefits of applying the PBL approach, three aspects were analysed in the research (indicated by a star in Figure 2).

1. The assessment of transversal competences using assessment rubrics (oral and written communication skills).
2. The technical skills of the students in the subjects covered in PBL. The academic results achieved during the course were compared with the marks obtained in PBL and in the PBL individual defence.
3. The results of the satisfaction surveys completed by the students after the completion of PBL (adapted from Dolman's questionnaire (Dolmans, Wolfhagen & Ginns, 2010)).

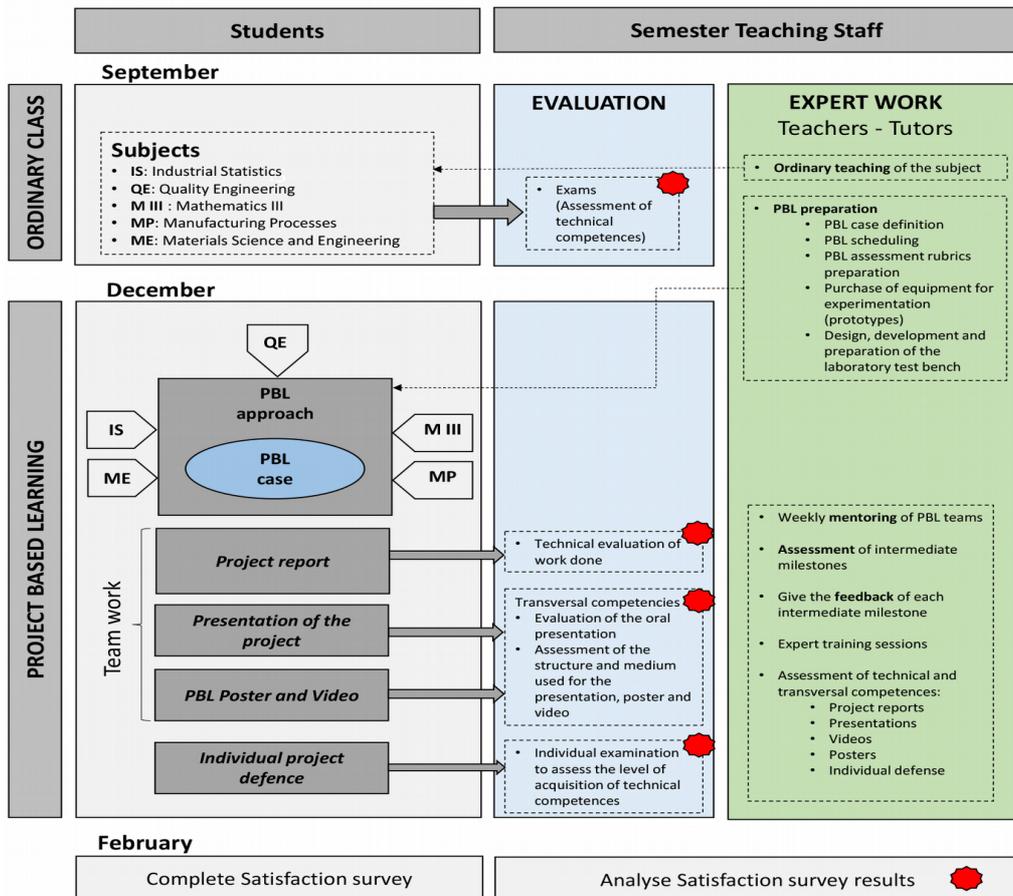


Figure 2. Methodology applied in the research and development of PBL.

The case study that was selected in PBL for developing the theoretical and technical competences of the semester subjects—Industrial Statistics (IS), Quality Engineering (QE), Mathematics III (M III), Manufacturing Processes (MP) and Materials Science and Engineering (ME)—was based on the development of a wind turbine manufacturing process. For this, PBL was conducted over a seven-week period by 12 teams (six teams in Group 1 and six teams in Group 2), each comprising 4-5 students; in total, 51 students participated. Each team analysed and defined the best material and manufacturing process to develop a predefined component of a wind turbine, analysed the vibration experienced using the Fourier series and designed the most effective wind turbine shovel by applying DOE. The effectiveness of the wind turbine shovel was evaluated by measuring the electric power generated as a function of wind speed. The power was measured using a multimeter, and the wind speed was measured using an anemometer (Figure 5). To design the wind turbine shovel, the students used SolidWorks software (SolidWorks Corp. (www.solidworks.com/es)). The designed component was cut using a laser cutting machine (A component, Figure 5), and the piece that defined the wind angle of attack (B component, Figure 5) was fabricated using a 3D printer [RAISE3D E2 (<http://www.raise3d.com>)] and IdeaMaker SW [Raise3D Technologies Inc., (www.raise3d.com)] to configure the 3D printer. The material used was polylactic acid (PLA).

The temporary planning of the activities associated with PBL is shown in Figure 3. During PBL, most of the activities were executed autonomously by the student teams. Four milestones were planned (M1 to M4). At the end of each milestone, meetings were held with each team to give them feedback on the work done, which allowed continuous evaluation and correction of the project. In total, each team received a minimum of 3 hours of feedback. Moreover, each team was able to request up to two tutorials of 30 minutes with each expert. The expert role was played by teachers with subject matter expertise in each area.

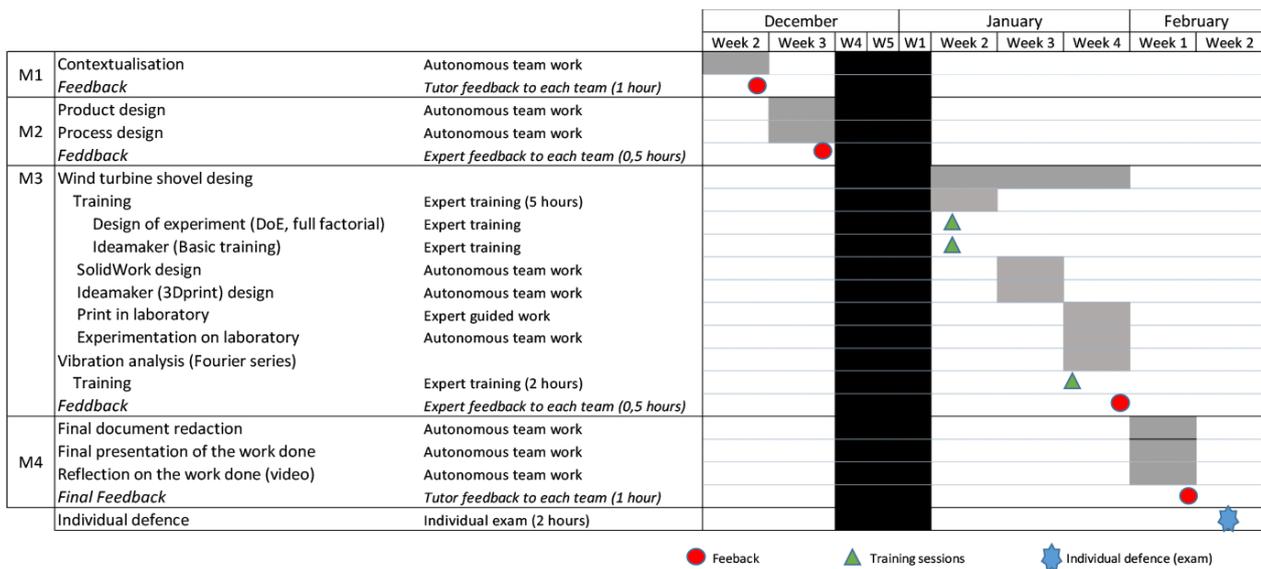


Figure 3. Planning of activities associated with PBL

For the first milestone (M1), every team developed the plan and contextualised the project by indicating its impact on the Sustainable Development Goals (SDG). For the second milestone (M2), each team defined the appropriate material and manufacturing process for a predefined wind turbine component (screws, hub, reduction gears, nacelle casings, mast, low-speed main shaft, variable-pitch component, main shaft bearings, hub cover, rudder, coupling flange and tower, and blade). Once the appropriate material and manufacturing process were selected, the manufacturing cost was estimated using the parametric method.

For the third milestone (M3), the whole group received training on DOE, Minitab 21 [State College, PA: Minitab, Inc. (www.minitab.com)], IdeaMaker, MATLAB [MathWorks corporation (www.mathworks.com)], R-Studio (<https://posit.co/products/open-source/rstudio/release-notes/>) and the Fourier series from experts in the field. For this milestone, each team used SolidWorks to design eight different wind turbine shovel configurations and

manufactured them using a 3D printer with IdeaMaker SW (Figure 4) and a laser-cutting machine to conduct experiments on the laboratory test bench (Figure 5). The teams then drew conclusions using statistical tools (ANOVA, factorial plots, a response optimiser, classification trees and clustering).

As this was a learning project in which the objective was to allow students to acquire basic knowledge about DOE, the variables to be experimented with were defined at the beginning (width, length and angle of the shovel). Following the DOE application methodology defined in Figure 1, students selected the appropriate experimental design (Unzueta et al., 2019). Full factorial design was applied using three variables at two levels ($2^3=8$) (Anderson & Whitcomb, 2015). After a preliminary analysis in which the standard shovel was used as a reference (Figure 5), each student team defined the maximum (+1) and minimum (-1) levels of each variable. Based on this, they designed eight configurations for the experiments. Each team conducted experiments on the laboratory test bench using a prototype (Figure 5) at three different wind speeds and obtained the necessary data for statistical analysis.

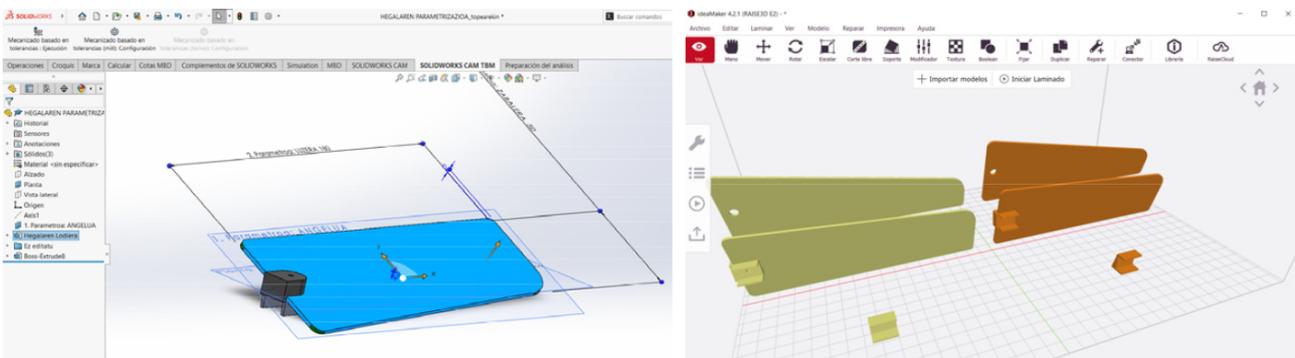


Figure 4. SolidWorks and IdeaMaker SW application

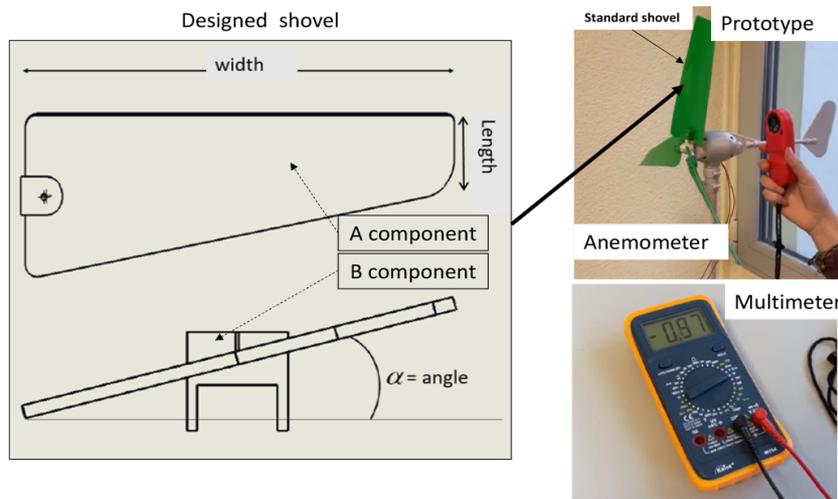


Figure 5. Variables in the wind turbine shovel design and the prototype setup

The design and experimental data of one of the student teams have been used here to explain the statistical tools applied and the results obtained (Table 2). Table 2 shows the eight configurations and the experimental results of each configuration as the electrical power obtained (Power v_i) at a given wind speed ($v_1=2.2$ m/seg; $v_2=2.7$ m/seg; $v_3=3.2$ m/seg). In total, 24 experiments were executed [$(2^3) \times 3=24$].

Minitab 21 and R-Studio were used to analyse the experimental results. Subsequently, ANOVA, factorial plots, a response optimiser, classification trees and clustering were applied to select the most efficient configuration.

Variables				Results		
Experiment number	Length mm	Width mm	Angle Degree°	Power v1 2.2 m/seg.	Power v2 2.7 m/seg.	Power v3 3.2 m/seg.
1	30	180	20	1.66	2.96	3.40
2	60	180	20	1.20	2.30	2.74
3	30	250	20	0.89	1.81	2.45
4	60	250	20	0.47	1.56	2.00
5	30	180	45	0.15	0.89	1.38
6	60	180	45	0.33	0.73	1.13
7	30	250	45	0.40	0.25	0.67
8	60	250	45	0.09	0.17	0.22

Table 2. Experimental results

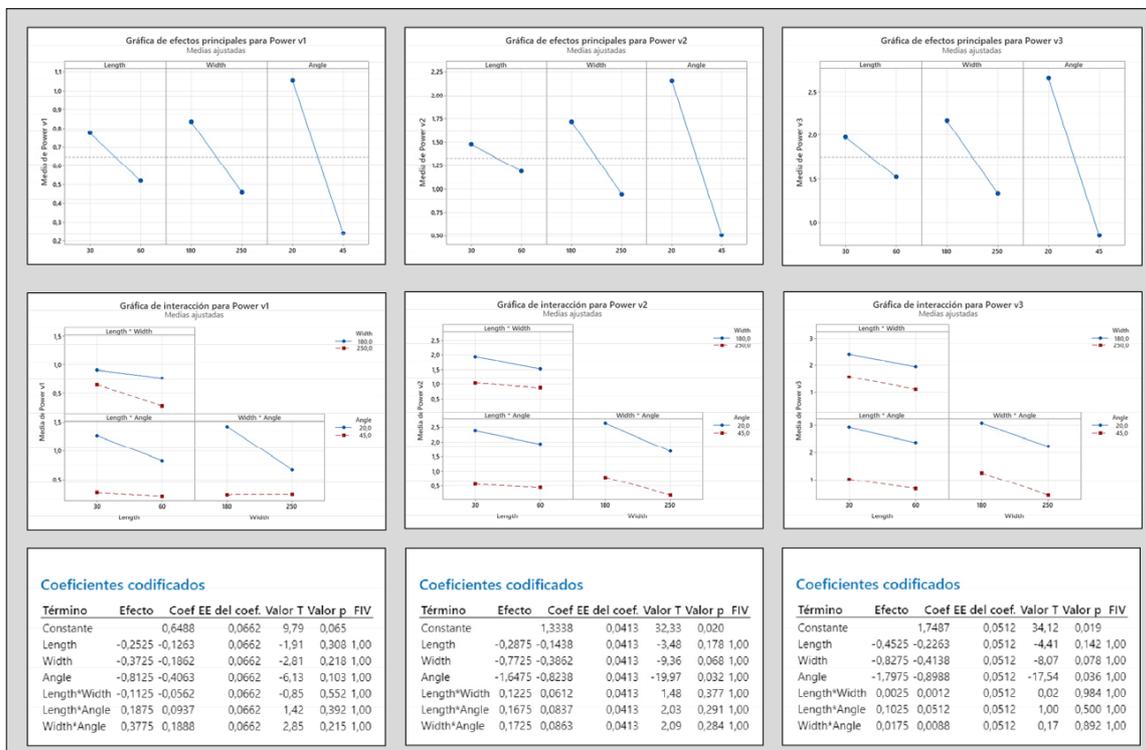


Figure 6. Factorial plots (Minitab 21)

In Figure 6, the factorial and interaction plots show which variables are significant, the effect of each variable and the optimal level of each variable to maximise the response. The ANOVA analysis verified the conclusions obtained graphically (Figure 7).

The Minitab 21 response optimiser indicates which variable configuration is appropriate for maximising the response at any of the three wind speeds (V_i) (Figure 7).

Once the optimal wind turbine shovel design was selected (Figure 7), confirmation experiments were conducted to compare the standard shovel design and the optimised shovel design using the ANOVA statistical technique. Although the differences are not statistically significant, it can be observed that there is an improvement in the response at each wind speed analysed (V_i) (Figure 8).

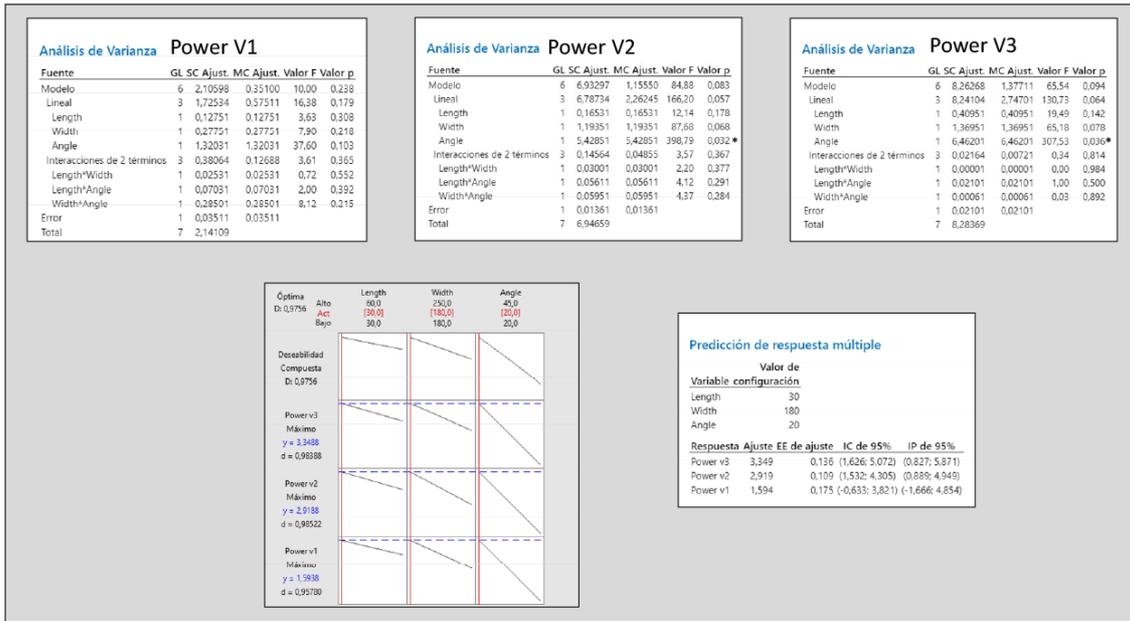


Figure 7. ANOVA of the factorial design and response optimisation (Minitab 21)

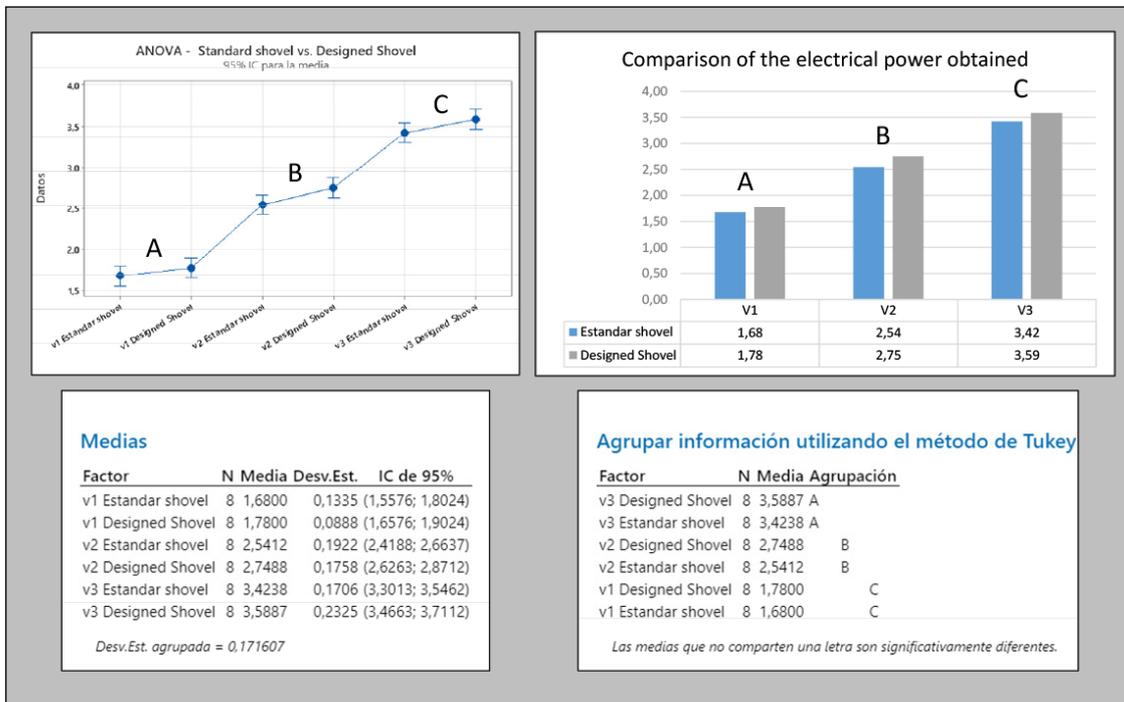


Figure 8. Comparison of the electric power obtained (Minitab 21 and MS Excel)

Using the experimental data (Table 2), the students also applied the classification tree statistical technique using R-Studio SW (Figure 9). The conclusions obtained were similar to those obtained using the ANOVA analysis and the effect and interaction plots. The length was not significant, and the best results were obtained with an angle of 20° and a shovel width of 180 mm.

For the last milestone (M4), the students produced a technical document detailing the executed project, in addition to a poster and a video explaining the project. Finally, each team presented the document to a panel of professors and explained their work as a team. An important section of the final report was the students' reflection on the knowledge acquired and the process followed during the execution of the project to improve the product (the shovel). The aim of this final reflection was to reinforce the assimilation of the knowledge acquired. Finally, to

ensure that all team members acquired the minimum knowledge and competences, an individual examination (individual project defence) was conducted.

At the end of the project, individual students completed a satisfaction survey to evaluate their experiences.

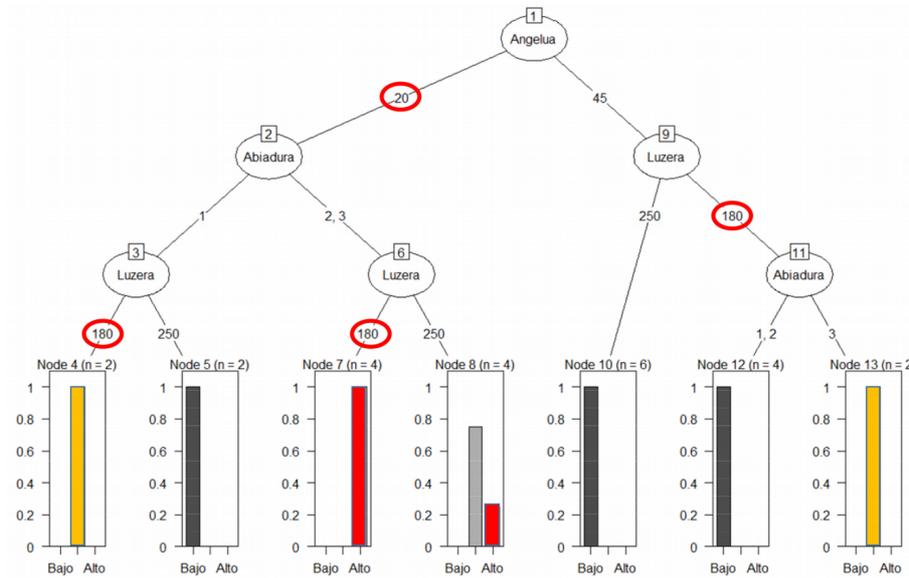


Figure 9. Classification tree (R-Studio)

5. Results and Discussion

The results are divided into three sub-sections. The first sub-section lists the technical knowledge targeted in each subject and the technical competencies that the students were able to develop during the project. This sub-section also describes the transversal competences that have been employed through the application of the PBL methodology carried out in teams of 4–5 students. The second sub-section compares the academic results obtained in the exams before the implementation of PBL with the results obtained in the project. The last subsection analyses the results of the satisfaction surveys completed by students at the end of the semester.

5.1. Knowledge and Skills Acquired by Students

During the development of the project, the students applied different technical knowledge related to each subject they worked on during the semester for which they acquired technical competencies (Table 3).

In addition, the application of the PBL methodology allowed the students to acquire transversal competencies (Table 4).

ID	Subject	Technical competency	Technical knowledge
IS	Industrial Statistics	Generate knowledge through the study of data	ANOVA, classification trees
ME	Materials Science and Engineering	Propose alternatives to problems in the industrial environment by applying knowledge of materials	Material selection methodology
MP	Manufacturing Processes	Defining and optimising manufacturing processes and ensuring that standards are maintained over time	Fabrication process selection methodology
M III	Mathematics III	Applies methods of integral calculus, differential calculus and Fourier series decomposition	Application of the Fourier series
QE	Quality Engineering	Identify, measure, analyse and improve processes and products to ensure zero-defect achievement	Design of experiment: Full factorial design, response optimiser, factorial plots, ANOVA, normal test

Table 3. Technical competencies and knowledge achieved for each subject

Transversal competency	How the competence was worked on
Solve problems and evaluate the consequences of the formulated solution by participating, coordinating and interacting with the team	<ul style="list-style-type: none"> • Material selection methodology • Fabrication process selection methodology • Fabrication process cost parametric estimation • Selection of the appropriate experimental design (DOE method) • Selection of the appropriate statistical methods to analyse the collected data • Definition of the experimentation process • Process of experimentation in a real-world environment • Teamwork
Write technical reports, present them orally and manage and organise information ethically and effectively	<ul style="list-style-type: none"> • Technical report written • Oral presentation of the obtained results • Organisation of experimental data

Table 4. Transversal competencies achieved during the project

5.2. PBL vs. Exam Marks

All students participated in PBL, and their work was analysed. The average student marks from the PBL approach were compared with the marks obtained in the exams during the academic year (Table 5). The marks obtained by participating in PBL increased by 0.8–1.6 (out of 10). No students failed in PBL, whereas 14% of the students failed the exams.

GROUP	Exam 1	Exam 2	PBL	Increase max	Increase min
Group 1	7.4	7	8.6	1.6	1.2
Group 2	7.2	7.6	8.4	1.2	0.8
Average	7.3	7.3	8.5	1.2	1.2

Table 5. PBL and exam marks

5.3. Learning and Satisfaction Surveys

To assess the implementation of PBL, the students completed a satisfaction survey (adapted from Dolman's questionnaire (Dolmans, Wolfhagen & Ginns, 2010)) by ranking the following statements using a Likert scale (out of 5):

- S1: The PBL methodology is suitable for understanding, generating and internalising technical knowledge.
- S2: The PBL methodology motivated me to study because it gives meaning to what I study.
- S3: Thanks to teamwork, compared to individual work, I have learned, among other things, to communicate better, to distribute responsibilities and to make decisions.
- S4: The presentation of the project has improved my communication skills.
- S5: The defence of the work has helped me acquire the minimum knowledge required in the different subjects and to evaluate the level of my colleagues.

QUESTIONS						
GROUP	No. of responses	S1	S2	S3	S4	S5
Group 1	25 (100%)	4.36	3.96	4.32	3.92	3.54
Group 2	25 (96%)	4.32	3.96	4.28	4.04	3.77
Average	50 (98%)	4.34	3.96	4.30	3.98	3.66

Table 6. Satisfaction survey results

Table 6 summarises the results of the satisfaction survey. The response ratio was high (98%), which indicates high student engagement. In general, the scores obtained in the satisfaction survey are high. The students understand

that PBL is suitable for understanding, generating and internalising technical knowledge (4.34 out of 5). They also believe that the PBL carried out in teams has taught them to communicate better, to share responsibilities and to make decisions as a team (4.30 out of 5). In contrast, the result obtained for S5 was lower than that obtained for the other aspects analysed. Individual preparation for the project defence did not help all students acquire the desired level of technical knowledge in the subjects they worked on (3.66 out of 5).

6. Conclusions

Most of the students positively evaluated the application of the PBL methodology to integrate the theoretical knowledge of several subjects into a single project. In this particular case study on DOE, the application of PBL facilitated the acquisition of theoretical knowledge in a practical manner and in a semi-industrial environment. This semi-industrial environment forced the students to apply the process of experimentation and measurement, for which they used advanced technologies, such as 3D printers, laser cutting machines and electronic measuring systems. To apply these technologies and analyse their results, they had to learn how to use different software, such as Minitab 21, IdeaMaker, SolidWorks and R-Studio, to successfully execute the project. Furthermore, working on the project as part of a team allowed them to gather transversal competences, such as teamwork, sharing responsibilities, decision making, writing technical reports, oral presentation and managing and organising shared information. Therefore, the results obtained show how the application of the PBL methodology facilitates the acquisition of both technical and transversal competences and reinforces the technical knowledge acquired during the course of the semester.

Several authors have identified the major limitation of PBL, which is the difficulty of applying it to a large number of students (Aldabbus, 2018; Córcoles & Martínez-Romero, 2020; Unzueta & Eguren, 2021). The methodology requires a great deal of dedication and involvement from the teaching staff before and during the PBL period. During routine classes, teaching staff had to develop a case study, define the case to be worked on in the PBL, design assessment rubrics for the competencies to be developed during the PBL (both technical and transversal), purchase the necessary material, design and develop the test bench for experimentation and schedule the activities to be carried out in the PBL. In addition, during the PBL period, they had to tutor the students, evaluate the progress of the students and share feedback on the final results of the project (Kokotsaki et al., 2016). To implement PBL successfully, it is necessary for the teaching staff to meet on a weekly basis. Nevertheless, our experience allows us to conclude that the hard work of the teaching staff is rewarded by the motivation and commitment of the students during the execution of the project. This commitment is clearly represented in the improved grades and in the results of the satisfaction survey. Based on the results of this study, it is clear that this improvement is due to the better assimilation of theoretical concepts and the enhanced ability of the students to apply them to a real-world scenario, which will be highly valued in the working environments they will encounter in the near future.

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

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