Engineering Educators Bringing the World Together
2025 ASEE Annual Conference & Exposition
Palais des congrès de Montréal, Montréal, QC • June 22–25, 2025
Paper ID #48055

Process Mining for Curricular Insight: Evaluating Student Progression in Environmental Engineering Programs

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Abstract

This study employs a Process Mining approach to analyze the academic trajectories and curricular compliance of the 2017 cohort in the Environmental Engineering program at a private Chilean university. Established in 1999 and accredited for five years (2018–2023), the program has undergone multiple curricular innovations to enhance training in environmental sciences and engineering. A comprehensive assessment of 57 students' progression was conducted to identify gaps and inform the ongoing curriculum redesign process. Results reveal significant variability, with 18 distinct trajectories observed. Only 53% of students remained active in the program by their fourth year, and less than 11% were on track for timely graduation. Delays in completing foundational courses, such as Introduction to Differential Equations and Non-Conventional Renewable Energies, were identified as key barriers to progression. Top-quartile students completed over 38 courses, while those in the bottom quartile passed fewer than 26, indicating delays of at least three semesters. Structural challenges, including limited credit flexibility and scheduling conflicts, further contributed to these delays. Process Mining provided actionable insights, revealing patterns of academic bottlenecks and non-compliance with curricular prerequisites. These findings emphasize the need for targeted interventions, including stricter enforcement of prerequisites, enhanced flexibility in academic administration, and tailored support programs such as tutoring and intensive recovery courses. This study demonstrates the potential of Process Mining as a strategic tool for higher education, offering a dynamic, data-driven perspective to support curriculum design, improve retention, and enhance student outcomes. Future research should extend this approach to additional cohorts and disciplines to validate these findings and guide broader educational innovations. This work positions Process Mining as an analytical technique and a strategic lens to align institutional policy with real student needs.

Keywords: process mining, educational innovation, student progression, environmental engineering, data-driven decision-making, higher education.

Introduction

Entering higher education is a pivotal stage in students' academic and personal growth. According to Tinto's theory of student integration, academic and social integration are crucial in reducing student attrition [1]. However, this transition often presents significant challenges, including adapting to rigorous academic expectations and managing greater autonomy in learning. At the same time, universities are responsible for meeting students' expectations by designing educational experiences that not only lead to a professional degree but also prepare graduates for an evolving job market. For many students, however, this stage brings difficulties that may lead to dropout, frustration, and economic consequences, highlighting the urgent need for institutional strategies that support student retention and academic success [2].

In this context, monitoring students' academic performance is crucial, particularly for those experiencing persistent challenges that can lead to delayed progression or attrition. Academic indicators are essential for evaluating institutional effectiveness, particularly in accreditation and quality assurance processes [3]. However, these indicators often provide only a statistical overview, failing to capture the complexity of educational trajectories or offer a comprehensive understanding of the factors influencing students' academic progress.

To thoroughly assess educational trajectories, it is necessary to move beyond traditional approaches. While university information systems supply quantitative data on student enrollment and performance, they cannot often pinpoint when and how academic difficulties arise. In this regard, Process Mining has emerged as an innovative tool for exploring educational pathways from a dynamic, process-oriented perspective [4]. This approach identifies patterns such as dropouts or delayed graduation and enables institutions to anticipate challenges and develop targeted intervention strategies [5], [6].

The application of Process Mining in education has proven effective in generating actionable insights by transforming raw data into visual and interpretable representations of academic processes [7]. This is particularly relevant in a global context where graduation rates remain low despite higher participation in tertiary education, especially in disciplines such as engineering [8], [9]. In Chile, where timely degree completion is a key accreditation metric, understanding students' academic trajectories and optimizing their progression is strategically important [10].

The Environmental Engineering program at the Faculty of Life Sciences is an illustrative example of these challenges. Established in 1999, this program integrates interdisciplinary training with a strong emphasis on sustainability. Over the years, it has undergone multiple curricular innovations to align with labor market demands and respond to national and international educational trends. These efforts aim not only to maintain curricular relevance but also to enhance student retention and academic progression.

In 2017, the program introduced a revised curriculum (DUN 2401-2016) and, in 2022, initiated another cycle of curricular innovation. As part of this process, evaluating the academic trajectories of students who enrolled in March 2017 is crucial in assessing potential gaps between the intended curriculum design and students' progress. The findings from this evaluation will provide valuable insights to guide the ongoing curriculum revision. While this study is limited to the 2017 cohort in one university, the observed patterns may reflect broader structural challenges common to engineering education programs in similar contexts.

Thus, this study aims to assess the curricular compliance of students who entered the Environmental Engineering program in March 2017 under the DUN 2401-2016 curriculum. Employing a Process Mining approach, it seeks to identify gaps and opportunities for improvement and offer data-driven recommendations to support the curricular innovation process within the program.

Methodology

Description of the Case Study

This study analyzes the academic trajectories of 57 students who entered the Environmental Engineering program in 2017, the first cohort under the DUN 2401-2016 curriculum. The Environmental Engineering program, housed within the Faculty of Life Sciences, spans ten academic semesters and awards a bachelor's degree in environmental sciences upon completing the eighth semester, followed by the professional title of Environmental Engineer after the tenth semester. The National Accreditation Commission accredited the program for five years (2018–2023) [11].

The curriculum comprises 51 courses, structured across theoretical classes, assistantships, laboratory work, workshops, and fieldwork. It also incorporates professional practices, capstone projects, and degree activities. Depending on course requirements, instruction is delivered in face-to-face, blended, or online modes. At the time of this study, the 2017 cohort was in its fourth year of the program. This research follows a quantitative approach, as outlined by [12], focusing on objective measurements of curricular compliance.

Experimental Design

A descriptive, cross-sectional, non-experimental design was employed to analyze student performance from 2017 to 2020, without formulating a specific hypothesis. Data collection occurred in April 2021, capturing a single temporal snapshot to examine key variables and their impact.

Student information was retrieved from the "Banner" system using each student's Chilean Unique Tax ID (RUT). The dataset included:

- Courses taken and failed
- Curriculum status (e.g., active, dropout, academically eliminated, degree awarded)
- Enrollment in the study program

Data Processing

Data processing involved standardizing course names to address inconsistencies in the curriculum records (e.g., removal of accents, abbreviations, and formatting errors). Additionally, a marker was added to denote failed courses.

Students' RUTs were replaced with unique identifiers to protect confidentiality, and the curriculum records were consolidated into a single dataset for analysis. Process Mining techniques were applied using *Celonis software*, and auxiliary activities were introduced to mark semester completion from Semester I to Semester VIII.

Quantitative and Qualitative Analysis

A quantitative analysis assessed students' curricular progress based on completed courses and prerequisite fulfillment, identifying potential delays and bottlenecks in academic advancement. A qualitative analysis complemented this by examining patterns in student trajectories to uncover factors affecting academic performance.

For the trajectory analysis, a vertical approach was used to examine prerequisite-linked courses, organized into three curricular axes:

- Axis 1: Calculus I (first semester), Calculus II (second semester), and Introduction to Differential Equations (third semester).
- Axis 2: Calculus I (first semester), Calculus II (second semester), Electricity, Magnetism, and Waves (fourth semester), Non-Conventional Renewable Energies (seventh semester), and Integrator I (eighth semester).
- Axis 3: General Biology (first semester), General Chemistry (first semester), Organic Chemistry (second semester), General Biochemistry (third semester), and Environmental Microbiology (fourth semester).

Ethical Considerations and Limitations

All data were handled in compliance with institutional and legal regulations, ensuring confidentiality and anonymity. The dataset was used solely for academic and research purposes. However, certain limitations should be acknowledged:

- The analysis focused on a single cohort, limiting the generalizability of the findings.
- Data were collected at a single point, restricting insights into longitudinal trends.
- Unrecorded activities, such as course waivers or external credits, may have influenced the interpretation of student trajectories.

Results

Figure 1 presents the 18 distinct academic trajectories of the 57 students who entered the Environmental Engineering program in 2017, depicting their semester-by-semester progression from 2017 to 2021 and their academic status at the time of the study. The academic status categories include career change, dropout, academic elimination, ongoing enrollment, degree awarded, and permanent withdrawal. Notably, by the fourth year, only 53% of students remained active, underscoring significant challenges in curricular compliance and student retention.

By their fourth year, 30 students remained enrolled, while one student had graduated—having entered with prior coursework via internal transfer—and 26 students had left the program. Among these 26 non-active students, 14 withdrew in the first year, and nine withdrew in the second year. In total:

- 15 students permanently dropped out,
- 5 students were academically eliminated,
- 4 students withdrew voluntarily, and

- 2 students transferred internally to other programs.

For simplicity, English and general education courses were excluded from the analysis.

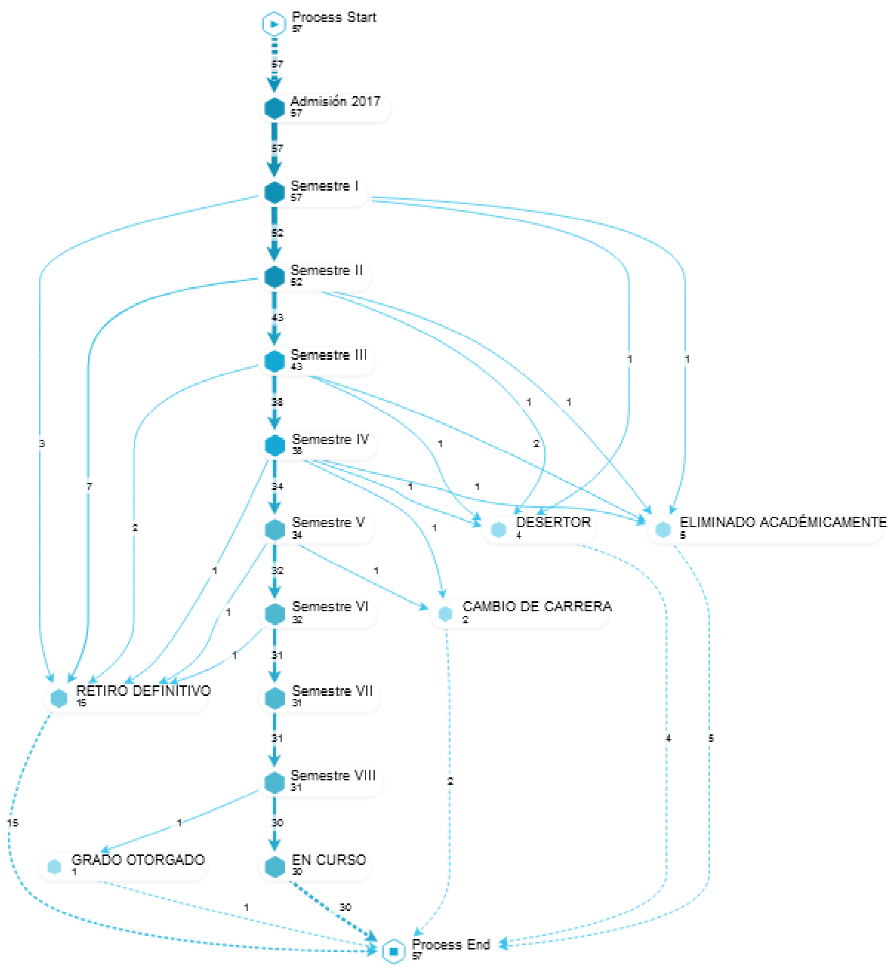

Figure 1. Situation and trajectory followed by students in the fourth year of the course.

Table 1 presents the percentage of completed courses among students in the Environmental Engineering program, categorized by academic status. The data indicate that currently enrolled students have the highest approval rate, with 87.15% of courses passed. In contrast, students who dropped out, changed careers, or permanently withdrew exhibit similar approval percentages. Notably, academically eliminated students demonstrate a significantly lower approval rate, having passed only 29.31% of their courses.

Table 1. Percentage of the total number of courses taken by students of the Environmental Engineering Career according to their academic status.

Academic Status	Courses Approved	Failed Courses
Career Change	56.76%	43.24%
Deserter	58.54%	41.46%
Academically Eliminated	29.31%	70.69%
Ongoing	87.15%	12.85%
Grade Awarded	98.08%	1.92%
Permanent Withdrawal	52.41%	47.59%

Table 2 presents statistical indicators based on the total number of courses passed by students in the program, categorized by quartile separation. The high variability in the number of courses passed (standard deviation: 6.01) reflects inconsistencies in student progress. Notably, only students in the top quartile are on track for timely graduation.

Table 2. Statistical indicators of curricular fulfillment of students in a course.

Statistical indicators	
Minimum	22
First quartile	26
Second quartile (Median)	33
Third quartile	38
Maximum	40
Average	32.33
Standard deviation	6.01

Table 3 presents the distribution of students by course, categorized by the number of courses passed. The lowest-performing students have passed only 22 courses, placing them at least four semesters behind compared to the highest-performing students, who have completed 40 courses by the eighth semester.

Students in the second quartile have passed 26 to 33 courses, indicating a two—to three-semester delay. The third quartile includes students with 33 to 38 courses passed, reflecting a delay of at least one semester. In contrast, students in the highest quartile, having completed over 38 courses, are on track for timely graduation. The standard deviation highlights the high variability in students' academic progress.

Table 3. Students in the course are grouped by the courses they have passed.

Number of courses passed	Number of students
22 a 26	9
27 a 33	6
34 a 38	9
39 a 40	6

Table 4 summarizes the curricular fulfillment of the 30 enrolled students in the Environmental Engineering program, analyzed by semester. The data reveal a progressive decline in the percentage of completed courses as students advance toward the eighth semester. By this stage, the approval rate drops to 61.33%, whereas the first semester is the only instance where all students pass 100% of courses.

A notable decline was observed in the seventh semester, attributed to an exceptional situation caused by the COVID-19 pandemic. During this period, one course remained pending, as its completion required postponing field activities until sanitary conditions permitted their execution.

Table 4. Percentage of curricular compliance by semester.

Semester	Curricular compliance (%)
1st Semester	100.00%
2nd Semester	98.67%
3rd Semester	90.00%
4th Semester	83.33%
5th Semester	82.00%
6th Semester	76.00%
7th Semester	46.67%
8th Semester	61.33%

Analysis and Discussion

The first vertical analysis examined introductory science courses taught by the Department of Mathematics, precisely the sequence of Calculus I (first semester), Calculus II (second semester), and Introduction to Differential Equations (third semester). According to the curriculum, these courses should be completed by the end of the third semester.

However, as shown in Figure 2, students followed 18 distinct trajectories, with only six students (20% of the cohort) completing the sequence as prescribed. The second most common trajectory involved four students (13% of the cohort) who completed all three courses by the fifth semester.

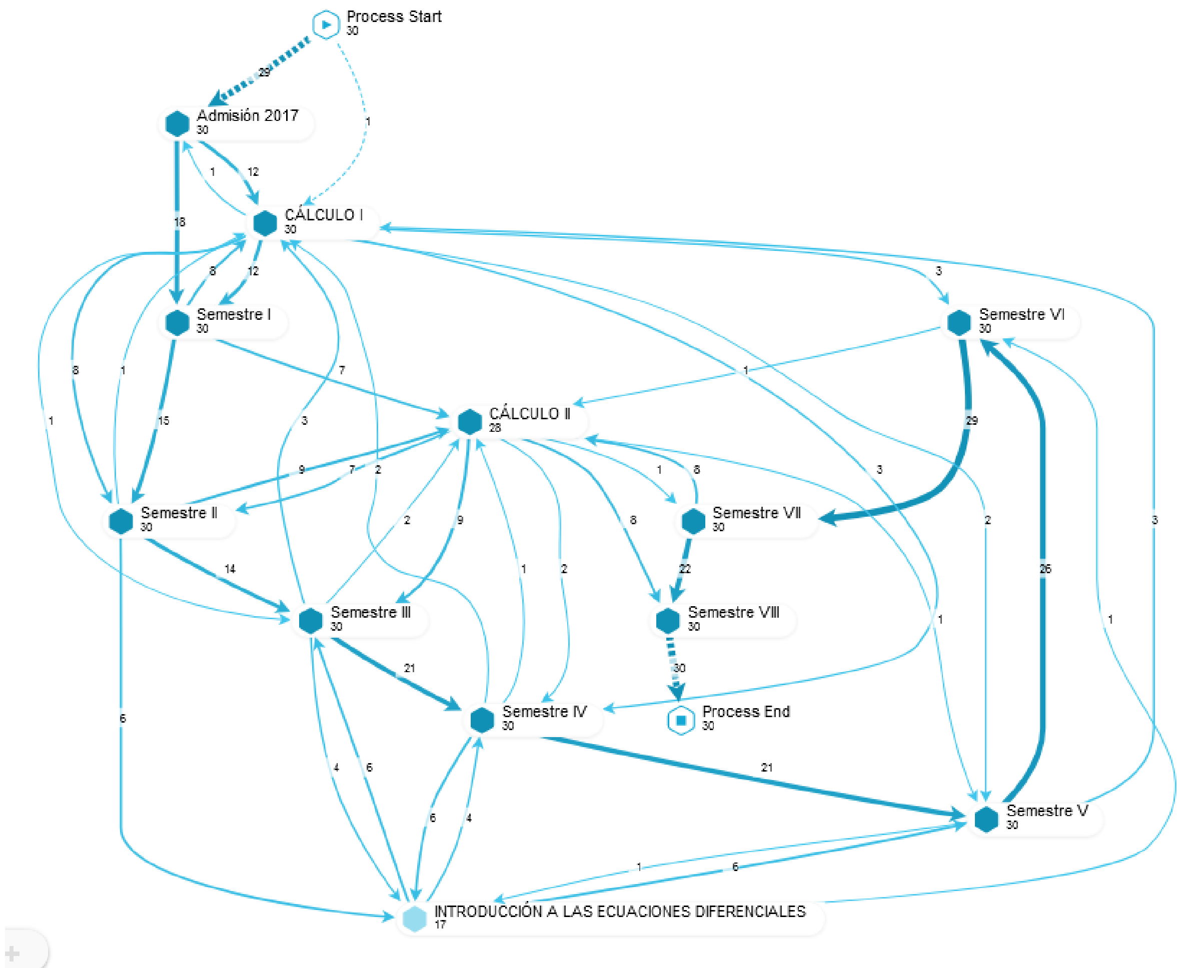

Figure 2. Trajectory followed by the students in the axis of the courses Calculus I, Calculus II, and Introduction to Differential Equations.

A notable finding is that two students have not taken Calculus II at all, and only 17 of the 30 currently enrolled students have passed Introduction to Differential Equations. Consequently, 13 fourth-year students have yet to complete this course.

One possible explanation for these results is that Introduction to Differential Equations is not a prerequisite for other courses within the curriculum. As a result, students may deprioritize it, opting to postpone completion. This lack of prioritization is concerning, as mathematics is the foundation for specialized courses in the program, particularly those related to Environmental Management and Waste Management. Delays in completing foundational courses may negatively impact academic performance in advanced courses and contribute to lower timely graduation rates. This issue is especially critical for the two students who, by the eighth semester, have yet to complete Calculus II.

Figure 3 highlights a third trajectory involving three students (10% of the cohort) who exhibit a unique pattern: They passed Calculus I in the sixth semester and Calculus II in the eighth semester while still pending Introduction to Differential Equations. In other words, now in their fourth year, these students are only beginning to complete first-year courses.

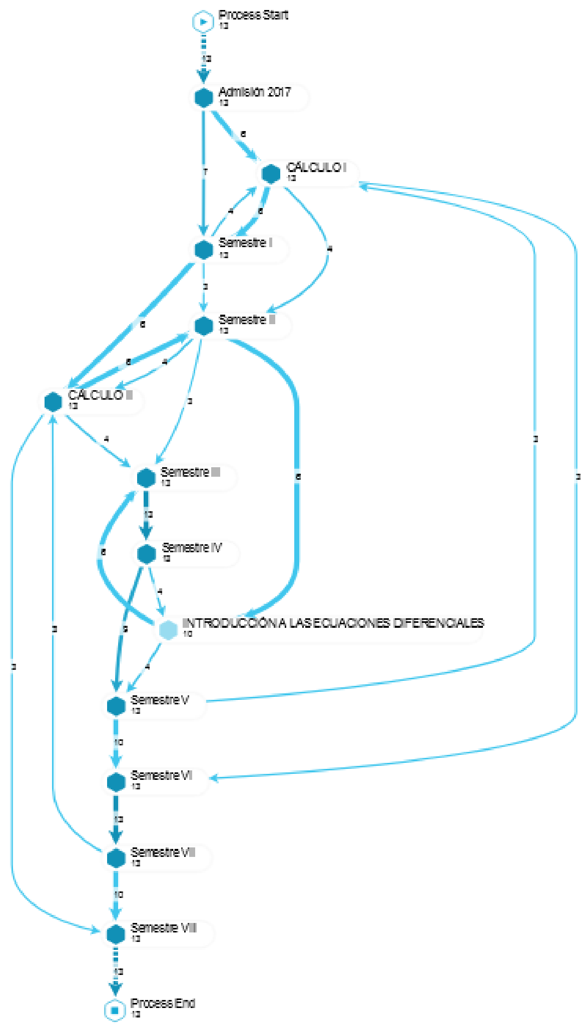

Figure 3. Trajectory followed by the students on the axis of the courses Calculus I, Calculus II, and Introduction to Differential Equations.

These findings underscore the need for targeted interventions to support students experiencing significant academic delays. Implementing concrete measures is essential to help these students complete pending courses without further failure, reducing the risk of delayed graduation or late program dropout.

The second vertical analysis examined the sequence of Calculus I (first semester), Calculus II (second semester), Electricity, Magnetism, and Waves (fourth semester), Non-Conventional Renewable Energies (seventh semester), and Integrator I: Environmental Engineering Project (eighth semester). Since Integrator I is part of the eighth semester, auxiliary activities were excluded to prevent excessive trajectories in the visual representation.

As shown in Figure 4, students following this vertical axis exhibit eight distinct trajectories. The most common trajectory, followed by 10 students (33% of the cohort), involves completing all five courses within the prescribed four-year timeframe. The second most frequent trajectory, observed among nine students (30% of the cohort), includes students who completed only up to Calculus II by the eighth semester.

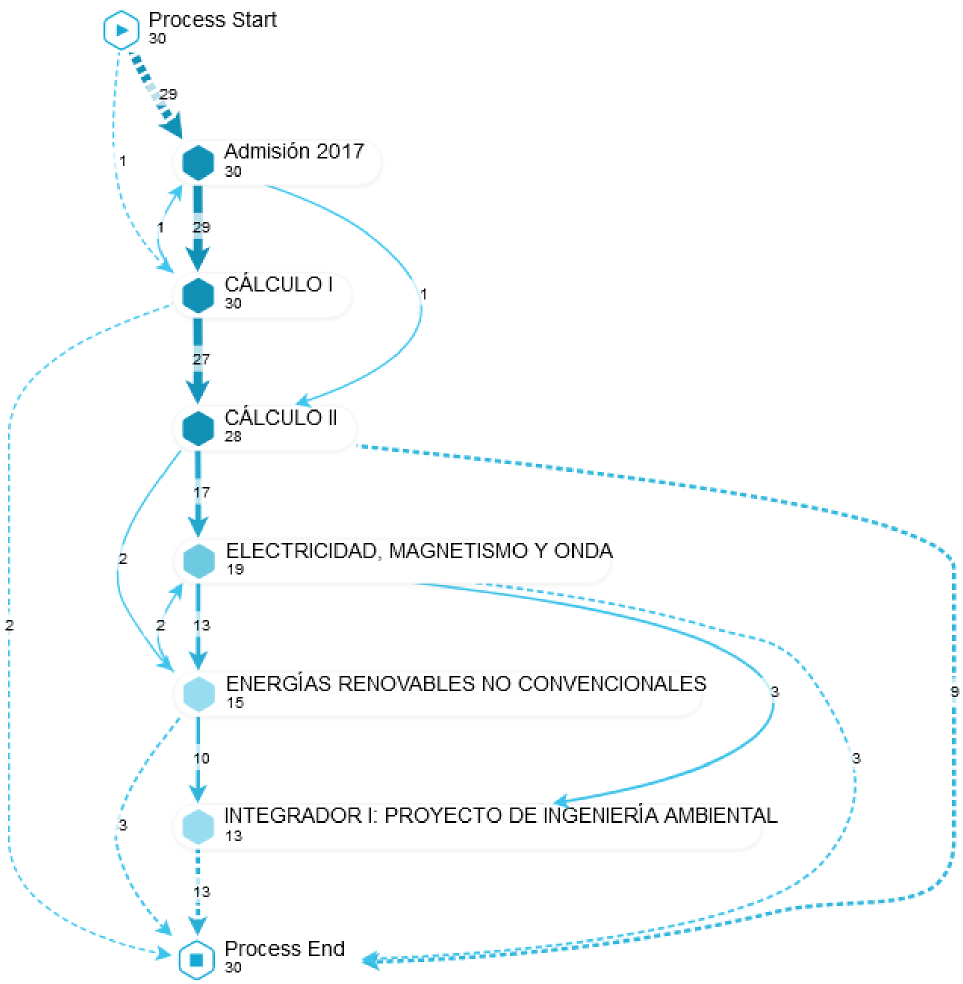

Figure 4. Trajectory followed by the students in Calculus I, Calculus II, Electricity, Magnetism and Waves, Non-Conventional Renewable Energies, and Integrator I: Environmental Engineering Project.

Additionally, two notable non-conformities were identified. Two students enrolled in Non-Conventional Renewable Energies without first completing Electricity, Magnetism, and Waves, and one student took Integrator I: Environmental Engineering Project without having passed Non-Conventional Renewable Energies. These instances represent violations of the curriculum's prerequisite structure.

Moreover, only 13 currently enrolled students (fewer than 50%) are taking Integrator I within the designated eight-semester timeframe. Consequently, only these 13 students remain potential candidates for timely graduation, provided they do not fail any additional courses in their final two semesters.

The observed non-conformities indicate that the logical course sequence and curriculum prerequisites were inconsistent. This suggests that some students enrolled in advanced courses without the necessary foundational knowledge, which could potentially affect their academic performance and progression.

The third vertical analysis examined the sequence of General Biology (first semester), General Chemistry (first semester), Organic Chemistry (second semester), General Biochemistry (third semester), and Environmental Microbiology (fourth semester). According to the curriculum, these courses should be completed by the end of the fourth semester. The auxiliary activity "Semester IV" was used to differentiate trajectories to identify students who adhered to the prescribed timeline.

Figure 5 reveals nine distinct trajectories among students in this sequence. The most common trajectory, followed by 11 students (37% of the cohort), involved completing Environmental Microbiology after the fourth semester. The second most frequent trajectory, observed among six students (20%), included students who completed General Biochemistry and Environmental Microbiology after the fourth semester. In the third trajectory, four students delayed the completion of Organic Chemistry, General Biochemistry, and Environmental Microbiology until after the fourth semester.

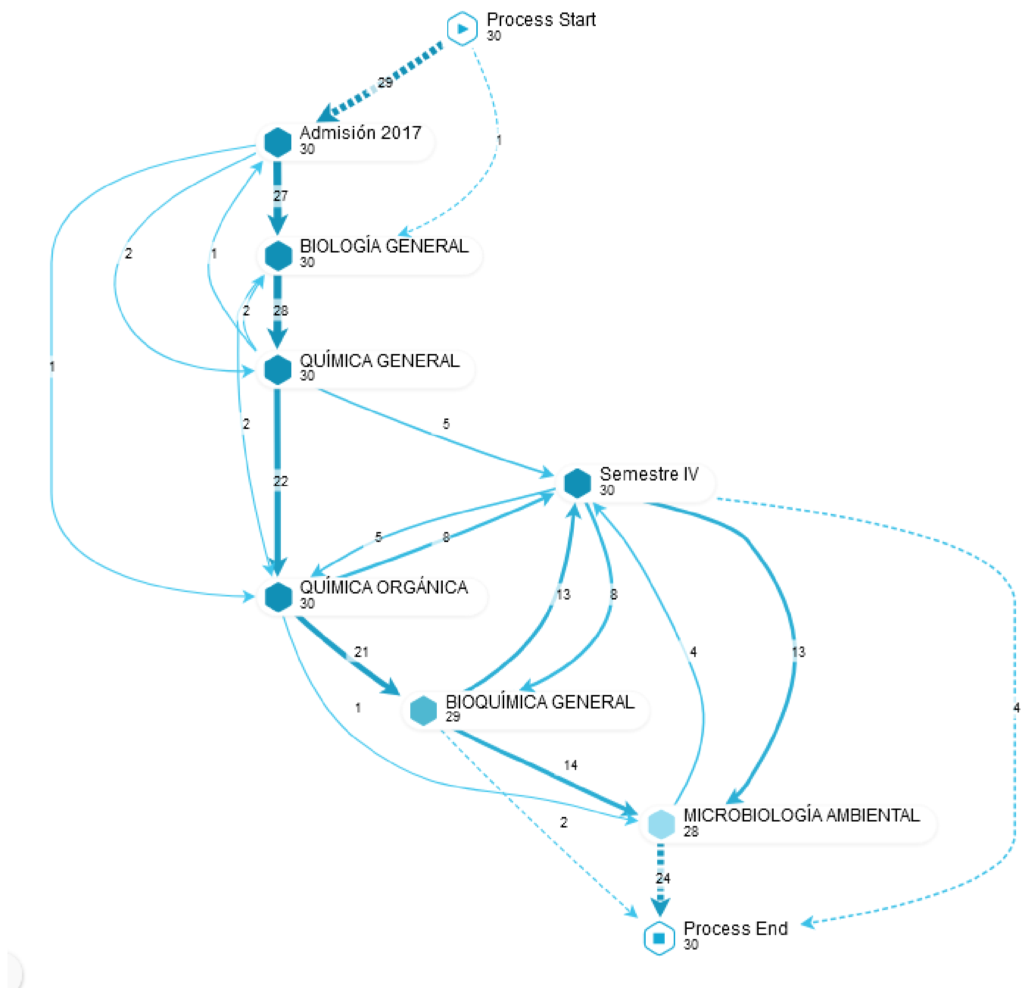

Figure 5. Trajectory followed by the students in General Biology, General Chemistry, Organic Chemistry, General Biochemistry, and Environmental Microbiology courses.

These findings indicate that 21 students (70% of the cohort) in the first three trajectories did not adhere to the curriculum's prescribed timeline. Only the fourth trajectory, followed by three students, aligns with the expected schedule for completing these courses within the designated timeframe.

The analysis of student trajectories across the three evaluated curricular axes reveals a significant gap between students' curricular compliance and the intended structure of the Environmental Engineering program's curriculum. This is evidenced by the following:

- Of the 57 students who entered in 2017, only 30 remain enrolled and/or active, with one student graduating and 26 leaving the program for various reasons.
- The overall curricular compliance of active students up to the eighth semester stands at 79.75% of courses completed.
- The ratio of courses passed to courses taken by active students is 87.15%.

- Only 13 students have completed Integrator I: Environmental Engineering Project by the eighth semester.

Additionally, 17 students are unlikely to graduate within five years, as they have not completed all eighth-semester courses, including Integrator I. Specific deficiencies were identified in earlier courses:

- 2 students have not passed Calculus II (second semester).
- 13 students have not passed Introduction to Differential Equations (third semester).
- 11 students have not completed Electricity, Magnetism, and Waves (fourth semester).
- 11 students have not passed Geology and Soils (fifth semester).
- 8 students have not passed Environmental Chemistry (sixth semester).
- 15 students in the seventh semester have not passed Non-Conventional Renewable Energies.

Notably, students above the 50th percentile (those who have completed over 33 courses) may require one to two additional semesters to graduate, while those below the 50th percentile may need up to four additional semesters. Conversely, only six students above the 75th percentile are on track to graduate within five years.

Table 7 summarizes the key factors contributing to curricular noncompliance in the DUN 2401-2016 curriculum among students who entered the Environmental Engineering program in 2017.

Table 7. Curricular noncompliance factors.

Non-compliance factors	**Remarks**
Students with a high number of failed courses	Failed courses generate delays and low curricular compliance because the failed course must be taken a second and even third time, with a quartile of students with a maximum of 26 approved courses.
Limitation of credits to be taken per semester	Students can only take a limited number of courses per semester, which means that they can only take five courses in a regular semester, except if they request authorization from the course director to take six courses exceptionally.
Availability of schedules	Students who fail courses face semester-to-semester schedules designed for students who are fulfilling their curricular requirements according to the course curriculum, so their fees prevent them from taking and making compatible courses of different levels.

While this study focuses on the Environmental Engineering program at a Chilean university, similar challenges in curricular progression have been documented in engineering programs worldwide. Studies in North America and Europe have highlighted that delays in foundational mathematics and physics courses are a significant barrier to timely graduation in engineering disciplines [8], [9]. In particular, the role of Differential Equations as a gateway course has been noted as a key predictor of student persistence in STEM programs [6]. Our findings align with these trends, reinforcing the need for strategic curriculum interventions to support student progression.

Our analysis found that Introduction to Differential Equations is not currently a prerequisite for advanced engineering courses despite being a crucial course. This has resulted in students delaying its completion, which may negatively impact their performance in subsequent courses that require mathematical modeling. Given the observed academic bottlenecks, a curriculum revision should consider enforcing stricter prerequisite requirements to ensure foundational knowledge before students advance to specialized topics.

The findings underscore the importance of structured prerequisite enforcement and academic support programs. Introducing mandatory prerequisite sequences for mathematics and physics courses could mitigate delays in student progression. Additionally, academic support mechanisms such as targeted tutoring and summer-intensive courses for at-risk students may enhance retention. Future curriculum updates should integrate these strategies to improve student outcomes and program efficiency. Furthermore, this study highlights the potential of Process Mining as an analytical tool for curriculum evaluation, offering insights that can inform data-driven educational policy decisions.

Conclusions

This analysis provides a comprehensive perspective on the challenges students face in their academic progression and the limitations of the current curriculum, contributing to the broader discourse on curriculum design and student retention within higher education, as highlighted in Kuh's framework for student success [14]. The study identified patterns, gaps, and key factors influencing academic performance and curricular compliance using advanced tools such as Process Mining. This approach enables the development of targeted recommendations to improve the curriculum and student support strategies.

Key findings

The analysis revealed significant variability in student trajectories, with 18 distinct patterns among active students and a low percentage completing the curriculum within the designated timeframe. These findings highlight several key issues:

- Delays in completing critical courses: Only 10% of students adhered to the prescribed prerequisite schedule, while the majority experienced delays of one to four semesters.
- Postponement of fundamental courses: The tendency to delay key courses, such as Introduction to Differential Equations and Non-Conventional Renewable Energies, underscores the need for stricter enforcement of curricular compliance. The lack of prioritization and insufficient prerequisite enforcement compromises students' progression in advanced courses.
- Structural and administrative challenges: Constraints in the credit system and rigid scheduling exacerbate difficulties for students who fall behind, limiting their ability to catch up and increasing their academic backlog.

- High attrition and low-performance rates: The 46% attrition rate and high failure rates in early courses align with Astin's involvement theory, which posits that higher student engagement reduces dropout risks [13]. These challenges negatively impact student motivation, institutional retention, and graduation rates.

The data further indicate that only six students (10.5%) are on track to graduate within five years, while the majority will require additional semesters. These delays result in financial and personal consequences for both students and the institution. These delays also impact program quality in accreditation and ranking evaluations.

Recommendations

To address the challenges identified in this study, it is essential to optimize curricular design by reinforcing the sequence of prerequisites in critical areas such as mathematics, basic sciences, and specialized courses. Strengthening prerequisite enforcement can help prevent cumulative delays in student progression. Additionally, greater curricular flexibility should be incorporated to allow for personalized academic trajectories that accommodate students who are behind, such as enabling them to take additional courses under specific conditions.

Implementing academic support strategies is also crucial in improving student outcomes. Establishing specific tutoring programs for courses with high failure rates, such as Calculus II and Introduction to Differential Equations, would provide struggling students with the necessary support to succeed. Furthermore, intensive recovery programs offered during summer semesters could assist students in addressing academic backlogs, ensuring they can regain momentum in their studies and stay on track for graduation.

Early performance monitoring is vital in identifying at-risk students before they accumulate academic deficiencies. Developing an early warning system that uses progress indicators and Process Mining tools would allow for personalized interventions from the first semester, ultimately improving student retention and academic performance. Consistent with the principles of formative assessment, timely feedback should be provided to guide students and help them adjust their learning strategies accordingly.

Flexibility in academic administration is another area that requires attention. Revising credit allocation and scheduling policies could give students better opportunities to optimize their academic load. Facilitating schedule compatibility between courses at different curriculum levels would further support students outside the regular academic sequence, allowing them to make up for lost time and reduce delays.

Fostering student engagement and a sense of academic responsibility is equally important. Workshops on time management, effective study strategies, and stress management could equip students with the tools needed to take greater control of their learning. Additionally, introducing incentives for timely graduation, such as partial scholarships for students who make consistent academic progress without failing, could motivate students to complete their studies within the designated timeframe.

Future research

This study provides a foundation for future research by enabling comparative assessments of curricular innovations and policy changes in the Environmental Engineering program. Future studies should evaluate the academic performance of the 2017 cohort beyond the eighth semester to determine their long-term outcomes and identify patterns that may inform further improvements. A follow-up analysis after the tenth semester would offer valuable insights into the long-term impact of curricular design and administrative policies on student retention and graduation rates.

Expanding the scope of research to include students admitted after 2017 would allow for a broader analysis and greater validation of the current findings. By examining multiple cohorts, researchers can assess whether curricular modifications and institutional interventions effectively address the challenges identified in this study. Additionally, future studies should explore the effectiveness of specific retention strategies and curricular adjustments in improving academic success and reducing delays. Understanding the impact of targeted interventions, such as early performance monitoring and academic support programs, would provide actionable insights for higher education institutions seeking to improve student outcomes.

Given that this study focuses on a single cohort and relies on Process Mining tools, future research should also consider alternative methodologies that capture longitudinal trends and the nuanced experiences of diverse student populations. Conducting comparative studies across different universities and disciplines would help validate the applicability of these findings in varying academic and cultural contexts. A cross-institutional approach would allow researchers to identify common trends and best practices, informing strategies that enhance student retention, timely graduation, and overall program quality.

Acknowledgments

The authors gratefully acknowledge the leadership and financial support of the School of Engineering at the Universidad Andres Bello, Chile. We also thank the Educational Research and Academic Development Unit (UNIDA) for its mentorship and guidance in developing research skills for higher education faculty.

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