2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering Education for 130 Years
ASEE
Paper ID #37360

Civil Engineering Curricula and Sustainability Education: An International Cross-Case Analysis of Alignments and Gaps

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Abstract

Engineering is essential to progress towards a sustainable future. Achieving this goal is supported in part by the profession's fundamental mission: to address basic human needs and improve quality of life. However, analysis shows that when the preparation of engineers at universities focuses on traditional and technical skills, such a curriculum is insufficient for preparing graduates to tackle current global challenges, such as climate change, poverty, and the humanitarian crisis. As with the Washington Accord, engineering accreditation bodies increasingly recognise that these challenges demand a new kind of engineer equipped with a new set of competencies and capacities. In some cases, this has led to evolution, if not revolution, in engineering curricula as the social compact comes to the fore. This study examines what is happening and which initiatives are promoted to embed sustainability considerations in two civil engineering curriculums: one aligned with the Washington Accord (in Australia) and one not (from Colombia).

The study proceeds from the understanding that while the volume and breadth of research about ensuring engineering education addresses sustainability well have increased rapidly during this century, there have been few empirical studies beyond a single institution's case. Furthermore, many case studies have also been limited to documenting changes in course maps or the explicit curriculum, i.e., what is overt in the documentation. In light of this, this research presents findings from a doctoral thesis that analyses educators' and students' experiences of the *explicit* and *implicit*—which is learnt from the organisation, intentions, attitudes and behaviours of the educators, for example, and what is not taught respectively—to provide a richer picture of what is understood and experienced as the intended and enacted curriculum.

In general, findings suggest that accreditation systems (such as the Washington Accord) highly influence the adoption of educational responses towards sustainability in the civil engineering curriculum. The accreditation requirements ensure that sustainability is addressed in specific discipline-based units, and to a greater extent, in the capstone unit. Barriers, however, occur in both cases because sustainability considerations are not scaffolded. The cross-case analysis also shows that while project-based environments were the most common type of educational responses implemented to strengthen students' sustainability-based knowledge and skills, findings suggested projects do not always encourage the same complexity of problems and, consequently, do not generate the same level of learning outcomes. Results also reveal that hidden-curriculum responses were decisive for students to embrace new sustainability perspectives. Finally, the research also provides insight into future curriculum strategies for developing engineering education for sustainability.

1 Introduction

Engineers have consistently been recognised for their ability to solve problems that address basic human needs. These abilities have framed the profession's fundamental mission to improve the quality of life and contribute to a sustainable future [1]. However, before the 21st century, engineering was considered "the art or science of making practical application of the knowledge of pure sciences" [2]. This definition raised the importance of technical and problem-solving skills in the engineers' profile [2], prompting a technocratic paradigm in engineering education [3]. Nevertheless, current global challenges have demanded a new set of competencies and capabilities in engineers that allow them not only to develop practical solutions but also to contribute to the common well-being of humans and more-than-humans [1].

Sustainability wicked problems require engineers to act as active citizens, working collaboratively with other disciplines to contribute to a better world for all. These demands have led to evolution, if not revolution, in engineering curricula, recognising the importance of sustainability considerations in the discipline [4]. Notably, learning outcomes stipulated by engineering accreditation bodies have been modified to respond to these challenges [5]. For instance, the Washington Accord have included criteria associated with sustainability, ensuring that students participate in learning spaces where they can develop engineering solutions framed under multi-constraint factors and contextual settings. Graduate attributes adopted by the Washington Accord have been reviewed since the beginning of this century to include sustainability considerations [6], which have increased the volume and breadth of research about how sustainability is addressed in engineering education [4, 5].

While numerous case studies have been reported in civil engineering showing how the explicit curriculum has adapted in response to these changes [e.g., 7], few empirical studies go beyond the case of a single institution to understand the broader phenomenon and develop comparative understandings of the challenges these new priorities present. To tackle this problem, this research presents findings from a doctoral thesis that develops a multiple-case design, focusing on the nature and purpose of responses toward sustainability adopted in two civil engineering programs.

The first case study is in Australia, part of the Group of Eight, which comprises this country's leading research-intensive universities. The second case study was conducted at a Colombian University within the top tier of public universities in Latin America. After completing a separate analysis of the cases and understanding how distinct forces influenced their educational responses toward sustainability at the curriculum and unit level, a cross-case analysis is elaborated. The cross-case study identifies similarities and differences between the cases to provide insight into recommendations for future curriculum strategies in developing engineering education for sustainability. Finally, limitations and suggestions for future research are provided.

2 Background literature

Scholars have documented some of the changes engineering curricula have experienced when integrating sustainability considerations. Lozano and Peattie [8] have claimed that engineering curricula have traditionally undergone four main changes when incorporating sustainability: 1) including additional content in existing units or courses; 2) designing and incorporating a new unit related to sustainability in the curricula; 3) integrating sustainability as a concept in current discipline-based units and redesigning the essence of the unit considering sustainability considerations; and 4) designing new programs as part of faculties and schools targeted exclusively at sustainability topics. These four changes include components of two of the three typical 'phases of pedagogy activity' described by Desha et al. [9] that compose engineering curriculum renewals towards sustainability, known as ad hoc exploration and the flagship approach. These two phases exemplify changes where there is an initial commitment to include sustainability topics, but the curriculum remains almost unaltered. Desha et al. included an additional phase called integration, when a full curriculum transformation towards sustainability is promoted, characterised by a gradual integration of sustainability topics in most discipline-based units.

Environmental and sustainability education (ESE) models have suggested that a transformation in the curriculum towards sustainability requires a cultural paradigm shift [10]. Students and academic staff, thus, need to experience transformation in their values, beliefs and attitudes that frame their professional skills and capabilities, contributing to a sustainable future. Juárez-Nájera et al. [11] have claimed that engineering education in tertiary institutions requires 're-education' and 're-programming' of teaching and learning practices to integrate a sustainable culture that fosters new epistemologies, mindsets, and ethics. This is in good agreement with Sterling [10], who indicates that transforming education towards sustainability requires the evaluation of the nature and purposes of educational responses in order to recognise the values that frame its orientations. Therefore, determining and evaluating the nature and purposes of educational responses in the civil engineering curriculum seems necessary to uncover assumptions about views and ends of engineering education for sustainability.

In addition, researchers [4] have found that curricula and learning space renewals require transgressing discipline-based or technical teaching strategies exclusively to the explicit curriculum to promote educational responses in the implicit curriculum. This is because implicit curriculum strategies might help engage students' interior attributes, such as awareness, values, and beliefs, into learning spaces. Here explicit or intended curriculum refers to the technical content that needs to be covered to prepare students with a specific set of knowledge and skills for the workforce [12]. On the contrary, the implicit or hidden curriculum is unpredictable and highly influenced by the social context of the university.

In response to the previous demands described in the literature, this research analyses educators' and students' experiences of the explicit and implicit curriculum—which is learnt from the organisation, intentions, attitudes, and behaviours of the educators, for example, and

what is not taught explicitly—to provide a richer picture of what is understood and experienced as the intended and enacted curriculum in relation to sustainability.

3 Research Methodology

This research has been framed under a multiple-case design, which uses two case studies in two different national contexts to analyse a common phenomenon and draw cross-case conclusions (i.e., how civil engineering education has responded to address sustainability considerations). Two case studies have been used because they bring different perspectives and contrasting results that enhance the understanding of the phenomenon [13]. The multiple-case design adopted for this research (see **Figure 1** and **Table 1**) shows that both case studies were treated as holistic, meaning there was a single unit of analysis, the civil engineering curriculum [13].

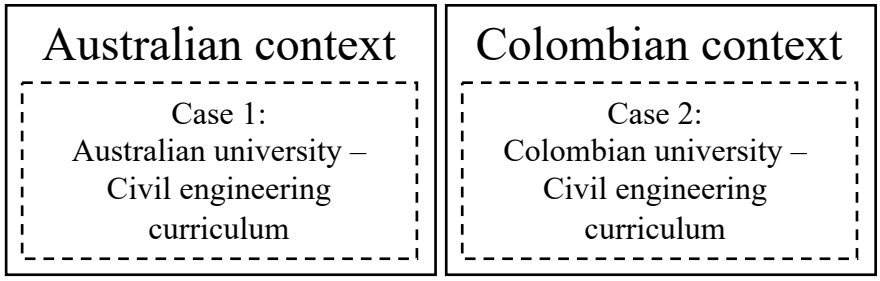

Figure 1. Multiple-case design.

Table 1. Features of the cases.

Feature	Australian University	Colombian University
Type	Public	Public
Accreditation	Engineers Australia – Washington Accord	EUR-ACE system
Duration civil engineering program	Four years	Five years

This multiple-case design has also been underpinned by a constructivist paradigm, which acknowledges that the researcher (lead author) has created meaning based on interpretations of the educational responses in the civil engineering curriculum. These interpretations are context-dependent and guided by people's actions under particular contextual settings [14]. Therefore, the findings of this research reflected the subjective construction of knowledge between the researcher and the interpretation of the data [15].

A cross-case analysis explored similarities and differences in the nature and purpose of responses adopted in both civil engineering programs to embed sustainability considerations. While this analysis was conducted to provide case-based insights into a global panorama of civil engineering education for sustainability, it is worth noting that both cases are influenced by their national contexts and, consequently, by distinct contextual forces, such as the

accreditation system, educational model, and resources available. Hence, findings of the cross-case analysis presented in this article have been obtained by exploring patterns between the cases alongside the specific national context and global features of engineering education [16].

A replication logic was ensured when collecting data to ensure consistency between both cases [13]. These data came from various qualitative sources and participant perspectives (**Figure 2**). The primary data corresponded to semi-structured interviews with educators of the units that addressed sustainability topics to obtain information about intended learning outcomes and priorities, educational approach and teaching learning activities, interactions within and outside the classroom, and experienced drivers and barriers. Likewise, last-year students were interviewed to explore their learning experiences and perceptions of their undergraduate studies.

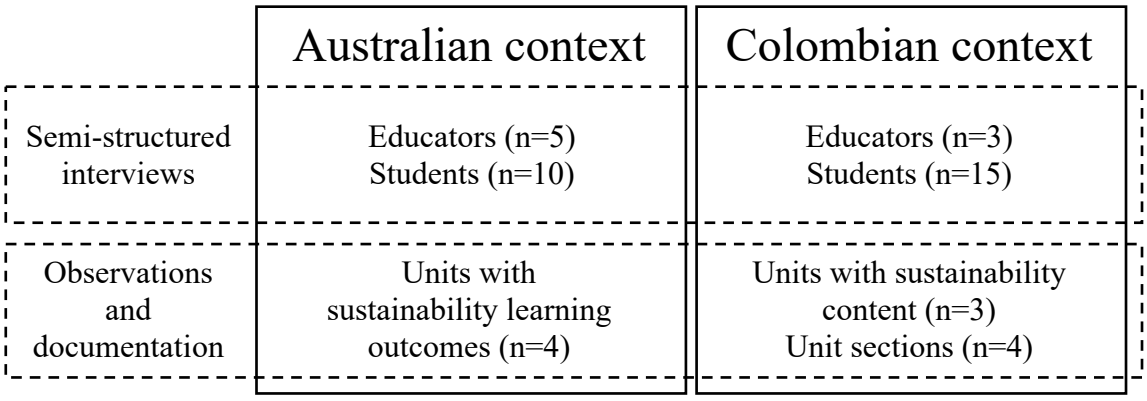

Figure 2. Data sources of the multiple-case design.

The secondary data entailed observations and documents of the units. On the one hand, two observations per unit were conducted to analyse enacted teaching and interaction within the classroom. On the other, accreditation documents, handbooks and syllabi were collected to complement information from the semi-structured interviews, particularly concerning intended learning outcomes and teaching learning activities. All data were collected between Aug. 2021 and Sep. 2022. Likewise, ethical approval for this research was obtained through the Univeristy Ethics Committee. Participants gave informed consent once they accepted to participate and had the right to withdraw from further participation without any consequences.

4 Results

Both civil engineering curriculums had already adopted educational responses to embed sustainability considerations at the time the data was collected. A common feature between both cases was related to the purpose for adopting these responses. Both cases aimed to approach civil engineering students to sustainable engineering practices, explaining how civil engineering projects affect the context and environment where they are developed. Sustainable engineering practices were formulated based on common methodologies, techniques, and tools used in the industry (e.g., life-cycle assessment or green building certification programs). Students, in both cases, also had learning opportunities to apply these sustainable practices in ‘real-life’ projects where sustainable engineering solutions were formulated and developed.

While there were similarities in the overall purpose behind adopting educational responses towards sustainability in the curriculum, some distinctions were also evident. The uniqueness of each case and the interconnectedness between specific case features, such as the accreditation system and the curriculum design (including explicit and implicit), have influenced the adoption of educational responses towards sustainability. The following sections present the national context of both cases and particular features regarding what is happening and which initiatives are promoted to embed sustainability considerations.

4.1 Case study 1: Australian University

The first case is from a four-year tertiary-level undergraduate civil engineering program. The course team has changed various aspects of the curriculum in relation to how students engage in sustainability since 2015, primarily following recommendations of Engineers Australia (i.e., Stage 1 competency standards [17]). The course team sees the standards associated with the accreditation regime as vital to the embedding process, where approximately 30% of the civil engineering units now have sustainability-related learning outcomes (percentage calculated based on the compulsory units at the time of data collection, without minor and technical elective units). One educator noted:

> There's also the imperative obviously from Engineers Australia. That's very clear that has changed in the stage 1 competencies; sustainability is now in that. It wasn't in it when I first came into the unit, or it might just come in. So, yes, it's an imperative through Engineers Australia accreditation… so I guess in this place (on the question of) drivers, I guess if you would say directly for this unit, one of the key ones was accreditation, and they need to demonstrate sustainability (coverage in their) teaching, and that's got stronger over the seven years that have been involved. (Educator A, Australian University)

Besides prescribing sustainability-related learning outcomes and competencies, the accreditation system has required a capstone unit in the last year of the curriculum that has proven critical for embedding sustainability in this university course. According to one educator, it allows students to focus on 'real-life' experiences and open-ended problems. In these settings, students are expected to apply all the knowledge acquired in previous units to design a civil engineering project, considering different streams and discipline requirements under sustainability objectives. The educator overseeing the capstone unit described how their teaching approach helps approach sustainability considerations:

> It's about getting them (students) to think about the project and the different sustainability outcomes. But it's a real project, so I think it's not just theory for them. It becomes more than theory … I think it's different from other units because it is really about a real project that they can then retrofit some of their learning, and they can learn more about sustainability. (Educator B, Australian University)

The justification for bringing a 'real-life' experience into the classroom is the synergy created between various technical requirements and sustainability outcomes. This characteristic differentiates a capstone project from a technical project commonly developed as part of a discipline-based unit (e.g., a structural or hydraulic engineering design unit only oriented

towards a single stream). According to the educators, the capstone project needs to be framed under 'real-life' conditions. Therefore, students conceive the project under multi-constraint objectives determined by scoping requirements associated with various civil engineering streams (e.g., structural, water, transport, etc.). Furthermore, the capstone unit in this Australian civil engineering program has been scoped to respond to diverse discipline requirements due to it has been available to civil and environmental engineering students:

> So, what we try and do is have a project that's a real project that hasn't been built and isn't going to be built during the time frame of the semester. It gives them the full experience of what it means to design a real project… We basically set up the project, and then we just scope to suit the types of disciplines that we have. We have things with environmental engineers with a slightly different scope. (Educator A, Australian University)

To incorporate sustainability considerations, students must identify sustainability outcomes for each stream and then define their respective solutions. These considerations should align with the whole project scope, considering the constraints placed by each stream (e.g., in terms of materials, resources, and contextual variables). Students are encouraged to evaluate these sustainability considerations from their conceptual design to determine how they will interact with each stream's technical design. One student described:

> I feel the most important learning is that you can always integrate sustainability into any project. The (capstone unit) was just about designing the whole building and the whole complex from scratch. Every aspect that you did could integrate some sustainable aspect to it, whether it's a big thing or a small thing. I definitely feel that was a key learning. Ultimately, you should always have sustainability in mind, have it through the design process, and then try and incorporate that with the other objectives you have for the project. Now sometimes it could be conflicting, or it could cost too much, which adds to the complexity, but I feel overall there's always room for some sustainable outcome or material, some choice that you can make that will be better for the environment. (Student A, Australian University)

The interaction between sustainability considerations and technical designs allows students to understand the complexity of addressing sustainability problems in civil engineering projects. Students are immersed in multi-constraint situations where they must conceptualise and develop an entire civil engineering project, meeting multiple constraints.

In addition to the capstone unit, sustainability was addressed in discipline-based units situated in the curriculum's third or fourth year. Their teaching approach varied between explicit and implicit strategies. Explicit teaching was followed when the topic covered was directly related to sustainability. For instance, sustainability was taught for one week in the project management unit. Students were first introduced to a general definition of sustainability. Then, sustainable engineering practices techniques, such as indicators for assessing sustainability in buildings and life-cycle assessment, were also covered. Similarly, in the water treatment unit, students resolved calculation-based problems with pre-defined solutions to quantify recoverable resources from wastewater treatment using anaerobic digestion.

The teaching approach becomes an implicit strategy recognisably when topics are not directly related to sustainability. In this instance, a common approach was to position engagement with

sustainability via a systems perspective that could influence any area of civil engineering. One educator illustrated this indirect route as follows:

> In our unit, what we try to do is to embed not directly, but everything we talk about is closely related to sustainability. We want students to have this in mind when they design the roads and in the construction of the road. (Educator C, Australian University)

Educators perceive sustainability could be connected to any engineering topic covered in the discipline-based units. This was particularly visible in units with sustainability-related learning outcomes that help students develop connections between particular technical aspects and sustainability objectives. For example, a student described the connections between safety perspective and road technical design when developing a design project as part of the road design unit:

> For example, in my roads project, choosing the alignments of the road to be in a good balance between impacting communities. They are like forested areas while also having good cost and safety. That stuff is very interesting to me, more so probably, checking whether the alignment you actually go with is safe. (Student B, Australian University)

The above statement shows how the student conceives the complexity of designing road alignment beyond technical requirements, including economic and safety considerations.

Another critical theme from this Australian case was the influence of internships on broadening students' awareness and perspectives regarding sustainable engineering practices. While it was not mandatory to undertake an internship as part of this civil engineering program, one-third of the students interviewed have done internships. As a result, those students recognised more constraints and characteristics of the complexity of sustainability issues in civil engineering. For instance, one student commented on the limitations of promoting sustainable practices, especially in civil engineering areas that are primarily technical (e.g., geotechnical engineering):

> We (civil engineers) do have a lot of say in how we design our solutions to become more sustainable. However, I feel it's limited to a client and stakeholders and what their aims are… Since I have been working, it's (sustainability) not really something you put as your priority. It's more about getting the job done with constraints that your clients put on. (Student C, Australian University)

Such comments illustrate how students perceive stakeholders' interests and how they may condition the possibility of embedding or demonstrating sustainability engineering practices in terms of enablers and barriers.

Another student had a different experience in a company highly committed to sustainability, to the point that the student believed the university was not encouraging them to adopt sustainability thinking and practices:

> I've only really been taught formally in one unit, which happened as a four-level unit. So, four years into my degree, that's when I first started actually hearing about sustainable practices and being taught: this is what sustainability is… but I still have a very vague idea of what it is; they

> briefly touched it… so it was something where it's been very glossed over. Only now, going into the industry, I have to prepare reports and monthly reports to the principal contractor on health, environmental, and social procurement statistics… That's how I've liked it. And now I see how it's really coming into the industry, and now the government's really pushing especially for social… I can see that it's going to be huge in the industry, I think. (Student D, Australian University)

It is worth noting that this student hadn't yet taken the capstone unit at the time of the interview. However, the student believed their university learning experiences related to sustainability were less meaningful than their industry experience, where sustainability got a higher priority.

4.2 Case study 2: Colombian University

In context, the Colombian civil engineering curriculum is accredited through the national system of accreditation, which assesses the quality of any tertiary program in Colombia. Still, this accreditation is not oriented towards engineering programs especially. As a result, it does not specify requirements or guidance concerning learning outcomes about engineering or sustainability. In November 2019, this Colombian civil engineering program started the international accreditation process with the EUR-ACE system, which provides standards for high-quality engineering programs mainly in Europe (https://www.enaee.eu/eur-ace-system/). To the data collection date, the international accreditation process had not generated changes in the curriculum or the units' contents. Its scope had been limited to reframing learning outcomes, among which few relate to sustainability.

Regarding the explicit curriculum, sustainability topics were directly involved in one final-year unit that focuses only on sustainable engineering practices (for this article, this unit is called 'sustainable civil engineering'). Indirectly, sustainability was included in a foundational unit comprising ecology topics, overseen by the science faculty, and fourth/fifth-year discipline-based units with a couple of classes connecting sustainability considerations. However, quantifying the number of units covering sustainability topics was challenging because while the department sets general objective requirements for each unit, the content covered relies on the educators' interests and expertise. Even in the case of the 'sustainable civil engineering' unit, the topics and content differed in the three sections available due to three different educators overseeing them. One educator noted:

> The educator varies the emphasis according to their experience and professional profile. The original syllabus aimed to guide civil engineering students towards sustainability issues. It had a very strong emphasis on environmental impact assessment processes (80%), and 20% were on sustainability and environmental concepts. I taught it like this the first semester, but I did not feel comfortable with the structure, and I kept changing it. I still change it. (Educator A, Colombian University)

Therefore, the key implication of this 'teaching autonomy' is that the extent and nature of the curriculum responses towards sustainability in this program depended exclusively on the educators and how they approach sustainability topics in their units.

Although the sustainability topics could vary, it was noticeable that if the educators have significant experience and background in sustainability, the extent of educational responses could be highly impactful for students. For example, one of the 'sustainable civil engineering' sections was overseen by an educator with an environmental engineering background who covered a comprehensive range of topics. The unit starts with a contextualisation of the global and local environmental crises and their relationship with civil engineering, differentiating fundamental sustainability-related concepts (e.g., ecosystem, environment, variants of sustainability in Spanish language–*sustentabilidad, sosteniblidad*). Likewise, it introduces students to global and local environmental legislation and common sustainable engineering tools and techniques (e.g., life-cycle assessment or green building certification programs). Similarly, another section of this unit also covered the contextualisation of environmental problems and their relationships with different economic sectors. Still, its primary focus was on introducing other techniques for quantifying the environmental impacts of civil engineering activities/projects. Therefore, while both sections covered the assessment of environmental impacts in civil engineering projects, the first one provided a complete contextualisation of sustainability in engineering and involved other sustainable engineering practices based on techniques and tools.

Besides the 'sustainable civil engineering' unit, some discipline-based units in the fourth and fifth years also involved sustainability content. Units linked to water resources and transport were commonly more aligned with sustainability compared to other areas (e.g., structural or geotechnical engineering). For instance, in addition to discipline-based units oriented towards managing hydraulic recourses, and water and wastewater service chains, students had to take one unit related to environmental sanitation. This unit encourages students to identify issues and solutions to improve a community's quality of life by optimising sanitation activities. One student described:

> In environmental sanitation, we carried out a solid waste management planning activity for a population. We had to estimate the mass of waste per capita and then by population, and the distance to the nearest landfill was considered, cost of transportation, and recycling use. We chose the population. (Student A, Colombian University)

Focusing less on the design of sanitation facilities, students had to work in a 'real-life' context to diagnose the current conditions and, based on that, propose solutions to ensure an adequate and sufficient supply of services, considering cultural and contextual variables. One educator explained:

> The students realise that there are populations with sanitary units but do not treat wastewater or do not have sanitary landfills. They identify certain activities that limit sanitation to improve the quality of life of these populations. (Educator A, Colombian University)

As a result, this unit can enhance students' systems thinking, broadening their perspective of sustainability issues related to the supply of services. In addition, students acknowledge the importance of promoting environmental sanitation to improve the quality of life of human beings.

A common feature between the sustainability-based units was that they promoted the development of projects where students propose sustainable engineering solutions based on the theoretical content covered in the units:

> At the 'sustainable civil engineering' unit, we had to develop an activity, which was to develop a solution to a civil engineering problem based on sustainable methods. It was a project that was in the design, construction or already built, and we had to look at sustainability applications, and it was related to the SDGs. (Student A, Colombian University)

> We develop a project in the 'sustainable civil engineering' unit. We did all the environmental impact assessments, including resources assessment and cost-benefit analysis, to carry out interventions as effectively as possible without affecting natural resources. Make the recovery evaluations, which is the time from the use of the resource to its recovery… This project was assumed. In my case, its scope was to build a lookout with an aerial cable car in one volcano. We had to gather all the information, and we had to take the information as it had been done in reality, gathering primary and secondary information, and we had to visit the area. (Student B, Colombian University)

Projects were used to approach students in 'real-life' conditions where they could apply the knowledge acquired theoretically, evaluate the viability of sustainable engineering practices, and assess the environmental impact of civil engineering projects.

As mentioned previously, an ecology unit in the first year aimed to introduce students to environmental elements and their structure and foster an understanding of their interaction with other organisms and complex social systems. While some topics seem directly related to ecosystems and sustainability, this unit is isolated from the units covering sustainability-related topics as the ecology unit is in the first year, and most sustainability-related units are in the fourth and fifth. In addition, the contents included in the ecology unit are not contextualised for the civil engineering discipline:

> In the first semester, they (students) take an ecology unit. Supposedly it is the foundation to prepare students to advance units related to sustainability and the environment. However, these sustainability and environmental units are only seen from the fourth year. But in the second semester, you forget the first, so we need to repeat the same content, and you lose time you could have used to cover more contextualisation topics. The other difficulty is that it is oriented toward principles of ecology, and it is overseen by science educators, biologists, and well, they see statistics and definitions of how a system works, an ecosystem, and its parts. That content for civil engineers doesn't work. (Educator A, Colombian University)

This clearly shows that the curriculum has a gap in its structure where most sustainability-related units are placed in the last years, and the first/second/third-year units do not support students for higher-level units. Likewise, this foundational unit lacks civil engineering contextualisation as another department oversees it, and there is no communication between the science and civil engineering educators.

Apart from the explicit curriculum, two distinct themes in the implicit curriculum strongly influenced students' learning process with sustainability. First, students can take elective units

overseen by other faculties with a strong focus on sustainability considerations. For instance, one student described one learning experience in an elective unit from the language faculty where students had to travel and share with an indigenous community. The purpose of this learning experience is that the students could learn more about their culture and can propose solutions, considering cultural and contextual settings:

> When I was taking the unit, I understood the purpose was to learn from their (indigenous) culture, which I was not related to. It was not only learning the language but the whole culture, how they live their childhood, how they relate to the environment, with society in general… For the first time in my career, I detected how I could apply engineering in many more aspects than I imagined… The idea was to propose a project because they do not believe in the national government. They have their own community and their own laws. The idea was to propose a project to help the community… Most (indigenous people) could not read or write. So, they have political proposals from the current government, and we sort of advised them. (Student C, Colombian University)

This experience increased the students' awareness, not only their perception of their role as an engineer but also the importance of contextualising engineering solutions to the culture of the community directly affected. The students also noted that the scope of the solutions involved a wide range of interests, as the unit was open to any discipline.

The second distinct aspect associated with the implicit curriculum was that more than half of the students interviewed (60%) participated voluntarily in research projects developed by research centres from the civil engineering department. These voluntary activities were in addition to the mandatory research project and engaged students in consulting projects focused on a single stream of civil engineering. Thus, students could reinforce discipline-based knowledge, but also some were directly linked with sustainability as students participated in real-life projects where they were able to apply engineering principles and generate sustainability-based solutions: "Then I participated in the research centre, and we worked with community aqueducts in communities… we have also developed workshops that seek to highlight the importance of taking care of the water." (Student D, Colombian University). As a result, students believed they could deepen some topics that directly affect sustainable engineering interventions, such as sustainable transport or urban drainage systems. These research experiences also approach students to topics not commonly covered in the explicit curriculum.

5 Discussion

From the above analysis, we can identify a few key elements shaping the curriculum responses towards sustainability adopted in the two civil engineering programs. Engineers Australia, and consequently, the Washington Accord, mandate standards for engineering programs in Australia and all other signatory countries worldwide, among which are guidelines for graduate attributes. Based on educators' statements, the accreditation requirements ensure that sustainability is addressed in specific discipline-based units, and to a greater extent, in the capstone unit. In contrast, the Colombian case study lacks this driver because the national

accreditation system does not address engineering or sustainability concerns. Only recently did they decide to adopt international accreditation. We agree with Byrne [18], who notes that sustainability considerations vary worldwide across professional accreditation bodies. Particularly in countries like Colombia, where the national accreditation body does not deal with accreditation aspects, professional engineering bodies might play a critical role in promoting national curriculum sustainability practices [18]. It is, therefore, suggested that professional engineering bodies work as facilitators and initial promoters to get national accreditation systems recognised as substantially international equivalents, having holistic sustainability-based guidelines. This might facilitate the first steps of curricular renewals and reforms towards sustainability in engineering programs worldwide, especially in those countries without national policies to accrediting engineering degrees with sustainability considerations.

Accreditation bodies commonly dictate sustainability-based learning outcomes to prepare students with 'appropriate' sustainability knowledge and skills. For instance, both case studies promote traditional lecture classes with supplementary calculation-based exercises to introduce students to common sustainable engineering techniques and tools. However, we also noticed that no interventions focused on students' values and beliefs, which also influenced students' learning processes [4]. As proposed by [4] and [19], the evidence we found points to further action being needed in the discipline to update learning outcomes, addressing not only students' skills and abilities but also their interior attributes and capabilities. Emphasising these interior dimensions can help engineering faculties support a more transformative or emancipatory approach to education where students can create new ways of thinking, being, and acting to contribute to a sustainable future [4, 20].

Findings also reveal that in some circumstances, curriculum responses towards sustainability largely depend on educators' interests and expertise. This was particularly noticeable in the Colombian case study, where the accreditation system has not traditionally supported sustainability considerations. In this case, findings demonstrated that the teaching content covered in the explicit curriculum was shifted based on the educators' professional experience. Although there could be good examples of units overseen by educators highly interested in sustainability, this is problematic due to students are not exposed to the same content, and there could be circumstances where students are not involved in sustainability at all.

Regarding the explicit curriculum, findings reveal that capstone or unit projects were the most common type of educational responses implemented to strengthen students' sustainability-based knowledge and skills. Projects were traditionally framed under 'real-life' conditions to simulate industry environments where students have learning opportunities to apply sustainability engineering techniques and tools learned theoretically. It is important to note that although educators always argued that the types of projects prompted were 'real' in nature, findings suggested that projects do not always encourage the same complexity of problems and, consequently, do not generate the same level of learning outcomes. As UNESCO and ICEE [1] put forward, educators should keep in mind that there are different types of projects (i.e., prominent, complicated, complex, and chaotic), each promoting various problems and

students' competencies. Thus, educators should constantly check how teaching and learning objectives are aligned with educational mechanisms designed under project-based environments, considering projects vary in nature and scope subject to learning outcomes.

Similar to the previous point, the complexity of the projects developed in the discipline-based units also depends on the types of collaborations stimulated. Results showed that the project-based learning experiences promoted in both cases implied different types of teamwork. While the capstone project in the Australian case study was open to environmental engineering (i.e., monodisciplinary), students in the Colombian case study had elective units with students from different disciplines (i.e., interdisciplinary or transdisciplinary). These collaborations imply that students might be exposed to diverse knowledge and competencies, increasing the complexity of the projects [1]. Furthermore, when students collaborate with other students from other disciplines, they can recognise the importance of considering and evaluating different perspectives in their engineering solutions. Therefore, curriculum and learning space renewals should also consider the collaborations promoted in project-based learning environments to scope the projects based on learning requirements and complexities and expose students to different types of teamwork.

Another outcome of this cross-case analysis is that both cases have a unit that has assigned more time to cover sustainability considerations (i.e., the capstone unit in the Australian case and the 'sustainable civil engineering' unit in the Colombian case) compared with traditional discipline-based units. In the Australian case study, the capstone unit draws on the content covered in previous discipline-based units. This is because the accreditation system in the Australian case study aims to ensure that sustainability is covered in at least one discipline-based unit in each curriculum year, and consequently, there are more changes to be scaffolded throughout the entire curriculum. Nevertheless, students' reflections on their experiences suggest this is not always felt to be the case. In contrast, the 'sustainable civil engineering' unit in the Colombian university seems to be disconnected from the rest of the curriculum. Findings showed that the first fourth years of the curriculum barely integrate sustainability considerations. Therefore, these results should be taken into account when planning and implementing curriculum renewals towards sustainability, ensuring a progressive integration of sustainability considerations throughout the course and guaranteeing enough scaffolding for learning.

While the Australian curriculum has been mapped to ensure progressive consideration of sustainability, following accreditation requirements, almost all students suggested that most sustainability-related units were placed in the last years of the curriculum, with nearly nothing in the first years. This mismatch raises implications in relation to the degree of convergence between the explicit and implicit/enacted curriculum. In addition to the learning outcomes mapping (macro), engineering curricula toward sustainability demand significant efforts to ensure that educators scaffold sustainability considerations (micro). However, this is only possible if core sustainability contents are covered since the early stages of the curriculum to be then scaffolding in the discipline-based units.

The first years of an engineering curriculum are commonly populated with foundational science units. Yet, these foundations unit are not always connected with sustainability considerations. For instance, the Colombia case study only had a foundational unit covering ecology and sustainability topics. However, it was isolated entirely from the rest of the curriculum because its content was not conceptualised for the civil engineering discipline. Therefore, our results indicate that curriculum and learning space renewals should support the gradual incorporation of sustainability considerations into foundational units framed under sustainable engineering practices where students can start acquiring engineering-based sustainability literacy and knowledge from the beginning of their studies.

Besides science-based foundation units, lower-level discipline-based units must also support the link between engineering content and sustainability. Both cases further confirm that the civil engineering curriculum requires a gradual and progressive embedding process of sustainability topics [9]. Rather than engaging students with sustainability considerations primarily in the final years of the curriculum, sustainability should be a core aspect of every curriculum year where educators build on what was already covered, following an 'integration approach' similar to the one proposed by Desha et al. [9]. This means discipline-based content is selected with a sustainability lens in mind, and students are encouraged to start creating connections between the technical aspects of engineering and its contributions to sustainability issues [9]. However, it is worth noting that these connections are not only the students' responsibility. The results from this multi-case design indicated that students might not have yet developed the appropriate systems thinking capabilities in the first years of the curriculum to build these connections. Therefore, facilitation from educators is also needed to explicitly understand how sustainability interacts with civil engineering considerations [21].

Finally, the cross-case analysis also reveals that implicit-curriculum responses were decisive for students in embracing new sustainability perspectives and questioning 'unsustainable' cultural and personal values, consistent with previous findings in the literature [4]. For example, in the Australian case study, internships enhanced students' awareness of the complexity of sustainability challenges in the industry, understanding how personal and institutional interests hinder/trigger engineering solutions addressing sustainability challenges. Similarly, the Colombian case study's elective units and extracurricular research activities were almost the only legitimate places to share with the community and students from other disciplines. Therefore, these 'socialisation' spaces can be rethought, mainly as they can engage students in social contexts where they develop critical thinking. At stake is how such programs broaden and deepen students' perceptions and understandings of their role as engineers for sustainability and the importance of considering cultural constraints when contextualising engineering solutions. Therefore, particular attention should be given to how these implicit-curriculum responses ensure engineering students are prepared effectively to interact with different external actors and communities, rather than assuming, for example, it will be picked up along the way without explicit *and* implicit provision for this in the curriculum.

6 Conclusions

The article discusses a cross-case analysis of two civil engineering programs in Australia and Colombia to identify critical elements shaping engineering curricula responses towards sustainability. The Australian curriculum is driven by accreditation requirements, which play a crucial role in promoting sustainability-based learning outcomes in specific discipline-based and capstone units. In contrast, the Colombian curriculum lacks this driver, as the national accreditation system does not address engineering or sustainability concerns. Findings also suggest that engineering curriculum responses towards sustainability depend on educators' interests and expertise. Likewise, results indicate that capstone or unit projects are the most common type of educational responses implemented to strengthen students' sustainability-based knowledge and skills. Still, the complexity of the projects and collaborations promoted in project-based learning environments should be considered as it affects students' learning process/outcomes. Finally, both cases have illustrated that the effectiveness of curriculum responses towards sustainability highly depends on the progressive integration of sustainability considerations throughout the course, ensuring enough scaffolding for learning.

As argued previously in the discussion, little evidence was found in both cases in relation to curriculum responses that engaged students' interior attributes, such as values and beliefs, which are critical to promoting deep learning. Previous research on ESE [22] has suggested that these interior aspects are required to simulate transformative learning, where individuals (students and educators) will go through deep reflection that might challenge current and existing unsustainable practices/values. Further examination of transformative learning in tertiary engineering education is needed to contribute to identifying what curriculum responses might trigger deeper and higher learning levels where students experience personal empowerment to become active global citizens.

7 Acknowledgement

This research is supported by an Australian Government Research Training Program (RTP) Scholarship. Special thanks to the Faculty of Education and Monash University for promoting transdisciplinary research toward sustainability. Additionally, the authors would like to extend their deepest gratitude to all participants participating in this research.

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