11th International Conference on Higher Education Advances (HEAd'25)
Universitat Politècnica de València, València, 2025
DOI: https://doi.org/10.4995/HEAd25.2025.19947

Multivariate Analysis of Academic Competencies in Civil Engineering Programs in Colombia

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How to cite: Delahoz-Domínguez, E.; Zuluaga-Ortiz, R.; Carmona-Armenta, L. (2025). Multivariate Analysis of Academic Competencies in Civil Engineering Programs in Colombia. In: 11th International Conference on Higher Education Advances (HEAd'25). Valencia, 17-20 June 2025. https://doi.org/10.4995/HEAd25.2025.19947

Abstract

This research aims to evaluate the academic efficiency of civil engineering programs in Colombia, using Data Envelopment Analysis (DEA) and the results of standardised tests at high schools and Universities and identifying significant differences in universities' academic performance through clustering (k-means) and Principal Component Analysis (PCA). As a result, disparities in educational quality were identified, suggesting that some universities face difficulties in preparing students. The conclusions revealed a need to implement strategies to improve education quality and strengthen civil engineers' training in Colombia.

Keywords: *Academic efficiency; educational quality; civil engineering; data envelopment analysis.*

1. Introduction

Adequate planning and structuring of the urban environment are fundamental to the development of a population because they become key tools for achieving a sustainable transformation (Barroso Del Toro et al., 2022). In addition, they help formulate medium—and long-term objectives in a way that fosters a collective and rational vision of the resources to achieve them.

In contrast, in countries with low urban development, a shortage of trained civil engineers and insufficient resources can make growing and maintaining adequate infrastructure complex (Theophilus, 2023). According to the Organisation for Economic Co-operation and Development (OECD) report "OECD Employment Outlook 2021", some developing countries still face challenges due to a lack of engineers and limited resources. As mentioned, civil engineering has been one of the most important agents for urban development today. The functionality of construction depends on this discipline since it offers society improvement and

advances in the environment, promoting progress in societies that are disadvantaged by others. The participation of civil engineering allows advances in infrastructure to occupy a relatively important place in society, and that can be used in a maximum way to improve the well-being of citizens (Polmear, 2022).

In this order of ideas, it can be said that engineering plays a fundamental role in the economic development of countries. Engineers apply science and technology to improve the development of society, thus increasing people's quality of life. Important entities related to the promotion and management of the discipline recognise engineering as a creative process, the maintenance or operation of systems, equipment, products and processes that respond to specific needs.

Therefore, evaluating academic efficiency in civil engineering programs in Colombia allows for guaranteeing educational quality in terms of training and developing competent professionals in this field. However, despite this need, the existing evaluations and controls in this situation have not been addressed comprehensively so far, so students' evolution throughout their university careers has been complicated. All this is because there are no adequate tools to measure and improve the quality of education.

2. Literature review

Various authors solve this problem from different approaches:

Their work (Zuluaga-Ortiz et al., 2022) carried out an efficiency analysis of higher education in Colombia, focusing on academic engineering programs. They used the data envelopment analysis (DEA) methodology with data from the Saber 11 Tests and Saber Pro Tests. The results indicated that industrial engineering showed greater efficiency than other programs and that non-accredited institutions had higher efficiency than accredited universities.

On the other hand, a study by (Visbal-Cadavid et al., 2017) efficiency study of Colombian public universities in 2012, conducted using the methodology of Data Envelopment Analysis (DEA) and the models CCR, BCC and SBM under output orientation. The results showed Tolima, Caldas and UNAD to be the best-performing universities, with Universidad del Pacífico as the worst performer. The malmquist index was applied to analyse the change in productivity from 2011 to 2012. The Universidad de La Guajira greatly improved technical efficiency between 2011 and 2012.

The authors (Puertas & Marti, 2019) also developed a sustainability indicator for higher education, evaluating academic and socioeconomic variables in a Data Envelopment Analysis model.

Consequently, Delahoz-Dominguez et al. (2020) developed an analysis of the competencies of the Saber Pro tests in Colombia based on the variable of Accreditation in the quality of Industrial

Engineering programs. The results show that accredited universities perform superiorly in each competency evaluated.

Considering previous research, it is necessary to conduct a study that seeks to estimate the academic efficiency of civil engineering programs in Colombia through data envelopment analysis (DEA), using the results of the SABER 11 tests and the SABER PRO tests as a database. The main objective of this research is to provide a comprehensive evaluation of existing university programs, identifying strengths and weaknesses in student training. Likewise, it will provide information to these entities for continuous improvement to identify factors that influence academic performance and implement specific strategies to optimise training quality.

3. Theoretical framework

This section presents the key tools for research.

3.1. Cluster analysis: k-means

The k-means algorithm (Clayman et al., 2020) or also called Cluster Analysis, is an experimental data analysis technique to solve classification problems. Arrange items into groups so that the similarity between members of the same profile is more compact than the association between members of different profiles. This allows you to discover structures in the data that are not very obvious but could be helpful to once they have been found.

3.2. Principal Component Analysis (PCA)

Principal Component Analysis is a statistical technique used to analyse large data sets containing many dimensions per observation, creating variables that function as linear combinations of the original variables. These new variables are weighted combinations of the original variables and are ordered according to their importance in explaining the variability of the data.

3.3. Academic competencies

The SABER 11 test is a Colombian secondary-level assessment designed to provide educational institutions with information on the development of basic skills that students must develop during their schooling. On the other hand, SABER PRO is an assessment for undergraduate students. Both evaluations are carried out by the Colombian Institute of Educational Evaluation (ICFES) and are designed to evaluate the quality of any public or private educational institution.

4. Methodology

This research proposes a methodology based on three stages: experimental data analysis, efficiency analysis and predictive data analysis (see Figure 1). In this first stage, a cluster analysis model is implemented using the K-means algorithm to help facilitate data clustering. In turn, the second stage is intended to carry out an exploratory analysis of data through principal component analysis (PCA) that allows reducing the dimensionality of the data and, finally, it is intended to diagnose the results delivered by the empirical methodology of the research.

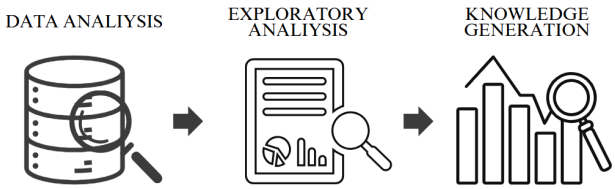

Figure 1: Research approach

5. Population analysis

The representative factors were identified through a rational analysis with a database containing 53,342 observations, each representing a student. This contemplation comes from applying state evaluations to 86 universities in Colombia for university students. However, in this research, the civil engineering program was considered. Only the parameters of universities and departments were established to reduce the number of observations, with 86 observations to be analyzed. Likewise, the data used in Table 1 reports the study's names, general average and standard deviation. The suffix for high school-level test variables and college-level assessments is S11 and SPRO, respectively. The indicators obtained corresponded to the results of the academic competencies presented above.

Table 1: Statistical summary of study variables.

VARIABLE	FULL NAME	$\bar{x}$	σ
MATH.HS	MATH - HIGH SCHOOL	58,40	6,17
CR. HS	CRITICAL READING - HIGH SCHOOL	55,43	4,14
SC. HS	CITIZENSHIPS SKILLS - HIGH SCHOOL	54,97	4,2
ENG.HS	ENGLISH - HIGH SCHOOL	55,88	7,05
NS. HS	SCIENCE - HIGH SCHOOL	56,11	4,86
CS.PRO	CITIZENSHIPS SKILLS – UNIVERSITY	101,83	17,93
WC.PRO	COMUNICACIÓN ESCRITA - UNIVERSITY	99,54	16,99
ENG.PRO	INGLÉS - UNIVERSITY	111,67	18,93
CR.PRO	LECTURA CRITICA - UNIVERSITY	107,78	18,05
QR.PRO	RAZONAMIENTO CUANTITATIVO - UNIVERSITY	116,95	22,15

6. Analysis by university

In the cluster analysis, the k-means algorithm was applied to improve the interpretation of the universities studied. Using a two-dimensional projection, the generated groups were represented in four clusters, each with specific dimensions.

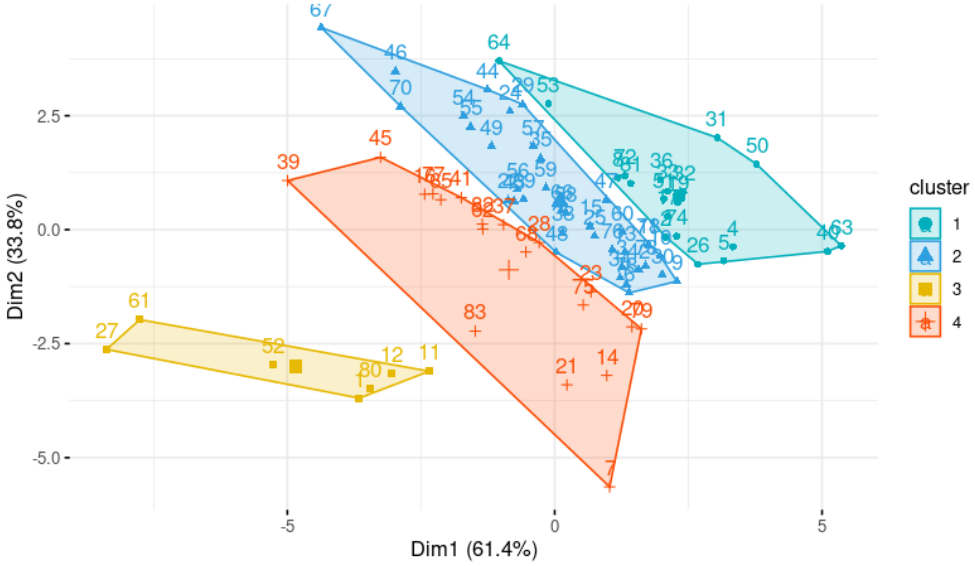

Figure 1. Cluster plot

The k-means method identified four different clusters. Figure 2 shows each cluster occupying a different region of the space and reflecting particular performance patterns based on Saber 11 and Saber Pro outputs.

Cluster 3 (High Performers): Located in the upper-right quadrant, this group includes universities that demonstrate strong outcomes across both Saber 11 and Saber Pro tests. Universities in this cluster present the highest overall academic efficiency, suggesting robust educational processes that effectively build on students' prior knowledge. These universities are closest to the direction of growth for Saber Pro competencies, which are aligned with the top-right direction of the first principal component (Dim1) and the second (Dim2), indicating advanced development in university-level skills such as critical reading, quantitative reasoning, English, and writing.

Cluster 1 (Low Performers): Positioned in the bottom-left quadrant, this cluster contains universities with the lowest performance across all assessed competencies. Their location—opposite to the vectors representing the growth of both Saber 11 and Saber Pro competencies—suggests significant challenges in incoming student preparation and institutional academic

development. Therefore, these institutions require support in curriculum design, pedagogical practices, and student support services.

Cluster 2 (Moderate Saber Pro Focus): Situated in the upper-center region of the plot, this group of universities shows a balanced but slightly stronger performance in Saber Pro competencies compared to Saber 11. Despite moderately prepared student cohorts, these institutions may be achieving learning gains during university education.

Cluster 4 (High Saber 11 Input, Low Saber Pro Output): Found in the lower-right region of the plot, this cluster represents universities with well-prepared incoming students (strong Saber 11 scores), but with less-than-expected development in Saber Pro competencies. This suggests a potential underperformance in value-added educational processes, where initial student potential is not fully realized during the university stage.

These clusters provide a meaningful segmentation of the civil engineering programs analyzed. While clusters 3 and 1 represent extremes in performance, clusters 2 and 4 reveal nuanced inefficiencies or mismatches between input and output competencies. This typology supports targeted policy interventions: strengthening pedagogical strategies in Cluster 4, leveraging best practices from Cluster 3, and designing support mechanisms for Cluster 1.

7. PCA Analysis by University

The graphical representation generated through principal component analysis (PCA) offers insight into the relationship between universities and the SABER 11 and SABER PRO competencies in the context of the Civil Engineering educational program. In this graph, the different universities' observations are dispersed and far from the competence variables.

The variability observed insinuates that most educational institutions that teach the Civil Engineering program show a limited level of mastery in the competencies evaluated in the SABER 11 and SABER PRO exams. Universities are far from proficiency metrics, suggesting an essential difference between the skills and knowledge students should acquire according to the standards established by these assessments and what they achieve during their academic training.

This graphical representation also suggests possible disparities in the quality of education offered by different universities in Civil Engineering. Distant observations of the variables may indicate deficiencies in the preparation and teaching of the competencies assessed, which in turn may have implications for students' training and competitiveness in the labor field.

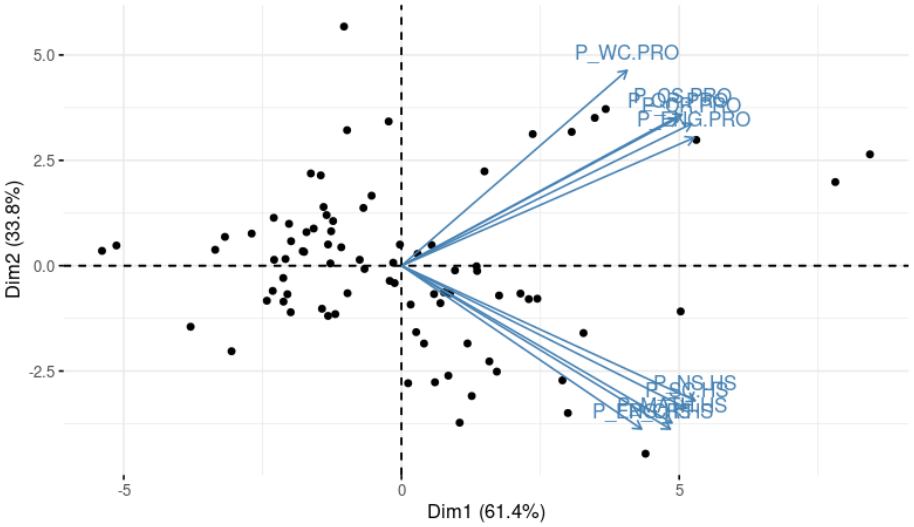

Figure 2. Two dimensions PCA-BIPLOT

8. Conclusions

Clustering analysis carried out in universities has been an important tool for discovering clusters similar to the Saber 11 and Saber Pro exams. This provides a unique opportunity to identify competencies requiring specific improvement in each set of departments and those you perform outstandingly. Such results are of fundamental importance for creating strategies for improvement in the educational system at the departmental level, providing a solid basis for informed decision-making in the educational field.

The information generated by the analysis of university clustering is relevant to understanding the performance and efficiency of the evaluated universities, which simplifies decision-making in the search for increasing the quality of education in the country.

Finally, the principal component analysis has provided the possibility of placing universities in four different quadrants according to their scores on academic tests. Quadrants one and three exhibit more modest averages, while quadrants two and four reveal a higher correlation in their achievements. These findings are invaluable for identifying patterns and trends in university performance and, consequently, implementing strategies that aim at improvement in specific areas.

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