BEYOND THE CLASSROOM: RETROSPECTIVE EVIDENCE FROM A DECADE OF CHALLENGE-BASED LEARNING

Mireia Sierra Andrés

Fusion Point, Esade Business School and Universitat Politècnica de Catalunya

Matteo Di Stasi

Department of Business and Economics, CUNEF Universidad

Ramon Bragós Bardia

Department of Electronic Engineering, Universitat Politècnica de Catalunya

ABSTRACT

CDIO-aligned Challenge-Based Learning (CBL) programs are frequently credited as developing transversal competencies, yet evidence about whether these outcomes build and transfer into professional practice years later remains limited. This paper investigates the long-term impact of Fusion Point's Challenge-Based Innovation (CBI) program through a retrospective qualitative study of alumni experiences spanning approximately a decade of cohorts. We conducted 20 semi-structured interviews with former participants from business, design, and engineering backgrounds and analyzed the data using reflexive thematic analysis supported by Atlas.ti. Alumni consistently portray CBI as a uniquely memorable, "real-life" learning experience that differs from conventional coursework by combining authentic constraints, external stakeholders, and interdisciplinary teamwork. Four clusters of durable outcomes emerge: First, alumni report sustained innovation practices, including stakeholder-oriented problem framing, iterative development, and safely working with uncertainty. Second, they describe persistent interdisciplinary teamwork capabilities, such as translating across disciplinary "languages," aligning diverse perspectives, and negotiating trade-offs under time pressure. Third, alumni highlight leadership and influence as practiced through facilitation, sensemaking, and coordination rather than formal authority. Fourth, they emphasize identity-relevant personal development, including increased confidence, professional maturity, and long-lasting bonds that continue to support collaboration. Participants also describe career-related effects, including increased readiness for project-based, consulting, and tech and innovation-oriented roles and greater openness to social impact pathways. We discuss implications for CDIO-aligned program design, suggesting that interdisciplinary, challenge-driven learning environments can cultivate professional competencies and mindsets that alumni perceive as both transferable and durable years after participation.

KEYWORDS

Challenge-Based Learning, Engineering Education, Retrospective Alumni Study, Professional Identity, Interdisciplinary Teamwork, CDIO Standards: 2, 3, 5, 8

INTRODUCTION

Today's global challenges demand engineers who can combine high-level technical expertise with the ability to empathize with users and communities, understanding real human needs to frame problems well and design solutions that are both technically sound and genuinely impactful. Challenge-driven and CDIO-aligned programs are commonly reported to foster professional competencies such as teamwork, communication, problem solving, and stakeholder engagement (Bravo et al., 2025a, 2025b). However, much of the available evidence focuses on immediate or short-term outcomes, often measured at the end of a course or within the same academic year (Doulougeri et al., 2024; Gallagher & Savage, 2023; Olateju Temitope Akintayo et al., 2024) which fails to capture the sustainability of learning gains or the permanence of shifts in professional identity (Helker et al., 2025). This creates a gap in understanding whether the reported learnings are durable and whether it transfers into professional practice after graduation (Doulougeri et al., 2024; Van Den Beemt et al., 2023).

This paper addresses that gap through a retrospective perspective on Fusion Point's Challenge-Based Innovation (CBI) program, an interdisciplinary model delivered in collaboration with CERN IdeaSquare across eleven editions since 2014 (Hassi et al., 2016; Papageorgiou et al., 2021), grounded in Challenge-Based Learning pedagogies (Dikilitaş et al., 2025; Doulougeri et al., 2024; Gallagher & Savage, 2023). CBI engages students from business, design, and engineering in authentic, open-ended challenges demanding problem framing, stakeholder interaction, interdisciplinary teamwork, and iterative prototyping, aligning with CDIO principles of authentic context, integrated skills, and iterative development cycles (Charosky et al., 2018; Crawley et al., 2014; Malmqvist et al., 2015; Sierra & Di Stasi, 2024). Focusing on alumni provides a unique vantage point: graduates' retrospective evaluations of their university experience are a recognized measure of long-term educational value, and what alumni choose to remember and apply years after graduation serves as a strong indicator of perceived transfer and professional relevance (Egan, 2020; Garcia et al., 2024; Ritella et al., 2020; Tuononen & Parpala, 2019; Wood et al., 2015). Alumni perspectives have been used in the CDIO community as an instrument for program evaluation and competency benchmarking (Kovacs et al., 2023; Wiklund et al., 2005), yet longitudinal qualitative accounts of professional impact remain scarce in this literature.

The study specifically addresses these gaps through the following overarching research question: RQ: How does participation in an interdisciplinary challenge-based innovation program shape alumni's professional development and career trajectories over the long term? This is explored through three sub-questions:

- SQ1: What competencies and mindsets do alumni report using in professional practice years after participating in CBI?
- SQ2: How do alumni describe the long-term value of interdisciplinary teamwork, communication, and leadership experiences on their professional development?
- SQ3: How do alumni connect their CBI experience to career choices, opportunities, and professional identity formation?

THEORETICAL BACKGROUND

This research is grounded in 4 theoretical pillars: CBL as transformative pedagogy, its alignment with CDIO standards and epistemic fluency, the durability and transfer of learning, and leadership as distributed practice, presented as a conceptual framework (Figure 1).

CBL as Transformative Pedagogy

CBL is an active-learning pedagogy that uses authentic, real-world open-ended "challenges" as the primary driver of the curriculum (Doulougeri et al., 2024; Gallagher & Savage, 2023; Leijon et al., 2022; Perna et al., 2023). Grounded in Kolb's (1984) experiential learning theory, involves an iterative cycle of engaging with "Big Ideas," investigating through stakeholder research, and acting via prototyping (Bravo et al., 2025b; Perna et al., 2023; Van Den Beemt et al., 2023). Interdisciplinary teams imply the need to negotiate meanings and co-create knowledge with peers, teachers, and external stakeholders (Helker et al., 2025; Van Den Beemt et al., 2023). This process often triggers a "disorienting dilemma" forcing students to re-evaluate their professional identities through a period of peak frustration known as the "Groan Zone" (Feng et al., 2025; Kulturel-Konak et al., 2025; Mezirow, 1991).

CDIO Alignment and Epistemic Fluency

CBL aligns with multiple CDIO approach standards (Gunnarsson & Swartz, 2022; Kohn Rådberg et al., 2020). A core cognitive outcome of this radical interdisciplinarity is the development of epistemic fluency; the capacity to recognize and shift between different disciplinary ways of knowing. Engineering students, for instance, must learn to integrate the “human-centered” logic of design (which prioritizes empathy, user needs, and iterative problem-finding over purely technical solutions) with the “feasibility” logic of business (which focuses on technical constraints, economic viability, and implementation requirements) (Barnard et al., 2013; Charosky et al., 2018). Navigating the uncertainty of the "Groan Zone" (a period of peak frustration in the CBL process (Kaner, 2014), develops personal skills such as affective resilience and ambiguity tolerance; critical professional engineering competencies (Helker et al., 2025).

Durability and transfer of learnings

Durability is defined as the learning that remains cognitively and affectively long after the initial instructional intervention while transfer implies the mobilization of those resources in novel, complex professional contexts. In the CBI framework, durability is operationalized through the retrospective tracking of the “Innovation Mindset” with evidence suggesting that shifts in dimensions such as ambiguity tolerance and iterative prototyping habits persist at least three years into professional practice (Papageorgiou et al., 2021). This “learning residue” is often the result of transformative learning processes where students navigate “disorienting dilemmas” that reconfigure their problem-solving abilities (Feng et al., 2025; Kulturel-Konak et al., 2025) and a learner’s frame of reference for their entire career (Martin & Bombaerts, 2024; Sluijs et al., 2024).

Professional identity and transversal skills

Professional identity is the integrated pattern of competences, performance, and recognition guiding career decision-making (Taconis & Bekker, 2023). CBL fosters this identity by functioning as a "social engine" where interdisciplinary friction forces students to negotiate professional boundaries, developing transversal skills: the 4C's (critical thinking, creative thinking, collaboration, communication) plus self-regulation, adaptability, and ethical reasoning (Haim & Aschauer, 2024; Helker et al., 2025; Ming et al., 2025). Acquired through the designed navigation of knowledge asymmetries within teams (Helker et al., 2025; Johnson et al., 2022; Nawawi et al., 2024; Papageorgiou et al., 2021). These gains are multidimensional, encompassing cognitive, metacognitive (self-regulation), affective (resilience), and socio-communicative components (Helker et al., 2025). By requiring collaboration with diverse stakeholders under conditions that simulate workplace dynamics, CBL accelerates professional identity formation and instils a sense of agency toward societal issues (Bravo et al., 2025a; Martin & Bombaerts, 2024).

Leadership as practice in team-based innovation work

This study adopts a “leadership as practice” lens, understood as the situated ability to enable collaboration and facilitate sensemaking under high uncertainty (Hurst et al., 2016; Yang, 2021). Aligning with team-centric transformational leadership (TTFL): conceptualizing leadership as a distributed phenomenon where progress depends on managing diverse disciplinary perspectives and "epistemic friction" (the tension between different disciplinary approaches) within cooperation, psychological safety, and shared vision rather than top-down authority (Jiang & Chen, 2018; Klaic et al., 2020).

Figure 1 synthesizes these four theoretical pillars into a conceptual framework mapping the pathway from the CBI learning environment to the durable professional imprint.

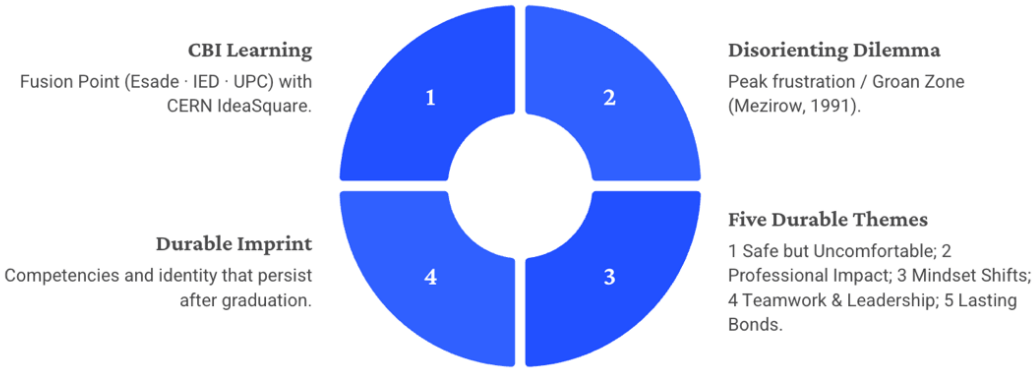

Figure 1. Conceptual framework: from CBI learning environment to durable professional imprint.

METHODS

This study employs a qualitative, retrospective research design targeting alumni who participated in the CBI program between 2014 and 2024, examining how experiences of "disorienting dilemmas" during the course have been metabolised into durable professional practices over the long term.

Research design and context

This study is a retrospective qualitative inquiry based on semi-structured alumni interviews. The institutional context is Fusion Point's CBI program: a four-month, in-person course running from September to December, which has engaged approximately 450 students to date (Hassi et al., 2016; Papageorgiou et al., 2021). It brings together MBA students from Esade Business School, design students from IED Barcelona, and engineering students from UPC (disciplines with varying levels of prior professional experience) working in interdisciplinary teams on challenges aligned with the Sustainable Development Goals, drawing on CERN IdeaSquare's pedagogies to translate science into societal applications (Charosky et al., 2022; Sierra & Di Stasi, 2024; Vignoli et al., 2021). Teams progress through problem exploration, ideation, iterative prototyping, and milestone presentations with stakeholder feedback, producing a written report, a public pitch, and a solution prototype. Assessment is conducted by an interdisciplinary coaching team (at least one coach per institution) who reach consensus in a joint grading meeting; peer assessment contributes 15% of the final grade (Dikilitaş et al., 2025). Feedback is embedded throughout from faculty, stakeholders, users, and peers, and is central to how the program progressively cultivates professional competencies.

Sample and recruitment

This study is focused on alumni that participated in the program from 2014 to 2024. Participants were contacted through multiple channels: snowball referrals, direct outreach via LinkedIn, and a dedicated invitation distributed for the program's 10th anniversary event. This multi-channel approach aimed to reach a diverse range of cohorts and disciplines, and the research seeks to move beyond immediate course satisfaction to understand the long-term "professional imprint" left by this pedagogical model.

It received formal approval from the Esade Research Ethics Committee (No. 027/2025). Following GDPR, all participants provided written informed consent prior to the interviews. Data is stored securely on a university SharePoint platform, and all records were fully anonymized with unique identification codes to ensure participant confidentiality.

At the time of writing, 20 interviews had been fully coded, the remaining interviews were transcribed and scheduled for integration in the next cycle. Of the 20 coded participants, 7 came from Esade (business), 5 from IED Barcelona (design), and 8 from UPC (engineering); 9 were female and 11 males. Fourteen participants had attended editions prior to COVID-19 (2014–2019) and six had attended post-COVID editions (2020–2024). No systematic thematic differences were identified between pre- and post-COVID cohorts in the coded set. Participants represented diverse disciplinary backgrounds and a range of graduation years, enabling exploration of perceived impacts at different time distances from the course.

Data collection

Interviews lasted around 45–75 minutes following a semi-structured guide designed to identify concrete episodes and reflections on long-term impact through the critical incident technique (FitzGerald et al., 2008). The core questions included:

- “What do you remember most vividly from CBI, and why?”
- “Can you describe a situation at work where you used something you learned in CBI?”
- “What was it like to work across disciplines, and how has that mattered later?”
- “Did CBI influence your career choices or professional identity? How?”

All interviews were conducted in English. Most participants, as well as interviewers, are non-native English speakers; the verbatim excerpts reported in the findings reflect authentic multilingual expression and are presented without linguistic correction to preserve meaning.

Analysis

Analysis followed a reflexive thematic approach (Braun & Clarke, 2019) using ATLAS.ti software, involving iterative coding and clustering. Coding was conducted by two researchers. Starting from an initial sensitizing list of topics grounded in the interview guide, both coders independently coded a subset of transcripts; these were then compared and discussed, to refine and expand the coding where new categories emerged. A final consistency review was conducted across a sample of fully coded transcripts to confirm category stability before proceeding to theme development. Analysis proceeded in four steps: (1) familiarisation (2) inductive coding (3) theme development through iterative clustering and refinement, and (4) theme validation through negative case checks and consistency review across transcripts. The table below summarizes the themes meanings and codes ‘groundedness’ (frequency across quotations) as an indicator of the number of coded quotations linked to each code.

Table 1. Themes, transfer to professional practice, and groundedness

Theme	Core meaning	Examples of transfer into professional practice	Groundedness (supporting codes)
1. A 'Safe but uncomfortable' learning space	Supportive but demanding environment (ambiguity, time pressure, real constraints) that stretches students	Tolerating uncertainty; persisting through setbacks; higher confidence in unstructured work; taking initiative without perfect instructions	Course (overall) (58); Experiences (55); Real-life experience (29); Time/Pressure (6)
2. Professional impact and workplace readiness	CBI as preparation for professional project dynamics	Handling open-ended briefs; structuring work under deadlines; presenting to external audiences; using CBI as a career narrative	Professional life (104); Project (63); Professional career impact (58); PM skills (25); Public speaking (13)
3. Mindset shifts toward user-centricity and systems thinking	Durable orientation toward people, context, systems, and trade-offs	Empathy/perspective-taking; reframing problems; considering constraints and consequences; integrating sustainability considerations	Empathy (38); DT process (36); User centric (24); Think big (23); Sustainability (15)
4. Interdisciplinary teamwork, communication, and leadership-as-practice across differences	Learning to collaborate across disciplinary 'territories' and assumptions, including coordination, influence, and facilitation under ambiguity	Translating between disciplines; negotiating priorities; coordinating cross-functional teams; managing conflict constructively; facilitating alignment and decision-making without formal authority	Team dynamics (82); Disciplinary diversity (81); Cultural differences (33); Soft skills (21); Management/Project skills (25); Public speaking (13)
5. Long-lasting social and affective bonds	Relationships and sense of belonging formed through intense collaboration that persist over time and continue to shape professional networks	Maintaining alumni connections; leveraging trusted relationships for collaboration, referrals, or advice; increased confidence through belonging to a strong peer community	Bonds created (44); Experiences (55); (optional context) Course (overall) (58)

FINDINGS

The thematic analysis of the 20 interviews reveals a consistent narrative of transformation, which we term a "durable professional imprint” characterized by five distinct thematic clusters that bridge the gap between the academic experience and professional practice.

Theme 1: A “Safe but Uncomfortable” learning space

Alumni identify CBI as a "life-changing" experiential anchor (Ojasalo & Kaartti, 2021; Papageorgiou et al., 2021). The 'Real-life experience' code (n=29) captures how the CERN environment anchors this memorability (the physical presence, the scientists, the "license to dream") as a uniquely authentic setting distinct from campus-based coursework (Vignoli et al., 2021).

“I think it wouldn't have been as memorable if we didn't go to CERN and we're physically there and talk to certain professors. And that, I think, is very, very, very important. Maybe the equivalent would be like doing a semester in another country and being able to meet people from different countries.” (UPC student, 2017)

The 'Experiences' (n=55) and 'Time/Pressure' (n=6) codes capture how this intensity functions as a "stretching", the program provided a "safe space" to navigate the uncertainty inherent in real-world innovation. Alumni describe the discomfort not as a problem but as a necessary condition for growth, distinct from the predictable structure of traditional courses.

"It stretches you physically, even more mentally... it makes you be at the limit every time, every day during the project. So, at the end you realize some things that could happen in a very extreme level... I’m sure that I won't learn that in the same way [in a normal course]." (business student, 2015)

“It gives you an interdisciplinary experience, which is super important after uni, and gives you an uncomfortable setting, but in a safe space […] it's a really nice environment to feel challenged and to feel that you can achieve something that out of it seems crazy.” (engineering student, 2019)

Theme 2: Professional impact and workplace readiness

The "Professional Life" code captures how CBI influenced career moves and self-efficacy. Alumni credited the program with providing the "real-life readiness" needed for leadership roles, often supporting earlier readiness for career advancements (Bravo et al., 2025a; Colombelli et al., 2022). The experience bridged the gap between student insecurity and professional confidence:

“When I finished my degree, I went directly to work to consulting. And I think that CBI probably was one of the main reasons. Because consulting is about a client giving you a problem and you need to find a solution. And not be that focused on the technology that we want to use... It's not that we want to use a technology, it's that we want to solve a problem” (business student, 2018)

The 'Professional career impact' code (n=58) also surfaces in how the exposure to both academic research (at CERN) and industry application helped alumni make informed career choices, with some explicitly citing CBI as the catalyst for deciding between a PhD track or an industry career:

"After CBI, inspired by CERN I’ve started a PhD, now I’m about to finish and I have to decide whether If I want to go for academia or for industry […] I feel it helped me to be able to make a more informed decision of what's best to do." (engineering student, 2016)

Theme 3: Mindset shifts toward user-centricity and systems thinking

A significant outcome is the permanent shift from "technology-push" to "problem-first" reasoning (Charosky et al., 2018). The 'DT process' (n=36) and 'User centric' (n=24) codes are the primary anchors here: engineering alumni specifically noted that CBI was the first time they were forced to "think about the problem" rather than focus solely on the technology (Charosky et al., 2018; Helker et al., 2025), describing this not just as a method but as a fundamental change in professional orientation:

“It was the first time that we were... thinking about the problem and then solve it. And not be that focused on the technology that we want to use." (engineering student, 2018)

“I would say that the main learning for me was the application of design thinking process solving the problem. I think finally this is the main learning” (business student 2014)

The 'Empathy' code (n=38) (the highest-groundedness code in this theme) captures a deeper shift: from analytical detachment to what one participant describes as a "warm point of view," understanding the user as a living part of a community:

"I always start with a very warm point of view... thinking a lot in the user, not only as a person... but as a part of society... This kind of project makes me think and design a lot in terms of warmness." (design student, 2016)

Theme 4: Interdisciplinary teamwork, communication, and leadership-as-practice across epistemic differences

The highest-ranking learning codes: 'Team Dynamics' (n=82) and 'Disciplinary Diversity' (n=81), reveal that learning occurred most intensely at the intersection of disciplines. Initial difficulty of communicating across disciplines generating a common “language” is described as becoming a core professional asset (Ming et al., 2025) later on.

*“She told me like” when you explain what's happening in your head, be conscious that we are not designers, so try to explain it clear and well defined. If you need more time, it's OK. If you need to spend 15 minutes to explain an idea that should be in five, it's OK. But it would help us to understand what's your point and she was right. […] this was a special an example of the communication between the teammates.” (*design student 2016)

"If you're building a product as an engineer... [clients] don't have this technical perspective, so you have to also be able to transmit this idea... being able to transform a product into something that people without a background can understand is a common exercise that you're doing continuously at CBI." (engineering student, 2021)

This "epistemic friction" was scaffolded by supporting on how to negotiate and lead in mixed environments, a skill they found rare among peers who had not participated in such programs.

Theme 5: Long-Lasting Social and Affective Bonds

Beyond technical skills, alumni consistently describe the affective and relational dimensions of CBI as among its most durable outcomes. The 'Bonds created' code (n=44) is the primary evidence base here: the intensity of collaborative challenge-work under real constraints created interpersonal bonds that many alumni continue to maintain professionally years after graduating, a phenomenon rooted in shared vulnerability and mutual reliance (Bravo et al., 2025b; Ojasalo & Kaartti, 2021). These bonds are not peripheral; peer networks built during CBI persist as professional support systems, referral channels, and collaboration opportunities.

"I still keep in touch with the people from my team in CBI. So, I guess that it shows you how we actually bonded a lot during the course, and we stayed friends still today." (UPC student, 2017)

"I made super, super good friends... every single time we've gotten back together we were like 'oh, if we would have to do one perfect team we would know how to choose perfectly and we would love to do it again'." (Interview 3, Business)

This suggests that the "imprint" of the program is not merely cognitive, it is social and affective, manifesting as a lasting professional community that increases confidence, enables future collaboration, and supports continued learning long after the course ends.

Mapping themes to CDIO standards

Table 2 provides a thematic map that synthesizes the qualitative findings and makes explicit how the durable outcomes of each theme can be interpreted through relevant CDIO Standard highlighting the mechanisms that alumni narratives suggest help these learnings to persist and transfer into professional practice years after participation.

Table 2. Themes and transfer mechanisms mapped to CDIO Standards

Theme	CDIO Standard / Syllabus (2, 3, 5, 8)	Durable Outcome / Mechanism (why it 'sticks' for years)
1. A 'safe but uncomfortable' learning space	S8 Active Learning: student-centred active and experiential learning; S5 Design–Implement Experiences: iterating and making under constraints; S2 Learning Outcomes: confidence, resilience, teamwork-related competences	Mechanism: repeated exposure to authentic ambiguity and time pressure creates productive discomfort that builds tolerance for uncertainty and iteration. Because students must act (not just discuss), they develop procedural know-how and self-efficacy that alumni later recognise and reuse when facing ill-structured workplace problems.
2. Professional impact and workplace readiness	S2 Learning Outcomes: professional skills (communication, project management, stakeholder interaction); S5 Design–Implement Experiences: delivery cycles with constraints; S8 Active Learning: student responsibility for decisions and outputs	Mechanism: authenticity generates performance-relevant rehearsal of professional practice (open-ended briefs, external audiences, delivery deadlines). This enables near and far transfer because alumni encode not only 'what' they learned but 'how' to behave in project-based work (structuring, communicating, presenting, prioritising).
3. Mindset shifts toward user-centricity and systems thinking	S2 Learning Outcomes: systems thinking, ethics and sustainability, societal/stakeholder awareness; S5 Design-Implement Experiences: challenges requiring stakeholders to be integrated into the design and reasoning process. S8 Active Learning: learners construct meaning through engagement and reflection; S3 Integrated Curriculum: reinforcement of professional mindsets across activities	Mechanism: repeated stakeholder-oriented reframing produces an identity-relevant shift from technology-push to problem-first inquiry. The mindset 'sticks' because it is tied to concrete episodes of seeing consequences, negotiating trade-offs, and making decisions that combine human needs, technical feasibility, and sustainability.
4. Interdisciplinary teamwork, communication, and leadership-as-practice across epistemic differences	S2 Learning Outcomes: teamwork, communication, leadership, collaboration; S3 Integrated Curriculum: mindset development reinforced by coordinated multidisciplinary curriculum design; S5 Design-Implement Experiences: teamwork and leadership practised within authentic project delivery; S8 Active Learning: negotiation, decision-making, and coordination in action	Mechanism: epistemic friction (different disciplinary 'languages' and assumptions) forces ongoing translation, negotiation, and alignment. Alumni learn to exercise informal leadership (facilitation, influence without authority) because progress depends on coordinating perspectives under ambiguity, making it transferable to cross-functional professional contexts.
5. Long-lasting social and affective bonds	S8 Active Learning: intense shared doing strengthens cohesion; S2 Learning Outcomes: interpersonal competence, collaboration; S3 Integrated Curriculum: sustained teamwork across course structures	Mechanism: high-intensity collaboration under challenge conditions creates social and emotional anchoring (shared struggle, mutual support, collective pride). These affective bonds persist as durable professional networks, increasing confidence, enabling future collaboration, and sustaining continued learning through peer exchange long after the course ends.

DISCUSSION

The alumni narratives collected across a decade of Fusion Point's CBI program suggest that challenge-driven, interdisciplinary immersion leaves a significant "learning residue" that remains salient long after graduation. The most practically significant dimension of this imprint (and the one with the most direct implications for CDIO program designers) is its career-shaping effect: alumni report concrete changes in occupational trajectories, informed transitions between academia and industry, and accelerated professional readiness that they trace directly to their CBI participation. This discussion interprets these findings through the theoretical lenses of transformative learning, epistemic fluency, and leadership as practice.

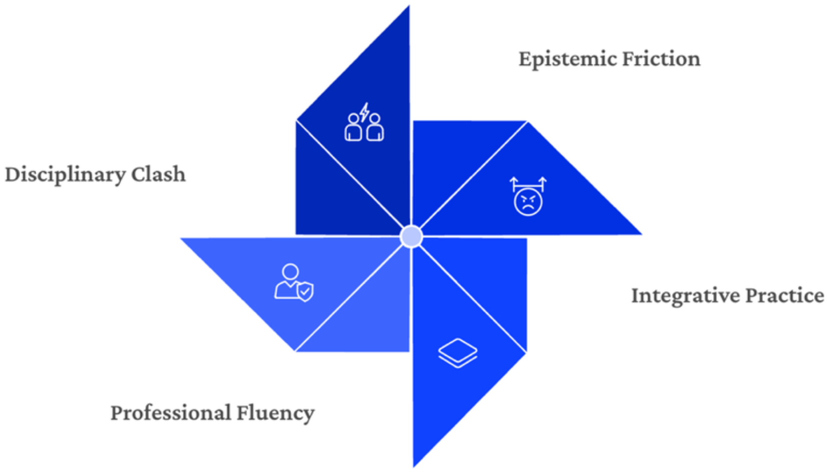

Figure 2. From Disciplinary Clash to Professional Fluency: The Epistemic Friction Mechanism

The Durability of Transformative "Learning Residue"

The most striking finding is the decade-long durability of mindset shifts, particularly the transition from "technology-push" to "problem-first" reasoning. While traditional engineering curricula often prioritize linear problem-solving (Dikilitaş et al., 2025), CBI alumni describe a permanent reconfiguration of their professional identity centered on user-centricity and empathy. This aligns with the "subjectification" function of learning, where students do not merely acquire skills but are transformed as individuals. The reported "Safe but Uncomfortable" environment acts as a catalyst for this transformation; by navigating the "Groan Zone", students develop affective resilience and a high tolerance for ambiguity (Huesca et al., 2024). These gains but represent what Mezirow (1991) defined as a shift in "meaning perspective"; a durable lens through which alumni continue to interpret complex professional challenges (Feng et al., 2025; Sundman et al., 2025).

Epistemic Friction as a Mechanism for Epistemic Fluency

The high groundedness of the "Team Dynamics" and "Disciplinary Diversity" codes indicates that the most significant learning occurs at the point of epistemic friction; the tension generated when diverse disciplinary ways of knowing collide (Dikilitaş et al., 2025). In contrast to "divide-and-conquer" strategies common in traditional group work, CBI forces a genuine integration of engineering feasibility, design desirability, and business viability (Charosky et al., 2018; Van Den Beemt et al., 2020, 2023). This process cultivates epistemic fluency, enabling graduates to act as "translators" across disciplinary and organizational silos (Kans & Gustafsson, 2016; Visscher et al., 2022). This ability to communicate complex ideas to non-experts is reported as a "core professional asset" (Dikilitaş et al., 2025). Confirming that interdisciplinary friction, while a source of peak frustration during the program, is the primary driver of the sophisticated communication and collaboration skills required in Industry 4.0 environments (Van Den Beemt et al., 2023). Figure 2 illustrates this mechanism.

Leadership as Distributed Practice and Collective Sensemaking

Rather than identifying a single "hero" leader, alumni narratives describe leadership as a distributed practice of enabling collaboration and facilitating sensemaking under uncertainty (McCrory et al., 2021). This enactment of leadership aligns with team-centric transformational leadership, where the focus shifts from top-down authority to the cultivation of cooperative norms and psychological safety (Jiang & Chen, 2018; Klaic et al., 2020). Graduates credit CBI with providing "real-life readiness" (Vilalta-Perdomo et al., 2022), reporting that the experience of managing a network of experts and stakeholders accelerated their seniority in leadership and consulting roles (Dikilitaş et al., 2025). This suggests that CBI functions as a "leadership laboratory" where the mastery of relational dynamics; such as conflict management and shared decision-making, predicts long-term professional success more effectively than technical mastery alone (Klaic et al., 2020).

The "Social Engine" of Innovation and Professional Networks

Finally, durable social bonds highlight that innovation is social as well as technical (Dikilitaş et al., 2025). The shared intensity of CBI creates lasting professional networks, a form of "social capital" that improves graduates' confidence and self-efficacy long after the program ends (Bravo et al., 2025a; Helker et al., 2025; Ojasalo & Kaartti, 2021). For engineering education, this underscores the importance of designing "memorable educational experiences" (Lara-Prieto et al., 2023) that leverage the "Human Dimension" of learning building not just engineers, but a connected community of change-makers (Ojasalo & Kaartti, 2021; Papageorgiou et al., 2021)

IMPLICATIONS FOR CDIO-ALIGNED COURSE DESIGN

The retrospective evidence suggests that the durability of competence is not driven by content knowledge, but by the intensity of the learning environment. For institutions aiming to replicate these long-term outcomes, we propose four design principles anchored in the CDIO Standards:

Table 3. Design principles for CDIO-aligned programs producing durable professional competencies.

Design Principle	CDIO Standard	Evidence from Alumni
Operationalise Epistemic Friction — intentionally form teams with maximum disciplinary distance	Standard 3 — Integrated Curriculum	Alumni attribute cross-disciplinary communication and negotiation skills to the friction of working across engineering, design, and business
Embrace the Pedagogy of Discomfort — avoid over-scaffolding; ambiguity is a feature, not a bug	Standard 5 — Design–Implement Experiences	The 'uncomfortable' open-ended challenge is the primary anchor for memory and professional confidence a decade later
Ensure Authenticity through External Stakeholders — feedback based on value and feasibility, not academic compliance	Standard 7 — Integrated Learning Experiences	Alumni credit accountability to real stakeholders — not grades — as the driver of user-centric mindset shifts
Structure Reflection as an Identity Mechanism — require students to articulate how they navigated conflict and ambiguity	Standard 8 — Active Learning	The 'Groan Zone' is only transformative when followed by structured reflection that cements the experience into professional identity

Table 3 synthesizes these principles as actionable guidelines grounded in alumni evidence. Two of the four principles map to Standard 5 (Design-Implement Experiences), reflecting distinct but complementary facets: the productive value of ambiguity in challenge design, and the accountability generated by genuine external stakeholders. Standard 3 (Integrated Curriculum) addresses team composition as a curricular design decision (De Fouw et al., 2020); Standard 8 (Active Learning) addresses the reflective practices that consolidate experiential learning into professional identity.

CONCLUSIONS AND NEXT STEPS

A decade of retrospective alumni evidence confirms that intensive, interdisciplinary, challenge-driven immersion leaves a "learning residue" that is cognitively and affectively salient long after graduation: a permanent shift from "technology-push" to user-centric reasoning that alumni trace directly to their CBI participation (Charosky et al., 2022; Ojasalo & Kaartti, 2021; Papageorgiou et al., 2021). Epistemic friction (navigated through the "Groan Zone") is the primary mechanism for this maturation (Sluijs et al., 2024): it produces the epistemic fluency required to act as a "translator" across disciplinary silos and the leadership-as-practice capability to facilitate collective sensemaking in mixed professional environments (Balboni et al., 2021; Van Den Beemt et al., 2023). This transformation is characterized by the far-transfer of core innovation skills such as ambiguity tolerance and iterative prototyping into diverse professional domains. As students navigate the “Safe but Uncomfortable” program environment, undergo through a “permanent reconfiguration of how they approach any complex problem” illustrating that challenge-based pedagogy acts as a “social engine” that fundamentally re-authors professional identity and fosters “Significant Learning” (Ojasalo & Kaartti, 2021).

These findings provide much-needed evidence to the CDIO community that epistemic friction is not merely a pedagogical abstraction, but the primary mechanism for professional maturation (Sluijs et al., 2024). By persisting through the frustration of the “Groan Zone” students develop the epistemic fluency required to act as “translators” across disciplinary silos (Balboni et al., 2021). It allows them to master leadership as practice, conceptualized as the situated ability to facilitate collective sensemaking and build alignment in mixed environments (Van Den Beemt et al., 2023). The ability to “break outside your disciplinary box” becomes a "core professional” (Figueiredo et al., 2022), shaping their careers in leadership and consulting roles (Colombelli et al., 2022; Pan et al., 2021).

Returning to the overarching research question and its sub-questions, the findings offer the following answers. Addressing SQ1, alumni consistently report using stakeholder-oriented problem framing, iterative development habits, ambiguity tolerance, and cross-functional communication as durable professional practices, competencies that they trace directly to their CBI participation. Addressing SQ2, the long-term value of interdisciplinary teamwork, communication, and leadership is most strongly attributed to the productive friction of working across disciplinary "languages"; alumni describe this experience as the origin of facilitation and sensemaking capabilities that distinguish them in professional settings. Addressing SQ3 (and responding to the overarching RQ) alumni describe CBI as the most career-shaping educational experience of their training: influencing entry into consulting, innovation, and project-based roles; informing consequential decisions between academic and industry pathways; and contributing to a lasting professional identity grounded in user-centricity, social impact, and collaborative agency. That alumni from business, design, and engineering backgrounds consistently converge on this career-level impact, despite arriving with very different prior experience and professional expectations, suggests that the programs interdisciplinary design generates effects that transcend any single discipline.

Despite these robust qualitative insights, the study’s reliance on retrospective self-report introduces potential recall bias and self-selection, (as those with more positive experiences may be more likely to participate), and social desirability bias; the tendency of respondents to present their experiences in alignment with perceived social norms or positive expectations rather than reflecting their true experience. The analysis focuses on perceived transfer rather than establishing direct causal links between specific course features and long-term career outcomes. To address these gaps, future research will implement a triangulation strategy by mapping interview themes against archival course artifacts, interdisciplinary grading rubrics, and process-tracking logs. By comparing longitudinal alumni accounts with nearer-term student data using advanced statistical models, we aim to further elucidate the specific “scaffolding mechanisms” (Gallagher & Savage, 2023) that ensure the persistence of innovation capabilities throughout the professional lifecycle (Ming et al., 2025).

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AI usage declaration

The authors utilized large language model (LLM) tools (Claude AI, ChatGPT and Gamma AI) during the preparation of this manuscript to assist with text structuring, grammatical refinement, the synthesis of qualitative coding data and figures and tables, The core research design, qualitative analysis, and final interpretation of findings were conducted entirely by the authors.

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BIOGRAPHICAL INFORMATION

Mireia Sierra is the Academic Coordinator, Faculty and Research Lead of Fusion Point, the innovation space between Esade, UPC and IED, and a PhD candidate in Education for Engineering, Science, and Technology at the UPC. Her research focuses on understanding the learning process and the longitudinal impact of Challenge-Based Learning (CBL) in higher education. Since 2014, she has led the pedagogical design and implementation of the Challenge-Based Innovation (CBI) program in collaboration with CERN’s IdeaSquare) coordinating different EU Initiatives such as the Fusion Point Consortium in Attract Academy. Her work bridges the gap between engineering, design, and business management to foster "future-ready" transversal competencies.

Dr. Matteo Di Stasi is a Professor at CUNEF Universidad (Madrid) and an expert in Innovation Management and Entrepreneurship. He holds a PhD in Business Administration from Esade Business School. His academic and professional work focuses on innovation, negotiation processes and leadership building. Having been deeply involved in Fusion Point EU projects such as Teach BEAST designing transversal skills effective educational activities in higher education. Now he is a professor at CUNEF in behavioral economics, organizational science and statistics, he keeps deeply collaborating with Fusion Point research initiatives.

Dr. Ramon Bragós is a Full Professor at the Electronics Engineering Department of the Universitat Politècnica de Catalunya (UPC) and associate dean of academic innovation at the Barcelona School of Telecommunications Engineering (ETSETB) of UPC.His research focuses both on biomedical engineering and on engineering education, with a specific focus on interdisciplinary teamwork and the assessment of professional competencies. He is the supervisor for the doctoral research.

Corresponding author

Mireia Sierra Andrés
Fusion Point, Esade Business School and
Universitat Politècnica de Catalunya
Avinguda de la Torre Blanca, 59, 08172
Sant Cugat del Vallès, Barcelona, SPAIN
mireia.sierra@esade.edu