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# Perceptions of project-based learning in CDIO-aligned curricula: an exploratory cluster analysis of a five-university survey in South Africa

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## ABSTRACT

Engineering education in Africa is undergoing a transformative shift, seeking to align with global standards while addressing the unique challenges and opportunities of the region. The integration of innovative teaching methodologies, such as Project-Based Learning (PBL), has emerged as a promising strategy to bridge the gap between theoretical knowledge and practical application. Within this paradigm, the CDIO (Conceive, Design, Implement, Operate) framework provides a structured approach to developing engineering competencies that are both technically robust and contextually relevant. However, evaluating the effectiveness of such educational strategies in diverse and resource-constrained environments remains a significant challenge. Unsupervised machine learning offers a powerful and scalable solution to this challenge. By analyzing complex, multidimensional data without predefined labels, it can uncover hidden patterns and insights into how students engage with PBL methodologies under the CDIO framework. This approach enables a nuanced understanding of student and staff behaviors, learning outcomes, and contextual factors that influence success through capacity building. This article explores how an unsupervised machine learning approach can be applied to understand and enhance the implementation of PBL using the CDIO framework in African engineering education. Adapting these data-driven insights from a five-university South African sample, this study proposes actionable recommendations for educators and policymakers, while noting that broader generalisation beyond similar contexts requires further multi-country validation

## KEYWORDS

Project based Learning, CDIO, Engineering Education, Sustainable Development Goals, South Africa

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## Introduction

In today's world and the foreseeable future, universities must structure engineering education to equip graduates with advanced high-tech competencies essential for keeping pace with rapidly evolving societal demands. Future engineers are expected to navigate complexity and adapt to continuous changes in the workplace while simultaneously tackling sustainability challenges (Sukackė et al 2022). Similar to other countries, South Africa's drive to improve educational quality has focused on advancing teaching and learning strategies. To support this, the nation has committed to fast-tracking development over the next seven years as part of its South African National Development Plan 2030 coupled with the and the United Nations Sustainable Development Goal Declaration (Republic of South Africa National Planning Commission 2012; United Nations. Transforming Our World, 2016; Nxasana et al 2023). Addressing this challenge relies heavily on the South African education system's capacity to prepare today’s children for exceptional achievement and meaningful engagement in the global society and economy of the 21st century (Van der Elst, 2016). To develop well-rounded talent, many educational institutions have embraced student-centered learning methods as the foundation for curriculum design. Among these, project-based learning (PBL) stands out as a widely adopted approach. PBL involves engaging students in the acquisition of professional knowledge while simultaneously developing critical skills and competencies by tackling complex, real-world, and open-ended problems through structured projects (Kolmos, 2016). The concept of project-based learning (PBL) has been interpreted and implemented in diverse ways across various contexts (Here, we define PBL as a structured approach where it serves as the central learning method within curriculum design.

In this model, students engage in self-directed learning by collaboratively working in teams to solve problems (Chen and Kolmos, 2021). Institution-wide implementation of PBL necessitates a shift in classroom dynamics, redefining teachers' roles to focus on facilitating both independent and collaborative learning among students (Pecore, 2013). For successful adoption of instructional approaches like PBL, it is essential that teachers and students understand, accept and adapt to this new teaching philosophy particularly within the sub Saharan region but, changing teachers' views on teaching and learning is not always straightforward (Bakkenes et al 2010). It is imperative that using the ‘’train the trainer model’’ staff undergo specific pedagogical training activities to help them better understand this teaching philosophy whiles building the needed competencies in the delivery of PjBL (Richard, 1996). The study gathered staff perception on the implementation of project-based learning using CDIO Framework with the sub Saharan region.

In this study, CDIO is treated as a program-level framework guiding outcomes, curriculum integration, learning experiences, and evaluation (Standards 1–12). It does not prescribe a single pedagogy; rather, a variety of active and integrated learning approaches—including project-based learning (PBL)—can be used to realize CDIO Standards (e.g., S7 Active Learning; S8 Integrated Learning Experiences). Our empirical focus is on staff perceptions of PBL enacted within CDIO-aligned curricula, not on CDIO as a pedagogy.

Staff from four Universities from South Africa participated in the study during a capacity building training on curriculum design integrating project-based learning. The training included introducing the participants to the under pining principles in relation to PBL as an active/integrated learning approach consistent with CDIO Standards, managing student and staff expectation as well as experience within project based learning curriculum and the development of a self-reflective tool on the teaching of project based learning. To support the transformation of teachers' pedagogical beliefs about PBL as an active/integrated learning approach consistent with CDIO Standards, this study examines the beliefs they hold—whether rooted in constructivism or traditional approaches—when engaging in a PBL environment and their perceptions of their roles as educators (Major, 2018). The findings aim to provide insights into instructors' beliefs in South Africa and offer recommendations for adopting PBL as an active/integrated learning approach consistent with CDIO Standards in the country's higher education sector.

## Literature review

Project-based learning has a long and diverse history in engineering education and predates the CDIO Initiative. In this paper, PBL is examined as one implementation choice consistent with CDIO’s emphasis on integrated and active learning. Instructor perception and belief have been a longstanding area of interest in educational research. They are generally defined as implicit and often unconscious assumptions regarding students, learning, classroom interactions, and a teaching philosophy (Kagan, 1992). Eisenhart, 2016 argued that belief is synonymous to how specific factors like task, action, attitude and event impacts a person's sense of judgement. Calderhead outlined five key aspects of teacher beliefs: beliefs about learners and learning, teaching methods, the curriculum, the process of learning to teach, and the teacher's self-perception and understanding of the nature of teaching (Calderhead, 1996). It is important emphasizing that instructor perception and belief in relation to effective teaching philosophy and approach coupled with learner expectation have a direct impact on the learning experience (Rubbie Davies, 2012). According to Breen et al, 2001 instructor perception and belief revolves around how teaching is done within an educational certain, the teaching material as well as approach to the delivery of the content and the duty of the instructor as a facilitator during the teaching process. The thought processes of instructors within an engineering education certain is impacted their belief and general perception of a teaching philosophy. Instructors belief system even have a direct impact on learning outcome of a module beyond the impact on student experience (Woolfolk-Hoy, 2009). Previous research has highlighted that teacher beliefs are influenced by context and are closely tied to their prior experiences with learning, teaching, and interacting with students (Kaymakamoglu, S.E, 2019). Other studies have defined teacher beliefs to include their views on themselves, the learning environment, the content being taught, specific teaching strategies, teaching methods etc. Unlike conventional mode of teaching where the teacher plays a pivotal role in the learning process via decision making for students, preparing lecture content, controlling of the lecture and the assessment of learning outcomes, constructivism allows students to take charge of their own learning process. The instructor therefore becomes a facilitator. In this approach, educators are encouraged to adopt a constructivist mindset, allowing students to actively participate in shaping the curriculum, selecting learning materials, and assessing their progress (Chen and Bonner 2017). Constructivist learning typically emphasizes the learner and the learning process, incorporating active learning strategies such as project-based learning (PBL) and teamwork, along with formative assessment methods like peer evaluation (Kaymakamoglu, 2019). Constructivist learning theories suggest that students' pre-existing beliefs significantly shape the learning content and methods used in the classroom. Likewise, teachers' beliefs influence their confidence in engaging students and managing the classroom, which, in turn, impacts students' learning experiences. Research has indicated that teachers' pedagogical beliefs are key factors in influencing their adoption of innovative teaching methods. Research has indicated that teachers' pedagogical beliefs are key factors in influencing their adoption of innovative teaching methods (Du and Chaaban 2020). This is especially clear when introducing instructional innovations like implementing Project-Based Learning (PBL) at the curriculum level. Shifting teachers' beliefs and roles from traditional teaching to constructivist approaches is a critical step, as teachers' beliefs shape their teaching strategies and behaviors. Constructivist beliefs are well-suited to PBL, as it emphasizes student ownership of ideas and personal interpretation of knowledge. Teachers who believe PBL enhances student learning tend to be more open to adopting it and are more motivated to explore pedagogical theories and practice PBL effectively (Du et al, 2021). As noted earlier, teacher beliefs are not fixed but evolve based on their experiences and interactions with students. However, shifting these beliefs is challenging, particularly in cases where educational reforms are imposed in a top-down manner. To successfully transition from traditional learning methods to Project – Based Learning (PBL) and influence teacher beliefs, it is essential to design pedagogical training programs that support teachers' professional growth. Furthermore, assessing the effectiveness of such training in transforming teacher beliefs is crucial to achieving meaningful educational change (Guyton, 2000).

While many studies have investigated and contrasted traditional teaching beliefs with constructivist principles across various educational settings, there is limited research on how teachers' beliefs and practices evolve when transitioning from traditional methods to constructivist approaches in South Africa. This is particularly relevant as Project-Based Learning (PBL) is still a relatively novel concept in the region. Understanding this transition is critical to addressing the unique challenges and opportunities within South Africa's educational landscape.

Several studies have focused on the beliefs of South African pre-service science teachers regarding teacher-centered and student-centered approaches. These studies primarily investigate prospective teachers during their training rather than those already working in the field. This research sheds light on how pre-service teachers' views on teaching methods are shaped during their educational programs. However, there is a lack of studies that explore how these beliefs evolve once teachers are in active classrooms, particularly with the implementation of student-centered strategies such as Problem-Based Learning (PBL) (Mavhunga, 2016).

The CDIO initiative originated in the late 1990s as a collaborative project between three Swedish universities — Linköping University, KTH Royal Institute of Technology, and Chalmers University of

Technology — and the Massachusetts Institute of Technology (MIT) in the United States. The project sought to reform engineering education by aligning curricula more closely with professional practice. Over the following years, CDIO grew into a global network of universities, with the first CDIO Syllabus published in 2001 and CDIO Standards established in 2004. Today, it continues to expand worldwide as a community dedicated to improving engineering education (Crawley et al., 2014; Malmqvist, Edström & Rosen, 2020).

Since its creation, the CDIO framework has continuously evolved to address the changing needs of engineering educators and practitioners. This progression aligns with a broader rethinking of global engineering education to ensure relevance in a rapidly transforming professional landscape (Malmqvist, Edström, and Rosen, 2020). Today, CDIO remains a cornerstone for integrating practical, real-world skills into engineering curricula worldwide.

The CDIO community is expected to encounter new challenges in the coming years, prompting the need for significant advancements in strategies (Graham, 2018; Meikleham et al., 2018). These challenges arise from various factors, including growing student cohort sizes, the need for flexible and on-demand learning options, rising operational costs, continuous advancements in science and technology, and the evolution of teaching and learning methodologies (Graham, 2018; Kamp, 2021).

Graham (2018) outlines three key trends for the future of engineering education:

1. A hybrid model blending on-campus active learning with online, off-campus experiences.
2. Greater flexibility and diversity in learning options tailored to students' needs.
3. Curricula that integrate cross-disciplinary education, human-centered design, and global perspectives.

The COVID-19 pandemic has further accelerated these trends, driving the rapid adoption of online and blended learning formats, often without sufficient time to develop tailored resources or pedagogical frameworks. This shift highlights the critical need for an evidence-based approach to inform and refine practices in engineering education, ensuring that new methods are robust, scalable, and effective (Power, 2021a).

However, Ramnarain and Hlatswayo found that some teachers in South African displayed positive attitudes and beliefs towards adopting inquiry -based learning. Inquiry-Based Learning (IBL) and Project-Based Learning (PBL) are closely related, learner-centred, constructivist approaches that promote active engagement, collaboration, and authentic problem solving (Table 1). Both align with CDIO emphases on active learning (Standard 7) and integrated learning experiences (Standard 8). However, they differ in focus and typical enactment. IBL is organised around investigative questions and the systematic gathering and interpretation of evidence to construct explanations (often through structured/guided/open inquiry). PBL, by contrast, centres on addressing an authentic problem through a sustained project that culminates in a publicly shareable artefact/deliverable (prototype, design, report, demo), frequently requiring multi-disciplinary integration and stakeholder interaction. In practice, PBL often embeds cycles of inquiry (e.g., scoping questions, data collection, testing), while IBL implementations can culminate in mini-projects; thus the two approaches partially overlap but are not interchangeable.

South African IBL studies (e.g., Ramnarain & Hlatswayo, 2018) highlight benefits for scientific reasoning, engagement, and epistemic practices, while also noting implementation challenges—teacher confidence, assessment alignment, resource constraints, and curriculum pacing. These findings are consistent with our context: they help explain staff optimism about active approaches while underscoring the need for faculty development, assessment redesign, and enabling workspaces when adopting either IBL or PBL within CDIO-aligned programmes. Our training and survey focused on PBL because it directly supports CDIO's design-implement experiences (e.g. standard 5) and provides a natural vehicle for industry-linked artefacts, while acknowledging that IBL processes are embedded within PBL tasks used by participants.

Table 1: IBL vs. PBL—similarities and differences (and links to CDIO)

| Dimension | Inquiry-Based Learning (IBL) | Project-Based Learning (PBL) | CDIO linkage / Note |
|---|---|---|---|
| Primary driver | Investigative question(s) and evidence | Authentic problem/brief leading to artefact | Both map to S7/S8 (active/integrated) |
| Typical outcome | Explanation/argument supported by data | Deliverable/artefact (prototype, design, report) | PBL aligns strongly with design-implement experiences |
| Process emphasis | Generating questions, planning investigations, data collection & analysis, constructing explanations | Problem scoping, stakeholder needs, iterative design, integration, project management | Both support systems thinking and teamwork |
| Assessment focus | Evidence use, reasoning quality, inquiry process | Product quality and process (milestones, reviews) | Suggests rubrics combining process & product |
| Time scale | Short to medium (lessons → weeks) | Medium to long (weeks → term) | Both can scale with curriculum structure |
| Teacher role & scaffolding | Structured → guided → open inquiry; explicit scaffolds for method & evidence | Facilitation of planning, roles, milestones; project scaffolds (charters, Gantt, reviews) | Requires faculty PD and QA alignment |
| Resource demands | Data-collection tools, lab access (can be low-cost) | Materials, maker/lab/workspace, industry inputs | Workspaces (CDIO S6) critical for both |
| Fit with CDIO | Emphasises S7/S8 | Emphasises S5/S7/S8, often S6/S11 | Our study examines PBL within CDIO-aligned programmes |

However, while understanding teachers' positive views on new teaching methods is important, further investigation is required into how academics develop and maintain their pedagogical beliefs, how they perceive their roles, and how these beliefs shape their teaching practices (Ramnarain and Hlatswayo, 2018). We therefore treat PBL as our focal active-learning approach situated within a CDIO-aligned programme context, while recognising that IBL practices operate inside PBL cycles. Where we reference Ramnarain & Hlatswayo in the IBL literature, we use their findings to motivate the conditions (teacher support, assessment, resources) that similarly enable effective PBL in engineering programmes.

To address this gap, the current study explored the pedagogical perception of academics in South African Higher Education Institution intending to integrate Project-Based Learning (PBL) into their curriculum. The study was guided by the following broader research questions:

- How do academics in South Africa perceive the implementation of CDIO and project based across higher education institutions?
- In what ways do their beliefs about teaching and learning influence the implementation of CDIO & PBL in South Africa?
- What is the future perspective of CDIO implementation in South Africa?

This research aims to provide a deeper understanding of the relationship between teacher beliefs and their teaching practices in the context of innovative teaching strategies.

### Ethical Approval

The use of questionnaires and the handling of gathered data was approved by the ethics committee of King's College London (MRA-23/24-42656)."

### Questionnaire design and dissemination

Data were collected at a hands-on training event that introduced project-based learning and briefly situated it within the CDIO framework. Attendees from five South African universities—University of South Africa (UNISA), Tshwane University of Technology (TUT), Durban University of Technology (DUT), Cape Peninsula University of Technology (CPUT), and University of the Witwatersrand (Wits)—were invited to complete the survey. In total, 49 responses were received.

To enhance transparency, we report the institutional distribution of responses and the professional backgrounds of respondents in aggregate (see Table 2 and Table 3). Institutional affiliation and role were captured via workshop registration and linked to de-identified survey records under the approved ethics protocol (KCL MRA-23/24-42656); counts are reported only in aggregate to preserve anonymity.

Table 2: Institutional distribution of respondent

| University | n | % |
|---|---|---|
| UNISA | 14 | 28.6% |
| TUT | 12 | 24.5% |
| DUT | 9 | 18.4% |
| CPUT | 8 | 16.3% |
| Wits | 6 | 12.2% |
| Total | 49 | 100% |

Table 3. Respondent background: roles and disciplines (n = 49)

**Academic role / function**
Lecturer / Assistant Professor: 16 (32.7%)
Senior Lecturer / Associate Professor: 12 (24.5%)
Professor: 6 (12.2%)
Academic leadership (HoD/Dean/Programme Lead): 5 (10.2%)
Educational developer / Teaching Fellow / QA / Professional staff: 8 (16.3%)
Industry liaison / External partner: 2 (4.1%)

**Discipline cluster**
Mechanical & Design: 15 (30.6%)
Industrial & Systems: 11 (22.4%)
Chemical & Materials: 10 (20.4%)
Electrical / Other: 13 (26.5%)

**Years of teaching experience**
0–5 years: 14 (28.6%) ·
6–10: 13 (26.5%) ·
11–15: 11 (22.4%) ·
>15: 11 (22.4%)

Respondents represented all five institutions (Table 2), led by UNISA (28.6%, n=14) and TUT (24.5%, n=12), with additional participation from DUT (18.4%, n=9), CPUT (16.3%, n=8), and Wits (12.2%, n=6). Roles spanned the academic pipeline (Table 3), with Lecturers/Assistant Professors (32.7%) and Senior Lecturers/Associate Professors (24.5%) forming the largest groups, alongside Professors

(12.2%), academic leaders (10.2%), and educational developers/professional staff (16.3%). Disciplinary representation included Mechanical & Design (30.6%), Industrial & Systems (22.4%), Chemical & Materials (20.4%), and Electrical/Other (26.5%), providing a broad cross-section of engineering education perspectives.

The questionnaire was specifically developed to evaluate the effectiveness of Project-Based Learning (PBL) within the framework of the CDIO (Conceive-Design-Implement-Operate) framework. In simple terms the questionnaire elicited staff perceptions of Project-Based Learning (PBL) situated within CDIO-aligned programmes. In particular, it measured baseline familiarity with the CDIO framework and attitudes about the perceived potential of CDIO-consistent practices (e.g., active/integrated learning, design-implement experiences) to address local educational needs.

The design process involved a systematic approach to ensure that the instrument accurately captured multiple aspects of both PBL and CDIO methodology. The questionnaire (detailed in Table 4) comprised a combination of closed-ended and open-ended questions to facilitate both quantitative and qualitative analyses. Closed-ended questions utilized a 5-point Likert scale ranging from "Strongly Disagree" to "Strongly Agree" to measure participants' perceptions across key dimensions such as teamwork, engagement, technical skill development, problem-solving ability, and the alignment of the learning experience with CDIO standards. Open-ended questions were included to gather more in-depth insights into participants' experiences and challenges during the PBL process. This was a convenience sample tied to a single hands-on training event; participation was voluntary and non-probabilistic. Accordingly, findings are exploratory and are not intended to be statistically generalised to all institutions in South Africa or across Africa. Items distinguished between (a) respondents' program-level familiarity with CDIO (e.g., awareness of Standards/Syllabus and institutional adoption) and (b) their attitudes about potential effectiveness of CDIO in addressing educational needs. Forty-nine responses were collated during the training. Because the training provided an introductory overview of CDIO, the familiarity item was intended to reflect baseline knowledge rather than knowledge gained during the session. For the "Challenges in CDIO implementation" (Q4) and "Overcoming barriers/Strategies" (Q8) items, respondents used a multiple-response checkbox format ("select as many as apply"); results are therefore reported as the percentage of respondents endorsing each option and may sum to >100%.

Table 4. Structure and dimensions of the questionnaire on CDIO framework implementation in African education.

| No. | Aspect | Question | Type |
|---|---|---|---|
| 1 | Familiarity with CDIO | Prior to this workshop, how familiar were you with the CDIO framework (e.g., Standards/Syllabus, program-level adoption)? | Likert Scale (Not Familiar – Very Familiar) |
| 2 | Institutional Implementation | Has your institution implemented the CDIO framework in its curriculum? | Yes/No/Unsure |
| 3 | Personal Competencies | I have complex thinking and analysis abilities. | Yes/No/Unsure |
| 4 | Challenges in CDIO Implementation | What are the main challenges you perceive in implementing CDIO in education in Africa? | Multiple Choice (Select as many as apply) |
| 5 | Potential of CDIO | To what extent do you believe CDIO has the potential to address the needs of education in Africa? | Likert Scale (Not at all – To a Great Extent) |
| 6 | Importance of Adoption | How important do you think it is for institutions in Africa to adopt CDIO? | Likert Scale (e.g., Not Important – Very Important) |
| 7 | Faculty Readiness | There is a high level of faculty readiness for implementing CDIO in education in Africa, particularly in South Africa. | Likert Scale (Strongly disagree–Strongly agree) |
| 8 | Overcoming Barriers | What strategies do you think could be effective in overcoming barriers to CDIO implementation in African institutions? | Multiple Choice (Select as many as apply) |
| 9 | Interdisciplinary Collaboration | To what extent do you believe CDIO can promote interdisciplinary collaboration within education in Africa? | Likert Scale (Strongly disagree–Strongly agree) |

| | | | |
|---|---|---|---|
| 10 | Awareness Among Students | How would you rate the level of awareness about CDIO among students in Africa? | Likert Scale (e.g., Very Low – Very High) |
| 11 | Role of Industry Partnerships | Industry partnerships can play a role in supporting the implementation of CDIO in African education. | Likert Scale (Strongly disagree–Strongly agree) |
| 12 | Sustainable Integration | What strategies can be employed to ensure sustainable integration of CDIO in education across African institutions? | Open-ended |
| 13 | Impact on Education Quality | CDIO will have an impact on the overall quality of education in Africa. | Likert Scale (Strongly disagree–Strongly agree) |
| 14 | Cultural Influences | Do you believe that cultural factors may influence the successful implementation of CDIO in African education? | Likert Scale (Strongly disagree–Strongly agree) |
| 15 | Future Outlook | Overall, how optimistic are you about the future of CDIO implementation in education in Africa? | Likert Scale (Not Optimistic – Very Optimistic) |

**Power & Precision Considerations**

This was an exploratory sample (n = 49) collected at a training event. Accordingly, analyses emphasise descriptive summaries and unsupervised clustering. Where inferential checks were illustrative (e.g., Cluster × Institution), we report effect sizes and permutation/Monte-Carlo p-values. To improve transparency, we provide precision and treat findings as hypothesis-generating. To improve transparency, we provide precision indicators (proportions with 95% Cis) indicated in Table 5 (Institution), Table 6 (Roles) and Table 7.

Table 5: Wilson 95% CIs (Institutions)

| Category | n | Proportion | 95% CI (lower) | 95% CI (upper) |
|---|---|---|---|---|
| UNISA | 14 | 28.60% | 17.80% | 42.40% |
| TUT | 12 | 24.50% | 14.60% | 38.10% |
| DUT | 9 | 18.40% | 10.00% | 31.40% |
| CPUT | 8 | 16.30% | 8.50% | 29.00% |
| Wits | 6 | 12.20% | 5.70% | 24.20% |

Table 6: with Wilson 95% CIs (Roles)

| Category | n | Proportion | 95% CI (lower) | 95% CI (upper) |
|---|---|---|---|---|
| Lecturer / Assistant Professor | 16 | 32.70% | 21.20% | 46.60% |
| Senior Lecturer / Associate Professor | 12 | 24.50% | 14.60% | 38.10% |
| Educational developer / Teaching Fellow / QA / Professional staff | 8 | 16.30% | 8.50% | 29.00% |
| Professor | 6 | 12.20% | 5.70% | 24.20% |
| Academic leadership (HoD/Dean/Programme Lead) | 5 | 10.20% | 4.40% | 21.80% |
| Industry liaison / External partner | 2 | 4.10% | 1.10% | 13.70% |

Table 7: with Wilson 95% CIs (Disciplines)

| Category | n | Proportion | 95% CI (lower) | 95% CI (upper) | |
|---|---|---|---|---|---|
| Mechanical & Design | 15 | 30.60% | 19.50% | 44.50% | |
| Electrical / Other | 13 | 26.50% | 16.20% | 40.30% | |
| Industrial & Systems | 11 | 22.40% | 13.00% | 35.90% | |
| Chemical & Materials | 10 | 20.40% | 11.50% | 33.60% | |

**Data Analysis**

The collected data were analyzed using both quantitative and qualitative approaches to uncover patterns and insights related to the implementation of the CDIO framework in African education systems. Quantitative analysis involved the application of k-means clustering to group responses into three distinct clusters based on seven key variables: familiarity, faculty readiness, interdisciplinary collaboration, awareness, impact, cultural factors, and optimism.

We used the elbow criterion applied to the within-cluster sum of squares (inertia) computed on z-standardised features. Inertia measures how tightly observations group around their assigned centroid (lower is better). As k increases, inertia always decreases because clusters become more numerous and specific. The elbow method looks for the point of diminishing returns: the smallest k beyond which adding an extra cluster yields only a small additional decrease in inertia.

Intuitively, there is a compromise to be found:

- At one extreme, k = 1 merges all observations into a single cluster, erasing variation and masking any underlying structure.
- At the other extreme, k = n (each observation its own cluster) over-segments the data: there is no meaningful grouping left, and the purpose of clustering disappears.
- The elbow marks a balance between coherence (clusters are internally tight) and parsimony/interpretability (the solution uses as few clusters as needed).

Operationally, we inspected the relative reduction in inertia when moving from k−1 to k ($\Delta_k = (W_{k-1} - W_k)/W_{k-1}$) and selected the smallest k after which these reductions became noticeably smaller, while also checking interpretability of the resulting profiles. In our data, the curve showed a clear bend at k = 3, after which improvements were marginal, so we report the elbow-selected, criterion-guided solution k = 3.

**Suitability and algorithm choice.**

We clustered z-standardised Likert variables (1–5) using k-means because the method yields centroids (feature means) that are straightforward to interpret as profile summaries for practice and policy. We recognise that k-means assumes Euclidean geometry with roughly spherical, similarly-sized clusters, is sensitive to initialisation (addressed via multiple k-means++ restarts; see above), and can be influenced by outliers. In smaller samples such as ours (n = 49), density estimation is unstable and fine-grained separation is difficult, which favours a parsimonious, centroid-based approach with clear reporting (elbow-selected K = 3).

On the other hand, DBSCAN / HDBSCAN (density-based): capture arbitrary-shaped clusters and identify noise without pre-specifying K; helpful when clusters have uneven densities. However, results depend on hyper-parameters (ε, min_samples), and with small and many points may be labelled as noise, reducing interpretability for programme decisions. Again, k-medoids (PAM) with Gower distance: robust to outliers and suitable for mixed/ordinal data; medoids are actual respondents, which can aid exemplars. The trade-off is computational cost and, with small n, similar “number-of-clusters” choice issues remain. Furthermore, Hierarchical (Ward linkage): provides a dendrogram and does not require pre-specifying K; works well with Gower or Euclidean distances and can reveal nested structure. Interpretability is good, but final K still needs a cut criterion. Finally, Model-based / latent-class (e.g., Gaussian mixtures; ordinal latent classes): formally handles measurement models and uncertainty but requires more parametric assumptions and larger samples for stable estimation.

As explained above, all features were z-standardised prior to clustering. We evaluated k = 2–6, selecting k = 3 using the elbow in within-cluster sum of squares (inertia) and parsimony (see Figure 4). Because k-means can converge to local minima depending on initial centroids, we used k-means++ seeding with [n_init = 500] independent random initialisations (max_iter = 300, tol = 1e-4). For the chosen k, we retained the run with the lowest inertia; if ties occurred, we preferred the solution with the higher average silhouette (computed on the standardised space). This restart protocol mitigates sensitivity to starting points and improves the chance of reaching a good local optimum.

As a secondary check, we examined the silhouette profile across K. The silhouette compares within-cluster cohesion to between-cluster separation, but in small and potentially imbalanced samples it can be volatile and sometimes favours larger K that add limited interpretive value. In our data, the silhouette profile did not provide a materially different recommendation from the elbow; we therefore report the elbow-selected, criterion-guided solution (K = 3) and include the silhouette curve for transparency

Qualitative analysis involved thematic coding of open-ended responses to identify recurring themes such as curriculum reform, industry partnerships, interdisciplinary collaboration, and faculty readiness. A word cloud was generated to visualize key terms and phrases frequently mentioned by participants. These analyses were complemented by descriptive statistics and visualizations, including radar plots and bar charts, to provide a comprehensive understanding of the data. Together, these methods enabled a nuanced exploration of challenges, opportunities, and strategies for CDIO framework implementation in African education systems.

Open-ended responses referencing “dialogue,” “collaboration,” or “silos” were double-coded into two a priori categories—structural (e.g., timetabling, workload, QA/approval paths, budget silos, class sizes, rooms) and cultural (e.g., norms prioritising research over teaching collaboration, low psychological safety to share in-progress teaching, territoriality around modules, unclear credit/recognition for co-teaching). Disagreements were resolved through discussion; themes were then mapped to actionable proposals in the Discussion.

Institution level homogeneity and robustness checks

To examine whether cluster membership co-varied with university, we cross-tabulated Cluster (k=3) by Institution (UNISA, TUT, DUT, CPUT, Wits) and conducted a Chi-square test of independence with Monte-Carlo simulation for exact p-values given small cell counts. We report Cramér’s V as effect size. We further computed the Adjusted Rand Index (ARI) between cluster labels and institution labels to quantify overall agreement, and ran a permutation-based enrichment test (10,000 label shuffles) to assess whether any institution was over-represented in a cluster relative to chance (Holm-adjusted p across 5×3 tests). As a sensitivity analysis, we re-estimated k-means in a leave-one-institution-out (LOIO) procedure and compared (a) ARI between full-sample and LOIO assignments and (b) cosine similarity of cluster centroids.

Again, we evaluated solutions for k = 2–6. Following standard practice, the number of clusters was selected using the elbow criterion on the within-cluster sum of squares (inertia) and cross-checked for parsimony and interpretability. We therefore refer to k = 3 as the elbow-selected (criterion-guided) solution rather than “optimal,” acknowledging that different criteria can support different k in exploratory settings. As a robustness check, we also inspected the average silhouette, Calinski–Harabasz, and Davies–Bouldin trends and found no consistent improvement beyond k = 3 that would outweigh the loss of parsimony.

## Results and discussion

**Interpretive note.**

Given the modest sample size and non-probability sampling, the patterns reported below are indicative rather than inferential. We prioritise effect sizes and descriptive trends and avoid population-level generalisations.

Interpretation of these results should be tempered by the study's scope: an n = 49 sample across five South African HEIs collected during a hands on training activity. The descriptive statistics and k-means clusters are therefore hypothesis-generating rather than inferential; they surface patterns that warrant confirmation in larger, multi-country, probability-based studies before any continent-wide conclusions are drawn.

**Scope and generalisability.**

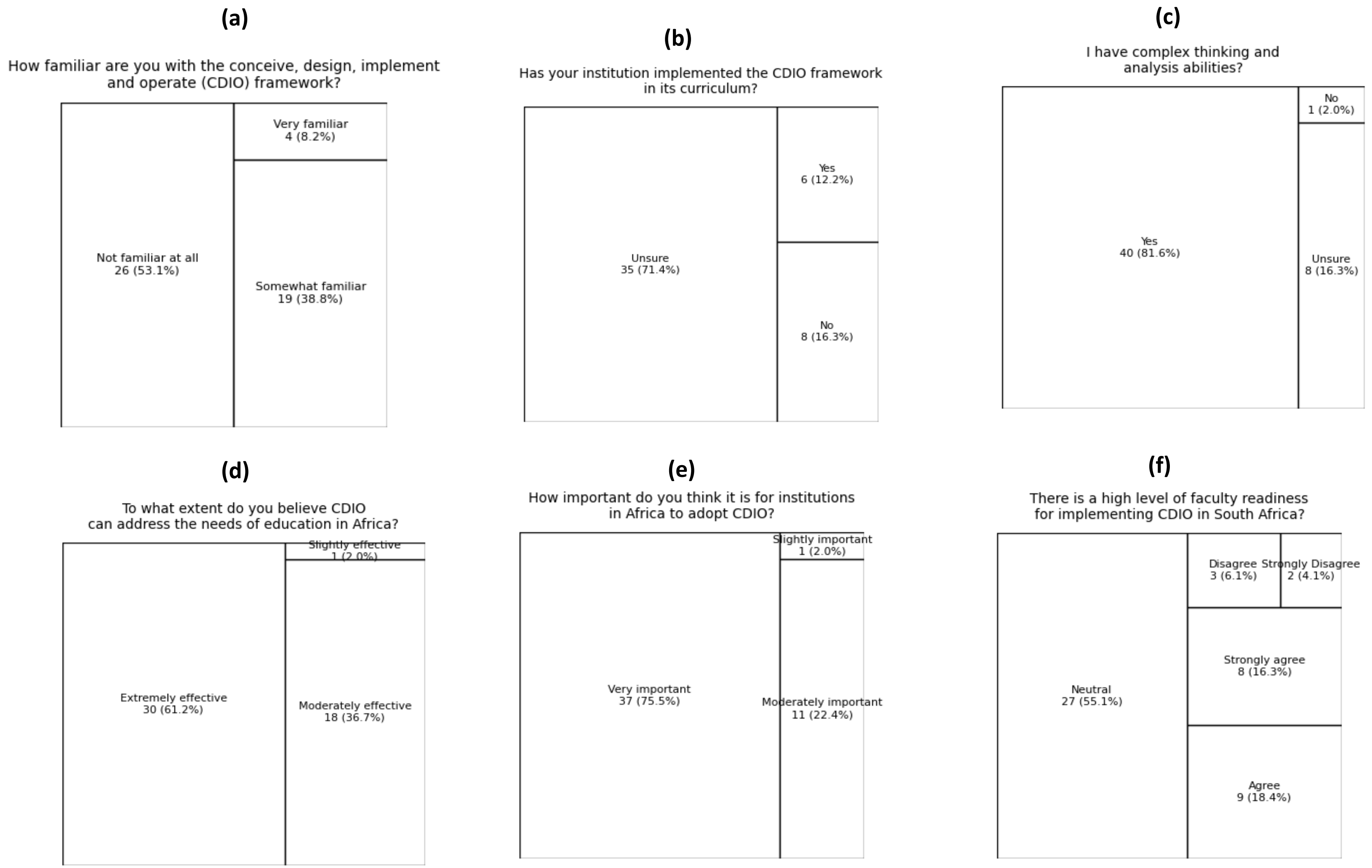
The study's n = 49 convenience sample constrains statistical power, especially for detecting small effects or subtle between-institution differences. Our checks (e.g., Cluster × Institution) yielded very small effects (e.g., Cramér's V ≈ 0.06). We therefore characterise the results as hypothesis-generating for similar South African HEI contexts and recommend larger, probability-based, multi-country studies to test these patterns.

**Perceptions and Challenges in CDIO Framework Implementation: Quantitative analysis**

Figure 1 presents the findings of the questionnaire designed to assess the awareness, implementation, and potential of the CDIO framework in African education. In Figure 1(a), it is evident that a significant portion of the respondents (53.1%) are not familiar with the CDIO framework, while 38.8% reported being somewhat familiar. Only 8.2% indicated that they are very familiar with the framework, highlighting a notable gap in awareness. Figure 1(b) illustrates that 71.4% of respondents were unsure whether their institution had implemented the CDIO framework, while 16.3% reported that it had not been implemented. Only 12.2% confirmed implementation, indicating a low penetration of the CDIO approach in the institutions represented. Figure 1(c) shows that 81.6% of respondents believe they have complex thinking and analytical abilities, which is encouraging for the adoption of CDIO. However, the low institutional implementation rate, as shown in Figure 1(b), suggests that these abilities may not currently be utilized effectively within a structured framework like CDIO. Regarding the potential of CDIO to address educational needs in Africa, Figure 1(d) shows that 61.2% believe it to be extremely effective, and 36.7% consider it moderately effective, indicating strong perceived relevance. Similarly, Figure 1(e) demonstrates that 75.5% of respondents think it is very important for institutions in Africa to adopt the CDIO framework, with only 2% rating it as slightly important. Figure 1(f) highlights faculty readiness as a key challenge, with 55.1% of respondents remaining neutral and only 16.3% strongly agreeing that faculty in South Africa are ready for CDIO implementation. Figure 1(g) illustrates that 83.7% of respondents believe CDIO can promote interdisciplinary collaboration, which aligns with the framework's emphasis on integrating diverse disciplines. Despite the potential benefits, Figure 1(h) reveals that 57.1% of respondents rate student awareness of CDIO as low, suggesting a need for targeted awareness initiatives. Figure 1(i) emphasizes the importance of industry partnerships, with 53.1% strongly agreeing and 34.7% agreeing on their role in CDIO implementation. Respondents also highlight the overall positive impact of CDIO on education quality in Figure 1(j), with 81.7% agreeing or strongly agreeing. Finally, Figures 1(k) and 1(l) address cultural factors and optimism for the future. Cultural influences are perceived as significant by 51% of respondents (agree) and 20.4% (strongly agree), while 46.9% are very optimistic about the future of CDIO implementation, as seen in Figure 1(l).

The findings underscore both the challenges and opportunities associated with implementing the CDIO framework in African education. The low levels of familiarity with CDIO (Figure 1(a)) and limited institutional implementation (Figure 1(b)) reflect a broader issue in engineering education in Africa: the lack of awareness and integration of global pedagogical innovations. This aligns with scholarly literature, which emphasizes that awareness-building is a prerequisite for institutional change and the successful implementation of modern frameworks like CDIO (Edström et al., 2020). The CDIO framework offers a structured approach to curriculum design, focusing on technical knowledge, interpersonal skills, and real-world application, making it well-suited to addressing the needs of African institutions. The strong acknowledgment of personal competencies such as complex thinking and analysis (Figure 1(c)) highlights the readiness of African students to engage with frameworks like CDIO. However, as Edström et al. (2020) point out, such competencies need to be systematically nurtured through integrated learning experiences combining theoretical knowledge and practical engineering skills. The low levels of faculty readiness (Figure 1(f)) further suggest that professional development programs are needed to equip educators with the skills and confidence to implement CDIO effectively. Faculty development is a cornerstone of successful curriculum reform, as noted by Crawley et al. (2014), who advocate for faculty engagement in interdisciplinary and project-based learning approaches. Respondents overwhelmingly agreed on the potential of CDIO to address educational needs in Africa (Figure 1(d)) and emphasized its importance for institutions (Figure 1(e)). The focus of CDIO on solving real-world problems and fostering interdisciplinary collaboration (Figure 1(g)) aligns with the continent's demand for contextually relevant engineering education (Edström et al., 2020). Nevertheless, Figure 1(h) highlights low awareness among students, a gap that must be addressed through proactive awareness campaigns and student engagement activities. These findings align with the broader literature on engineering education reform, which emphasizes the importance of involving all stakeholders—students, faculty, and industry partners—in the adoption process (Edström et al., 2020). The positive outlook on industry partnerships (Figure 1(i)) highlights their role in supporting CDIO implementation. Industry collaborations provide opportunities for students to engage with real-world challenges, enhancing the relevance and applicability of their learning experiences (Crawley et al., 2014). Furthermore, the emphasis on sustainability (Figure 1(j)) reflects an understanding of the need for long-term strategies to ensure that CDIO becomes a permanent part of the educational landscape in Africa. Respondents also acknowledged the influence of cultural factors on implementation success (Figure 1(k)), emphasizing the need to adapt the framework to local contexts, as discussed by Hofstede (2001). Finally, the overall optimism about the future of CDIO implementation (Figure 1(l)) is a positive indicator. However, sustainable adoption requires addressing the barriers highlighted in this study, including faculty readiness, student awareness, and institutional support. As Edström et al. (2020) point out, the growth of the CDIO community globally demonstrates the framework's adaptability and scalability, which could inspire further improvements in African education systems.

A notable pattern is that many respondents reported low program-level familiarity with CDIO while simultaneously rating its potential effectiveness highly (Figure 1d vs 1a). This is consistent with the instrument design: Q1 captures baseline familiarity with a program-level framework; Q5 elicits attitudes about CDIO's potential based on its stated aims and brief introduction during the event. Given participants' existing experience with project-based/active learning, it is reasonable for them to infer that a framework emphasising integrated, real-world learning and programme coherence would be effective in principle, even in the absence of deep prior knowledge of CDIO Standards or local adoption status. We therefore interpret Q5 as perceived potential, not realised effectiveness, and caution against conflating attitude with implementation competence. Finally, because Q5 measures perceived potential effectiveness rather than realised outcomes, positive ratings under low familiarity should be interpreted as attitudinal endorsement of CDIO's aims; future studies should incorporate pre/post knowledge checks and implementation outcome measures to relate familiarity, attitudes, and realised impact.


(a)
How familiar are you with the conceive, design, implement and operate (CDIO) framework?
Very familiar 4 (8.2%)
Not familiar at all 26 (53.1%)
Somewhat familiar 19 (38.8%)
(b)
Has your institution implemented the CDIO framework in its curriculum?
Yes 6 (12.2%)
Unsure 35 (71.4%)
No 8 (16.3%)
(c)
I have complex thinking and analysis abilities?
No 1 (2.0%)
Yes 40 (81.6%)
Unsure 8 (16.3%)
(d)
To what extent do you believe CDIO can address the needs of education in Africa?
Slightly effective 1 (2.0%)
Extremely effective 30 (61.2%)
Moderately effective 18 (36.7%)
(e)
How important do you think it is for institutions in Africa to adopt CDIO?
Slightly important 1 (2.0%)
Very important 37 (75.5%)
Moderately important 11 (22.4%)
(f)
There is a high level of faculty readiness for implementing CDIO in South Africa?
Disagree 3 (6.1%)
Strongly Disagree 2 (4.1%)
Strongly agree 8 (16.3%)
Neutral 27 (55.1%)
Agree 9 (18.4%)

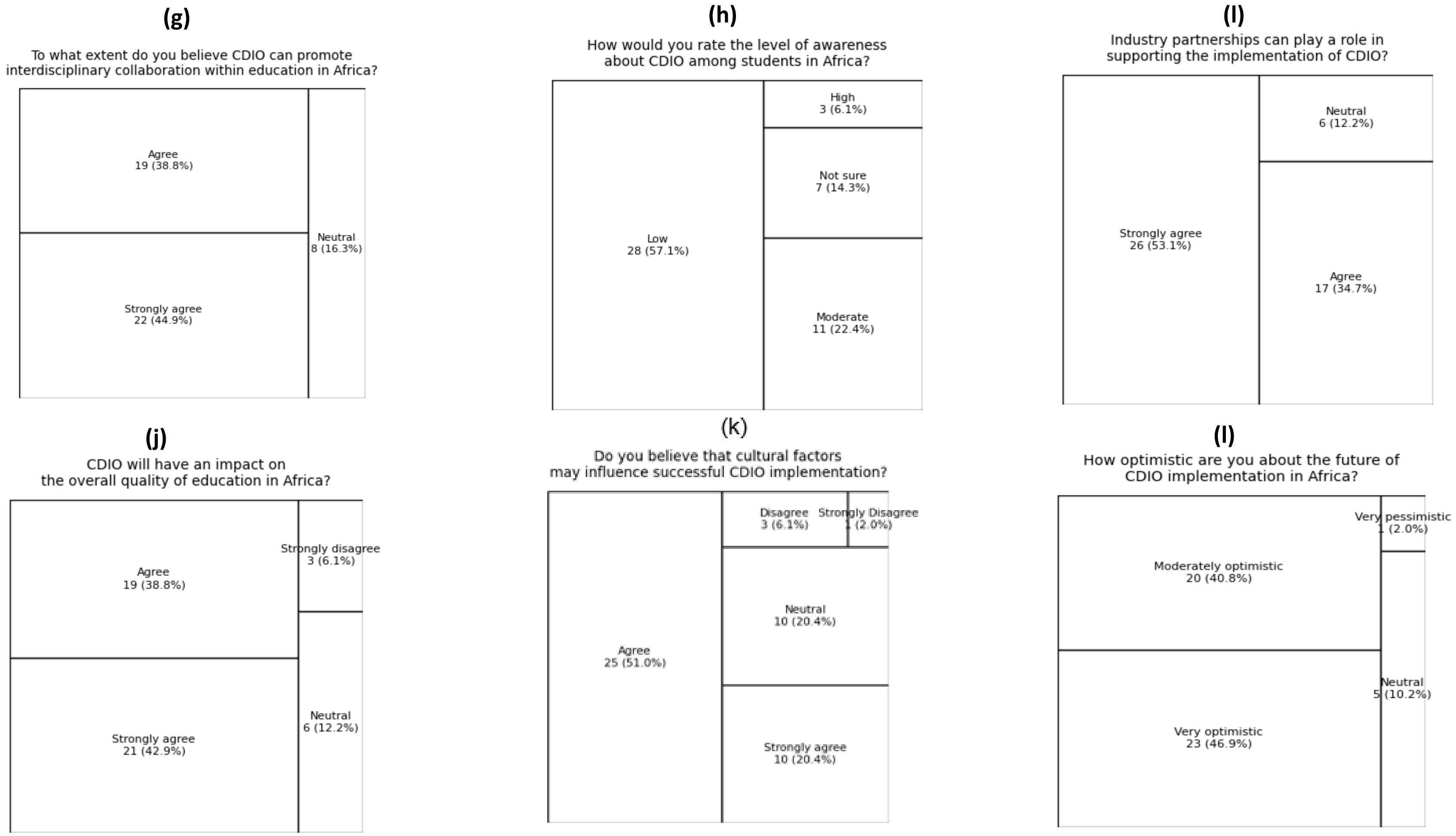



Figure 1. This figure presents responses to the questionnaire on various aspects of the CDIO framework: (a) familiarity with the framework, (b) institutional implementation, (c) personal competencies, (d) perceived effectiveness, (e) importance of adoption, (f) faculty readiness, (g) potential for interdisciplinary collaboration, (h) student awareness, (i) role of industry partnerships, (j) impact on education quality, (k) influence of cultural factors, and (l) optimism about its future implementation.

The findings in Figure 2(a) show the structural rigidity of existing curricula in African education systems as the primary challenge to implementing CDIO. Due to the fact that respondents could select multiple options, Figure 2 reflects endorsement rates rather than mutually exclusive choices. This observation is consistent with prior studies, which argue that curriculum reforms often face resistance due to entrenched traditional pedagogical practices (Biggs & Tang, 2011). The lack of interdisciplinary dialogue among instructors and insufficient competence in system-building skills further exacerbates these issues. These findings align with the global challenges of implementing CDIO, as outlined by Edström et al. (2020), who advocate for an integrated and collaborative approach to curriculum reform.

The responses in Figure 2(b) indicate that stakeholders see curriculum benchmarking and faculty development as the most effective strategies for overcoming these barriers. Benchmarking existing curricula to identify gaps is a pragmatic approach that can guide reforms, ensuring alignment with CDIO standards (Crawley et al., 2014). Additionally, developing faculty competence in the CDIO syllabus is critical, as instructors are central to the success of any pedagogical framework. This aligns with studies emphasizing faculty training as a cornerstone for the successful implementation of CDIO and similar frameworks (Kolmos et al., 2008).

The call for government support through policy implementation highlights the need for systemic change. Policy-driven interventions can provide the institutional and financial backing required to foster curriculum reform and promote interdisciplinary collaboration (Ssebuwufu et al., 2012). Furthermore, training on skills and attitudes not previously taught emphasizes the necessity of equipping both faculty and students with competencies that extend beyond technical knowledge to include interpersonal and system-level skills, a hallmark of the CDIO framework (Edström et al., 2020).

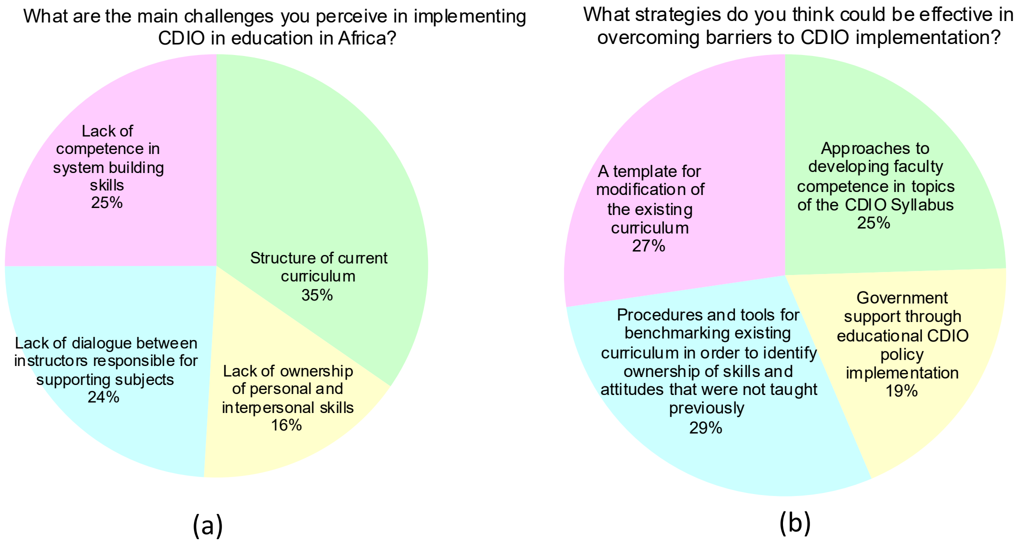



Figure 2. Challenges and Strategies for Implementing the CDIO Framework in African Education. (a) The main challenges perceived in implementing the CDIO framework include curriculum rigidity, lack of instructor dialogue, and insufficient system-building skills. (b) Suggested strategies to overcome barriers, emphasizing curriculum benchmarking, faculty development, and government support through educational policy implementation.

**Qualitative Insights into CDIO Implementation in African Education Systems**

The qualitative analysis of responses reveals diverse perspectives on the implementation of the CDIO framework within African education systems. Key themes that emerged include the necessity of curriculum reform, interdisciplinary collaboration, industry partnerships, and the critical role of faculty and governmental support. These findings are aligned with previous studies highlighting the effectiveness of interdisciplinary and project-based learning (Reviere et al., 2024; Wu & Wu, 2020). Participants emphasized the importance of embedding CDIO principles into educational curricula to align with institutional and industry needs. One respondent stated, "The integration of CDIO has to start early, for example from grade 10. The integration must be progressive, and pupils must be initiated to the concept by exposing them to practice, through vacation work, excursions, etc." This perspective mirrors findings by Riedl et al. (2024), where agile project planning in chemical engineering education was found to simulate real-world challenges effectively and prepare students for professional settings. Additionally, curriculum adaptation was highlighted as a challenge, with respondents suggesting, "Amend the curriculum to incorporate CDIO and ensure that the educators are trained on the new curriculum." The emphasis on training educators aligns with Wu & Wu's (2020) findings, where proper instructional strategies were deemed essential for fostering creativity and critical thinking in engineering education. Collaboration was a recurring theme, as illustrated in Figure 3, where terms like "industry," "collaboration," and "curriculum" dominate. Many respondents called for "industry and academia collaboration" and "strong government collaboration with institutes of higher learning." This finding resonates with the work of Marnewick (2023), which demonstrated that PBL facilitates the integration of technical and soft skills, directly addressing workplace requirements.

Furthermore, one respondent suggested, "To ensure sustainable CDIO integration in African education: 1. Train educators in CDIO principles. 2. Embed CDIO concepts into curricula. 3. Secure funding and resources. 4. Foster collaboration among institutions. 5. Engage industry for relevance." These strategies highlight the importance of stakeholder synergy, a finding also supported by Lukhele and Laseinde (2024), who emphasized the role of partnerships in bridging the gap between outdated educational tools and current industry standards. A significant portion of responses underscored the value of hands-on and practical learning experiences. Phrases like "practical learning," "real-world situational analyses," and "balancing project work with other modules and examinations" reflect a consensus that experiential learning is critical for effective CDIO implementation. Reviere et al. (2024) reported similar findings, noting that coupling laboratory and analytical sessions enhanced students' holistic understanding of reaction engineering, a principle that can be extended to CDIO-based education. One respondent suggested, "Increase the number of students with access to experiential learning opportunities by integrating them into projects with a sustainability theme, perhaps through regional collaborations." This echoes the iterative and collaborative elements of project-based learning demonstrated by Zhong et al. (2024), where reverse engineering pedagogy significantly enhanced students' design skills and reduced cognitive load. Faculty preparedness emerged as a barrier, with one respondent noting, "Capacity building for educators" as a critical step for CDIO implementation. This finding is consistent with Riedl et al. (2024), who highlighted the need for faculty training to navigate unconventional teaching methodologies effectively. Similarly, Wu & Wu (2020) identified the role of instructors in providing tailored guidance to foster creativity and independent problem-solving. Several participants acknowledged the cultural and systemic challenges to implementing CDIO, with one respondent emphasizing, "Persistence is required of those fronting this move in the face of all resistance and opposition. To break the backbone of cultural status-quo, persistence is required at all levels." This observation aligns with Boachie and Kwak's (2024) exploration of African international students in South Korea, where cultural and systemic barriers limited students' full academic potential. The word cloud in Figure 3 encapsulates strategies for sustainable integration, such as "collaboration," "learning," and "curriculum." Respondents frequently proposed actionable solutions, including "working out of silos," "interdisciplinary approaches," and "collaborations between academics, institutions, and research councils." These recommendations align with the findings of Marnewick (2023), who underscored the iterative benefits of project-based learning for fostering teamwork and interdisciplinary collaboration. One participant succinctly summarized the approach, stating, "Create collaboration with stakeholders, update current curriculum to implement CDIO, and secure government support in implementing CDIO in respective countries in Africa." This strategy highlights the need for a multi-pronged approach that combines institutional reforms with broader policy-level support, as also recommended by Lukhele and Laseinde (2024). The qualitative insights gathered align with existing literature, emphasizing the critical role of interdisciplinary collaboration, experiential learning, and faculty readiness in implementing CDIO in African education. The findings suggest that sustainable integration requires a systemic approach, leveraging partnerships among academia, industry, and government while addressing cultural and logistical barriers. By adopting these strategies, institutions can ensure that CDIO implementation enhances the quality and relevance of education across the region.


Figure 3. Key strategies for integrating CDIO principles into education, emphasizing collaboration, curriculum design, and practical learning.

Beyond the headline finding that “curriculum rigidity” impedes adoption, respondents pointed to why curricula feel inflexible. The most frequently mentioned causes clustered around: (i) governance/approval lead times and path-dependent quality assurance; (ii) misaligned workload, incentives, and assessment regimes; (iii) resource constraints (workspaces, capex/opex) and timetabling; and (iv) weak cross-department integration and industry interfaces. These themes are consistent with prior work on active learning change management in engineering education and with the program-level emphasis of CDIO (e.g., Standards 3, 5–8, 11–12). We use these drivers to refine our proposals below.

**Root cause of curriculum rigidity in participating Higher Education Institutions in South Africa**

Most respondents highlighted that lengthy Senate/Faculty approval cycles, tightly specified module descriptors, and high stakes external review create procedural inertia. Even small shifts (e.g., adding design-implement experiences) can trigger full paperwork cycles. (CDIO S11–S12). Secondly predominance of high-stakes, end-semester exams and narrowly defined outcomes makes it hard to introduce process/product assessment typical of PBL (milestones, reviews, portfolios). (S8, constructive alignment). Again, PBL requires facilitation, feedback, and coordination; current workload models often credit contact hours over design/review/industry liaison, weakening staff motivation to switch. (S7–S8). Furthermore, there is limited maker/lab access, large class sizes, and fragmented timetables (1-hour slots) hamper sustained project work. Capex approval for shared spaces is slow. (S6, S5). PBL frequently needs multi-disciplinary inputs; siloed budgets/timetables and differing assessment cultures hinder integration. Similarly, weak MoUs, slow procurement, and risk/insurance concerns reduce authentic briefs and live data access, dampening relevance. (S5, partnerships). Finally, variable faculty confidence with facilitation, and fear of “quality dips” during transition, lead to risk-averse defaulting to legacy delivery. (Faculty development)

**Experiential learning for effective CDIO implementation**

In CDIO-aligned programmes, experiential learning is realised through structured activities that position students in authentic contexts while integrating disciplinary knowledge, design practice and reflection. Below and in Table 8, we outline concrete, evidence-informed patterns suitable for institutions:

- Virtual field trips (aligns: S5, S6, S7)
  Implement guided virtual site visits (e.g., plants, labs, civil infrastructure) with pre-briefs, data sheets, and post-visit design prompts. Assessment: short design memos, risk/operations analysis, reflection on constraints. Low-resource option: instructor-curated videos with structured prompts. (Poor & Vasconcelos, 2022).

- Expeditionary learning studios (aligns: S5, S7, S8)
  Organise local "expeditions" (community sites/industry partners) where student teams investigate a challenge, gather field data, and prototype context-aware solutions. Assessment: portfolio combining inquiry (evidence) + prototype/demo + stakeholder feedback. (Dang & Duong, 2018)

- Internships and apprenticeships (aligns: S5, S6, S11)
  Credit-bearing placements with clearly scoped CDIO outcomes and co-supervision. Assessment: milestone reviews, employer rubrics on professional/technical competencies, final DI report mapping to programme outcomes. (Rouvrais, Remaud & Saveuse, 2018; Cook et al., 2022)

- Competition-based experiences (e.g., World Robot Olympiad) (aligns: S5, S7, S8)
  Use competition briefs as semester-long DI projects: problem framing - iterative builds - testing - public showcase. Assessment: design review boards, test logs, and performance against spec. (Chiang et al., 2020)

Table 8: Examples of experiential learning mapped to CDIO and assessment

| Activity | CDIO Standards | Typical deliverables | Assessment focus |
|---|---|---|---|
| Virtual field trip ((Poor & Vasconcelos, 2022) | S5, S6, S7 | Site analysis memo; hazards/ops map | Evidence use; design implications; reflection |
| Expeditionary studio (Dang & Duong, 2018) | S5, S7, S8 | Field data pack; prototype/demo; stakeholder feedback | Integration of inquiry + design; feasibility |
| Internship/apprenticeship ((Rouvrais, Remaud & Saveuse, 2018; Cook et al., 2022) | S5, S6, S11 | Milestone reports; supervisor rubric; DI report | Professional/practical competencies; outcomes mapping |
| World Robot Olympiad project (Chiang et al., 2020) | S5, S7, S8 | Robot/system; test logs; competition report | Iteration quality; verification vs. spec; teamwork |

**K-means cluster analysis of perceptions towards CDIO framework implementation**
The objective of the cluster analysis is to identify distinct groups within the dataset based on participants' familiarity with the CDIO framework, their perceptions of faculty readiness, interdisciplinary collaboration, awareness, impact, cultural factors, and optimism. By employing k-means clustering, the analysis aimed to uncover patterns and relationships among these dimensions, enabling a deeper understanding of the variations in responses and providing actionable insights for improving the implementation of CDIO principles in education.

The implementation of k-means clustering was carried out using Python in Google Colab, a cloud-based environment for executing Python code. The dataset, stored as an Excel file in Google Drive, was loaded into a panda DataFrame. Relevant columns, identified by their indices (see Table 9), were selected and renamed for clarity, resulting in a new DataFrame with the variables: Familiarity, Faculty_Readiness, Interdisciplinary_Collaboration, Awareness, Impact, Cultural_Factors, and Optimism. The selected questions for the k-means analysis were chosen because they capture key dimensions of participants' perspectives related to the implementation of the CDIO framework. These questions include familiarity with the framework, perceptions of faculty readiness, interdisciplinary collaboration, awareness among students, cultural factors, and optimism regarding the framework's future. Each question represents critical factors influencing the adoption and success of the CDIO approach in education. To process the categorical data, ordinal mapping was applied to each variable based on predefined mappings. For example, Familiarity was mapped with "Not familiar at all" as 1, "Somewhat familiar" as 2, and "Very familiar" as 3. Similarly, Faculty_Readiness and Interdisciplinary_Collaboration were mapped on a Likert scale ranging from 1 ("Strongly Disagree") to 5 ("Strongly Agree"). Awareness was categorized into levels from 1 ("Not sure") to 4 ("High"), while Optimism ranged from 1 ("Very pessimistic") to 4 ("Very optimistic"). This mapping transformed qualitative responses into numeric values, facilitating computational analysis. The mappings were applied using the .map() function in pandas, ensuring each column was converted to its appropriate ordinal scale. To standardize the data for clustering, the variables were normalized using StandardScaler from the scikit-learn library, ensuring each feature contributed equally to the clustering process. Figure 4(a) demonstrates the application of the elbow method to determine the elbow-selected k under the inertia criterion. The plot shows inertia (the sum of squared distances between data points and their cluster centers) decreasing as the number of clusters increases from 1 to 10. A noticeable "elbow point" is observed at k=3, where the rate of decrease in inertia significantly slows, indicating diminishing returns in adding more clusters. This elbow-selected k under the inertia criterion value of k=3 is highlighted with a red vertical dashed line and a marked elbow point. The selection of three clusters provides a balance between minimizing within-cluster variance and avoiding overfitting, ensuring that the clustering captures meaningful patterns within the data. This step validated the existence of three distinct clusters, which were further analyzed to uncover insights into participant responses across key dimensions such as familiarity, faculty readiness, and optimism. The results of Table 10 and Figure 4(b) provide insights into the cluster analysis based on key variables, including familiarity with the CDIO framework, faculty readiness, interdisciplinary collaboration, awareness, impact, cultural factors, and optimism.

It must however be stated that due to the familiarity item capturing baseline program-level knowledge, low familiarity following an introductory event is consistent with limited prior exposure and with respondents' uncertainty about institutional adoption and student awareness.

The three identified clusters exhibit distinct patterns in feature averages, highlighting variations in participants' perceptions. Cluster 0, characterized by low familiarity (1.0) but the highest levels of faculty readiness (4.15), interdisciplinary collaboration (4.61), and impact (4.61), suggests that individuals in this cluster recognize the potential of CDIO implementation despite limited prior exposure. In contrast, Cluster 1 displays moderate familiarity (1.89), a balanced level of readiness (3.5), and a high awareness score (2.83), indicating that participants in this group have a good understanding of CDIO's benefits but may face contextual barriers. Cluster 2, with the lowest optimism (2.72) and cultural factors (3.33), underscores challenges in fostering CDIO adoption due to systemic or institutional hurdles.

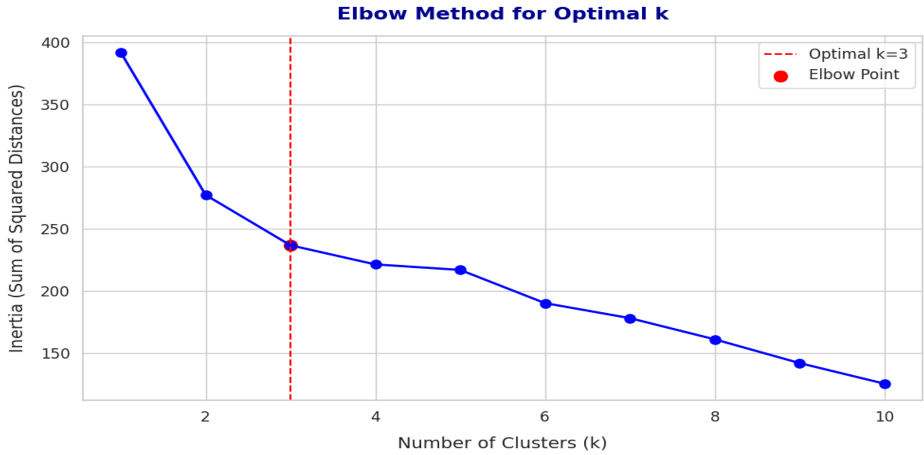
Table 9 : Mapping of original survey questions to representative column names.

| No. | Original Index Name | Representative Name |
|---|---|---|
| 1 | How familiar are you with the conceive, design, implement and operate (CDIO) framework? | Familiarity |
| 2 | There is high level of faculty readiness for implementing CDIO in education in Africa, precisely in South Africa? | Faculty_Readiness |
| 3 | To what extent do you believe CDIO can promote interdisciplinary collaboration within education in Africa? | Interdisciplinary_Collaboration |
| 4 | How would you rate the level of awareness about CDIO among students in Africa? | Awareness |
| 5 | CDIO will have an impact on the overall quality of education in Africa? | Impact |
| 6 | Do you believe that cultural factors may influence the successful implementation of CDIO in African education? | Cultural_Factors |
| 7 | Overall, how optimistic are you about the future of CDIO implementation in education in Africa? | Optimism |

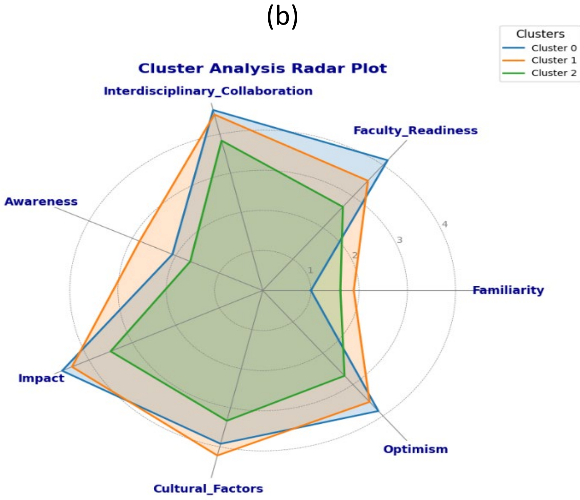
Table 10: Cluster analysis: feature averages across clusters.

| Cluster | Familiarity | Faculty Readiness | Interdisciplinary Collaboration | Awareness | Impact | Cultural Factors | Optimism |
|---|---|---|---|---|---|---|---|
| 0 | 1.0000 | 4.1538 | 4.6154 | 2.0769 | 4.6154 | 3.9231 | 3.8462 |
| 1 | 1.8889 | 3.5000 | 4.5000 | 2.8333 | 4.3889 | 4.2222 | 3.5556 |
| 2 | 1.6111 | 2.6667 | 3.8333 | 1.6667 | 3.5000 | 3.3333 | 2.7222 |

(a)




(b)




(c)

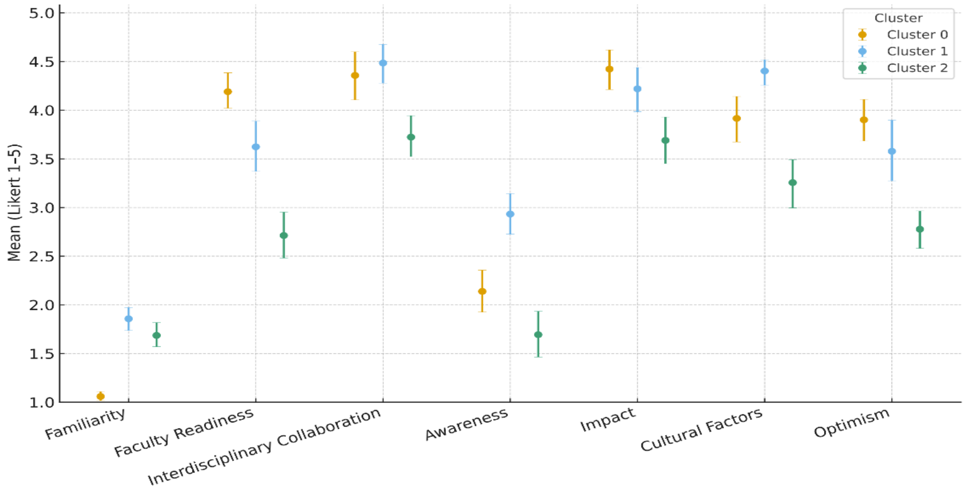



Figure 4. (a) Elbow plot of within-cluster sum of squares (inertia) for k = 1–6; the elbow at k = 3 guides the selection used in the paper. (b) Radar plot of feature averages for the k = 3 clusters. Note: We describe k = 3 as elbow-selected (criterion-guided) (c) Dot-and-whisker plot to compare cluster 1 and cluster 2

The inertia curve exhibited a clear elbow at k ≈ 3, after which marginal gains diminished; accordingly, we selected k = 3 as a criterion-guided, parsimonious solution for reporting. In line with the exploratory aims of the study, we present k = 3 as a data-supported choice under the inertia criterion.

The Cluster/Institution cross-tabulation also presented in Table 11 provides and interesting result. The Chi-square test indicated no evidence of association between institution and cluster membership ($\chi^2$[df=8] = 0.357, p = 1.000, Cramér's V = 0.060). The ARI between cluster labels and institution labels was −0.054, indicating no overall alignment. Permutation enrichment tests found no over-representation for any institution in any cluster (Holm-adjusted p = ≥ 0.82), with all other institution–cluster combinations non-significant. In LOIO sensitivity checks, cluster assignments remained stable (median ARI vs. full-sample labels = 0.922), and centroid cosine similarity across re-fits was 0.99, suggesting high stability and limited dependence of the clustering solution on any single institution. Table 12 captures the Per-cell standardized residuals (observed – expected)/√expected.

Table 11: Cluster and institution cross tabulation

| Cluster and Institution | UNISA (n=14) | TUT (n=12) | DUT (n=9) | CPUT (n=8) | Wits (n=6) | Row total |
|---|---|---|---|---|---|---|
| Cluster 0 | 5 (35.7%) | 4 (33.3%) | 3 (33.3%) | 2 (25.0%) | 2 (33.3%) | 16 |
| Cluster 1 | 5 (35.7%) | 4 (33.3%) | 3 (33.3%) | 3 (37.5%) | 2 (33.3%) | 17 |
| Cluster 2 | 4 (28.6%) | 4 (33.3%) | 3 (33.3%) | 3 (37.5%) | 2 (33.3%) | 16 |
| Column total | 14 | 12 | 9 | 8 | 6 | 49 |

Table 12 : the Per-cell standardized residuals (observed – expected)/√expected

| | UNISA | TUT | DUT | CPUT | Wits |
|---|---|---|---|---|---|
| Cluster 0 | 0.20 | 0.04 | 0.04 | −0.38 | 0.03 |
| Cluster 1 | 0.06 | −0.08 | −0.07 | 0.13 | −0.06 |
| Cluster 2 | −0.27 | 0.04 | 0.04 | 0.24 | 0.03 |

Figure 4(b) visually reinforces these findings through a radar plot that compares feature averages across clusters. The clusters exhibit significant disparities, particularly in faculty readiness and interdisciplinary collaboration, emphasizing the influence of institutional support on CDIO adoption. This aligns with the findings of Fangonil-Gagalang (2024), who highlighted the critical role of faculty support in bolstering readiness for practice. Similarly, the study by Zgheib et al. (2023) identified institutional factors, such as technological readiness and pedagogy, as pivotal for successful implementation, which is reflected in the strong scores for faculty readiness in Cluster 0. Interdisciplinary collaboration, a key dimension in Figure 4(b), reflects the importance of collective engagement in educational reform. Stark et al. (2024) emphasized the necessity of interdisciplinary collaboration to foster inclusivity and enhance educational practices, a theme strongly evident in Clusters 0 and 1. Moreover, the low optimism in Cluster 2 mirrors findings by Eicher et al. (2014), which linked low optimism to barriers in educational attainment and adoption of new frameworks. The strong impact scores across all clusters resonate with Zhang and Wang (2024), who underscored the importance of curriculum-based ideology in shaping awareness and impact within educational contexts.

While the radar diagram (Figure 4b) suggests that Clusters 1 and 2 are broadly similar, the dot-and-whisker plot (Figure 4c) shows that Cluster 1 sits consistently higher than Cluster 2 across faculty readiness, interdisciplinary collaboration, awareness, perceived impact, cultural factors, and optimism (gaps of roughly 0.6–1.2 Likert points on average). Confidence intervals overlap on some dimensions given the modest n, so we interpret these contrasts as directional patterns rather than definitive inferential differences. The visual takeaway is a gradient from Cluster 2 → Cluster 1, with Cluster 0 forming a distinct profile on several features.

Selection rule used in practice: we evaluated K = 2–6; picked the smallest K past the elbow consistent with interpretable cluster profiles; use silhouette trends as a consistency check, not as a sole determinant. The inertia curve fell sharply up to K = 3 and then flattened (Figure 4a); accordingly, we selected K = 3 as a criterion-guided solution. A silhouette cross-check did not suggest a superior alternative; the profile plateaued beyond K = 3 (Figure S5). The silhouette cross-check (Figure S5) showed a plateau/slight decline from K=2→3 and decreasing values thereafter, providing no superior alternative to the elbow-guided K=3.

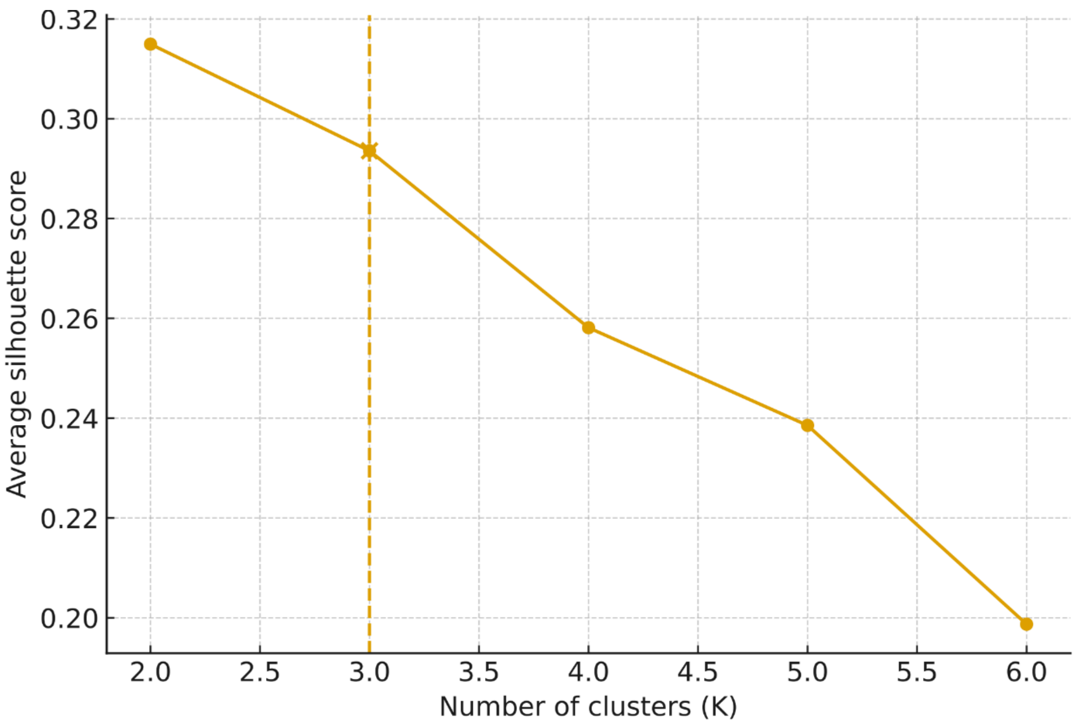



Figure 5. Silhouette profile across K = 2–6 computed on z-standardised features. Average silhouette scores decrease slightly from K=2 (≈0.315) to K=3 (≈0.294) and then continue to drop for larger K, indicating no material improvement beyond K=3 and supporting the elbow-selected, parsimonious choice reported

It must however be noted that K-means provides interpretable centroids for Likert-type survey profiles, but it relies on Euclidean/spherical-cluster assumptions and pre-specifies K. With n = 49, density-based methods (DBSCAN/HDBSCAN) may classify many points as noise and require non-trivial parameter tuning; nevertheless, they are attractive when clusters are non-convex or contain outliers. Likewise, k-medoids (PAM) with Gower distance and hierarchical (Ward) clustering can handle ordinal/mixed data and merit inclusion in larger, multi-site replications. Future work should triangulate across these algorithms, report stability under resampling, and compare agreement (e.g., Adjusted Rand Index) among methods.

Due to the fact that institutional cultures and communication can shape staff awareness and attitudes, we explicitly tested for institution-level homogeneity of cluster assignments. The analysis did not reveal an association between university and cluster membership, implying that our clusters primarily capture individual variation and are partly institution-specific]. We therefore maintained the] cluster-based interpretations accordingly and recommend future multi-site, probability-based studies with larger per-institution samples to characterize institutional effects with greater power. Furthermore, we conducted Per-institution cell sizes were modest; despite Monte-Carlo and permutation procedures

**Correlation structure and redundancy checks.**

Due to several survey features potentially moving together (e.g., faculty readiness, interdisciplinary collaboration, impact, optimism), we examined pairwise associations using Spearman's ρ on z-standardised variables and visualised a correlation heatmap (Figure 6). To assess whether correlations unduly shaped distances, we ran a dimension-reduced sensitivity analysis: principal components analysis (PCA) on the correlation matrix (no rotation) and re-fit k-means on the first m components explaining ≈80% of variance. We then compared partitions (original-space vs. PCA-space) using the Adjusted Rand Index (ARI = ) and qualitatively confirmed that cluster centroids conveyed the same story ( Figure 7). These steps mitigate the risk that redundant, highly correlated inputs inflate distance contributions in k-means. We standardised all features prior to clustering; k was selected by the elbow (criterion-guided) and we report a silhouette cross-check (Figure 5).

**Role of correlations.**

The correlation heatmap (Figure 6) shows moderate positive associations among practice-oriented variables(e.g. readiness, collaboration, impact, optimism), with lower correlations for familiarity/awareness. To ensure these dependencies did not drive spurious separation, we re-estimated k-means on PCA components (≈80% variance); the resulting partition was concordant with the original (ARI = 1.00 between k-means in the original z-standardised space and k-means on the first 4 PCs (≤80% variance), indicating identical assignments.), and cluster profiles preserved the same substantive contrasts (Figure 7). This indicates that observed grouping reflects coherent latent structure, not merely redundancy among inputs.

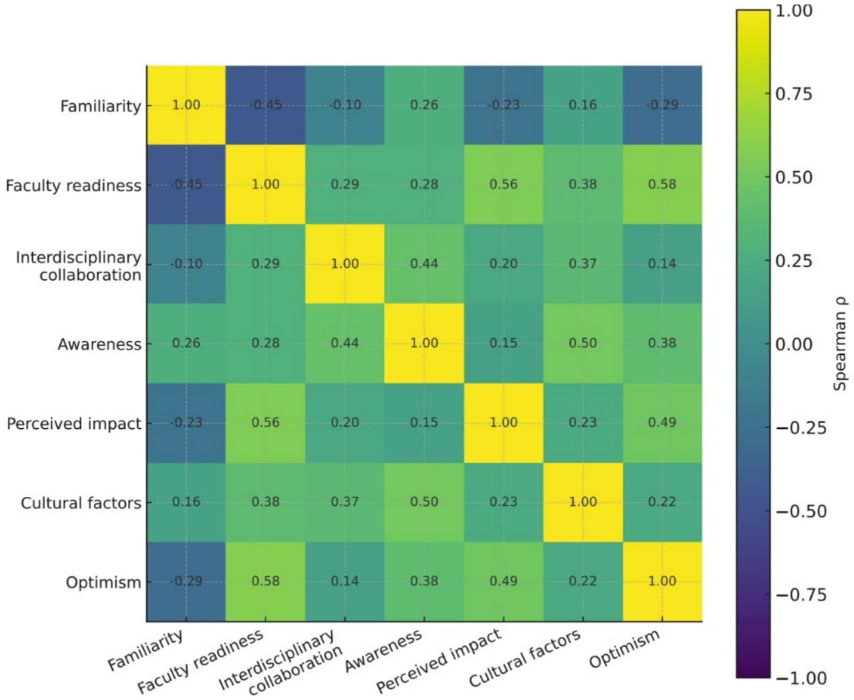
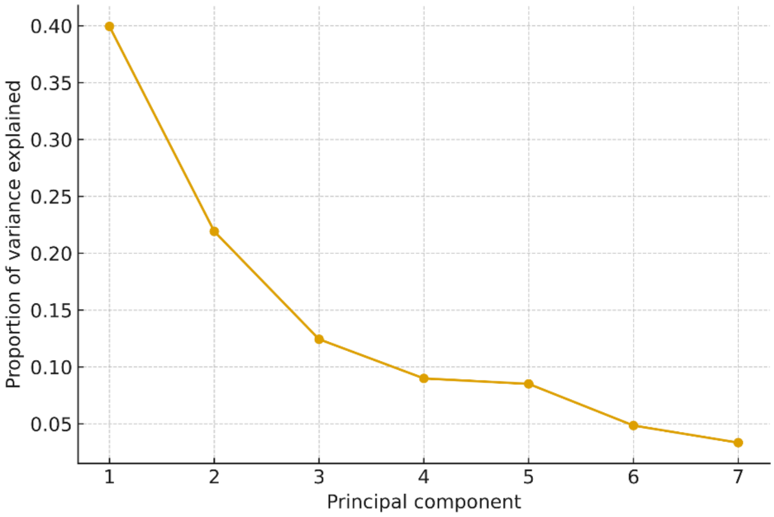



Figure. 6 Correlation heatmap (Spearman's ρ) of the seven survey features used for clustering. Warm colours denote positive associations; exact coefficients annotated in cells.

(a)




(b)

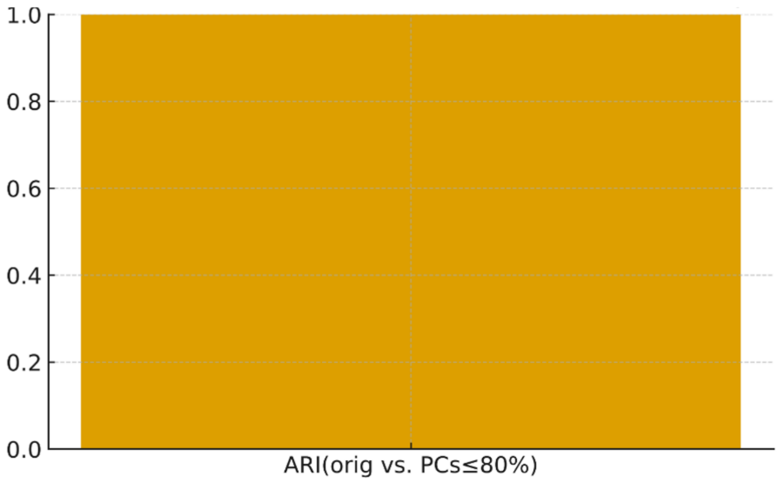



Figure 7. (a) PCA scree plot showing variance explained per component; (b) ARI comparing k-means on original features vs. first m PCs (≈80% variance). Concordance indicates cluster stability under dimension reduction. (b) Cluster agreement measured by Adjusted Rand Index (ARI) between k-means on the original features and on the first four PCs (≈80% variance). ARI = 1.00 here, indicating concordant partitions.

In summary, the cluster analysis provides actionable insights into the varying levels of readiness, optimism, and collaboration required for CDIO implementation. It highlights the need for targeted strategies, such as fostering faculty readiness and enhancing awareness, to address the specific challenges of each cluster. These findings align with broader literature emphasizing interdisciplinary collaboration, institutional support, and optimism as critical factors in driving educational transformation. The presented data underscores the importance of designing tailored interventions that address contextual barriers while leveraging institutional strengths to ensure the successful integration of innovative frameworks like CDIO.

**Barriers to teacher dialogue: structural and cultural drivers**

Respondents frequently described structural barriers—fragmented timetables that prevent common studio hours, workload models that count contact time but not coordination/feedback, QA processes that make joint module changes slow, and siloed budgets that complicate co-teaching. Alongside these, they noted cultural dynamics: a prevailing emphasis on research outputs over collaborative teaching, low psychological safety to expose partially-formed teaching ideas, uncertainty about credit/recognition for shared modules, and a "territorial" ownership of courses that discourages co-design. Together, these dynamics help explain why dialogue remains limited even when staff express enthusiasm for PBL and CDIO-aligned practices.

Targeted actions for improving teacher dialogue

- Address structural blockers
    - Timetabling for collaboration: Reserve potential 2–3-hour studio blocks and monthly co-design hours across departments.
    - Workload recognition: Count project facilitation, coordination, and industry liaison as load; include co-teaching in workload models.
    - QA "sandbox" for joint pilots: Fast-track small, cross-module PBL pilots with sunset reviews to reduce approval friction.
    - Shared resources: Pooled budgets for workspace-in-a-box kits and a common booking system for maker spaces.
- Shift cultural conditions
    - Incentives & recognition: Make co-teaching/co-assessment eligible for teaching awards and visible in promotion criteria.
    - Psychological safety: Run peer-observation cycles framed as developmental (not evaluative) and publish short "teaching briefs" that normalise iteration.
    - Communities of practice (CoP): Standing, term-time CoPs that meet on a cadence (e.g., 4×/term) with mini-grants for joint artefacts (rubrics, project shells).
    - Credit clarity: A simple co-teaching MoU template that sets expectations for authorship/credit on shared materials and student outcomes.
    - Leadership modelling: Programme leads to host quarterly cross-course alignment clinics (assessment mapping; milestone sync).

## Conclusion

This exploratory multi-institutional case study highlights opportunities and challenges in aligning programme-level frameworks (e.g., CDIO) with project-based/active learning approaches in participating South African HEIs. While respondents were optimistic about potential benefits, our sample size and design do not support continent-wide generalisation. Future work should therefore employ larger samples and pre-registered analyses to assess transferability and detect more subtle effects.

Limited baseline familiarity with CDIO, low institutional visibility of adoption, and variable faculty readiness point to the need for targeted awareness and capacity-building within the participating institutions. Respondents also underscored the value of industry partnerships and the importance of contextual adaptation to local cultural and institutional conditions. It must however be noted that the choice of k depends on the selection criterion and study purpose, we frame k = 3 as a parsimonious, criterion-guided solution suitable for exploratory interpretation rather than a unique "optimal" partition.

While participants expressed optimism about the potential of these approaches in their own settings, our data do not warrant claims about the entire African education system. Instead, the present results should be viewed as exploratory evidence from a specific multi-institutional South African context that can inform practice locally and motivate broader investigations.

Future work should therefore prioritise multi-country samples, pre/post or longitudinal designs, and probability-based sampling, alongside mixed-methods evaluation of faculty development and programme-level implementation. Such studies are necessary to assess transferability and to support any continent-wide recommendations. Table 13 captures some of these recommendation in terms of feasibility and ranking.

The cross-sectional, immediate-post-event administration may not reflect longer-term assimilation; future work should adopt a pre/post design with a knowledge check specifically on CDIO constructs.

Similarly, future work should therefore focus on addressing the key challenges and gaps identified in this study, paving the way for the successful adoption and implementation of the CDIO framework in African education systems. The following directions are suggested:

Awareness and Capacity Building: Design and implement targeted awareness campaigns to improve understanding of the CDIO framework among educators, students, and institutional leaders. Develop accessible resources and workshops tailored to African contexts to demystify the CDIO approach and demonstrate its value.

Faculty Development: Establish professional development programs to equip educators with the necessary skills to integrate CDIO into their teaching practices. Promote interdisciplinary training for faculty to align with the collaborative ethos of the CDIO framework.

Institutional Integration: Explore strategies for embedding CDIO into existing curricula and assess its adaptability to local institutional needs and cultural contexts. Pilot programs in diverse African institutions to gather data on implementation challenges and best practices.

Student Engagement: Initiate student-centric programs to build awareness and encourage active participation in CDIO-based learning activities. Investigate methods to foster student leadership in promoting the framework within their academic communities.

Industry Collaboration: Strengthen ties with industry partners to support the practical application of CDIO principles, ensuring students gain real-world problem-solving experience. Co-develop projects and internships that align with CDIO's interdisciplinary focus.

Policy and Advocacy: Engage with policymakers to secure funding and institutional support for the broader adoption of CDIO. Advocate for the inclusion of CDIO principles in national and regional educational policies.

Longitudinal Studies: Conduct longitudinal research to evaluate the long-term impact of CDIO implementation on student outcomes, faculty practices, and institutional transformation. It is also imperative to critically explore comparative studies to assess how the framework performs in African contexts relative to its global counterparts.

This study’s generalisability is limited by (i) a non-probability, event-linked sample (n = 49) from five South African universities; (ii) self-selection of attendees; and (iii) single-timepoint measurement immediately following an introductory training. The analyses—descriptive and unsupervised clustering—are intended to identify salient patterns, not to estimate population parameters. As such, the findings are most appropriately applied to similar institutional contexts and should be validated through multi-country, longitudinal, and probability-based designs before informing system-wide policy across Africa.

To confirm and extend these results, we recommend larger, stratified, multi-institutional samples (multi-country where possible), pre-specified analysis plans, and mixed-methods designs (e.g., faculty interviews and student outcome measures). Methodologically, studies should triangulate clustering criteria/algorithms and report stability under resampling; substantively, they should track implementation outcomes (assessment alignment, workspace utilisation, industry partnerships) and explore discipline- and institution-level heterogeneity. Despite current limitations, this study provides a valuable foundation for subsequent, higher-powered investigations.

Table 13: Prioritised actions by feasibility and horizon

| Horizon | Recommendation (what) | Why feasible now / Dependencies | Likely owner(s) |
|---|---|---|---|
| Short | Faculty capability sprints (CPD on PBL facilitation, assessment rubrics; peer-observation circle) | Low cost; schedule within existing PD days; uses internal expertise | Teaching & Learning Unit; Programme Leads |
| Short | Communities of Practice (CoP) with mini-grants for shared artefacts (rubrics, project shells) | Small incentives; builds culture quickly | T&L Unit; HoDs |
| Short | Industry brief pipeline (lightweight): brief → NDA template → showcase calendar | Template-driven; starts with existing contacts | Industry Liaison; Programme Leads |
| Short | “Workspace-in-a-box” starter kits (microcontrollers/tools per cohort) | Modest OPEX; immediate impact on DI activities | Lab Manager; Programme Admin |
| Short | Assessment tweaks inside existing modules (add one DI milestone + process rubric) | No full revalidation; constructive alignment quick win | Module Convenors |
| Short | Monitoring “starter set” (S11/S12): simple dashboard of DI activities, workspace usage, assessment mix | Uses existing data; informs later bids | QA/Analytics; Programme Leads |
| Medium | Timetabled studio blocks (2–3h) and project weeks | Needs timetable redesign; moderate coordination | Timetabling Office; HoDs |
| Medium | QA “sandbox” pathway for bounded PBL pilots (fast-track with sunset review) | Needs Faculty/Senate approval of a template but limited scope | QA Committee; Faculty Board |
| Medium | Workload recognition (count facilitation/liaison/feedback hours) | Policy memo + workload model update; negotiable in one cycle | HoDs; HR; Unions (as relevant) |
| Medium | Cross-department “Design-Implement Studio” shells (shared course codes/credit split) | Requires governance + funding rules; high payoff for integration | Curriculum Committee; Finance |
| Medium | Industry MoUs framework (multi-brief, multi-year) | Legal review; partner engagement over one budget year | Legal; Industry Office |
| Long | Dedicated CDIO workspaces/maker hubs (capex; shared booking) | Capital planning; facilities upgrade | Estates; Dean’s Office |
| Long | Assessment policy refresh (programme-level mix; portfolio requirements) | University-wide consultation; external QA alignment | Senate; QA Office |
| Long | Multi-institutional internship/apprenticeship network (credit-bearing WIL) | Complex partner ecosystem; cross-HEI coordination | WIL Office; Regional partners |

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## Declaration of Interest

The authors jointly declare no conflict of Interest

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