BEYOND DEMONSTRATIONS: STUDENT-LED LEARNING LABORATORIES THROUGH A CDIO LENS

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ABSTRACT

Laboratory-based learning is central to engineering education and can be a natural mechanism for implementing CDIO principles, yet traditional "follow-the-recipe" formats can limit student autonomy and engagement. In programmes where integrated CDIO design–build–test (DBT) experiences already exist, the continued use of traditional, standalone laboratories raises questions about how students perceive these, and how they might better complement the wider CDIO ethos. This study describes a workshop which explored what students currently value in traditional laboratories in a Mechanical and Aerospace Engineering undergraduate degree course, identifies perceived gaps, and maps these to the CDIO Syllabus. Students recognised the benefits of traditional laboratory formats and cited aspects that mapped across the whole CDIO syllabus, with the highest emphasis on Section 2: Personal and Professional Skills and Attributes (~40% of comments). When suggesting areas for improvement however, suggestions were concentrated in Section 4: Conceiving, Designing, Implementing and Operating (>68% of comments), with students calling for greater involvement in designing, setting up and operating experiments, more complexity, integration of design and manufacture, smaller group sizes and tighter lecture-laboratory alignment. Students also proposed concepts for multi-session, DBT laboratory activities that culminate in testing and analysis, shifting emphasis from commercial teaching laboratory equipment toward authentic, iterative projects aligned with the CDIO ethos and with Student Centred Learning (SCL) principles. These student-generated concepts were also found to be readily shaped to meet required learning outcomes. The findings from this study will drive the next phase of development and transformation of the laboratory programme at the authors' institution with planned future work to redesign laboratories with the aim of developing a student-centred structure that allows students to take ownership of their practical learning and enhances the opportunities for students to achieve and excel in CDIO-aligned learning outcomes.

KEYWORDS

Laboratory-based learning, Student-centred learning, CDIO Syllabus, Engineering education, Design–build–test, Standards: 5–8, 11–12

INTRODUCTION: LABORATORY BASED LEARNING IN ENGINEERING

Laboratory-based learning has historically been a fundamental component of engineering education, providing students with opportunities to apply theoretical concepts in practical settings and develop essential technical and transferable skills (Feisel & Rosa, 2005). However, traditional laboratory formats, which often involve following rigid, step-by-step instructions to achieve predetermined outcomes, have been criticised for limiting creativity and autonomy, leaving students feeling unchallenged and disengaged (McAfee, Armstrong, & Cunningham, 2009). In CDIO Institutions, as far back as 2008, it was argued that design-build-test projects were displacing traditional laboratories (Murphy, Surgenor, & Cunningham, 2008) and called for a review of how these were implemented.

At an early stage in development of CDIO, the focus on redesigned student workspaces was highlighted as being a key requirement in enabling the implementation of practical design-build-test experiences (Young, et al., 2005) and these purpose-built spaces highlight the kinds of environments that are needed to support authentic engineering learning. However, the same emphasis has not been placed on developing traditional engineering principles labs into active-learning activities which focus on experimentation skills. Challenges in implementing complex hands-on activity in terms of staffing, logistics, equipment and cost can often limit the opportunities for optimal delivery (Malmqvist, Hugo, & Kjellbery, 2015).

Several pedagogical strategies have been introduced to embed CDIO principles into laboratory environments. A recent study from outside engineering found that redesigning chemistry laboratories in line with CDIO principles notably improved students' experimental competence (Cao et al, 2025), while a materials course used the approach of design, manufacture and test to evaluate 3D printing materials (Zheng et al, 2025) and demonstrated improved knowledge and competencies as a result. This fits with broader work which shows that hands-on experimental work including project-based learning (PjBL), problem-based learning (PBL), inquiry-based learning (IBL), flipped classrooms, and peer teaching can improve academic performance, motivation, and engagement while fostering professional skills such as collaboration, experimental design, and project management (Friend, Woodcock, & Huang-Saad, 2021), all of which fit well within a CDIO-based curriculum.

Other strategies, such as use of digital tools and pre- and post- laboratory activities have been used to attempt to better prepare students for attending laboratory sessions, with the intention of increasing students' knowledge and understanding and enabling them to take more control of their learning experience while in the laboratory. For example, a study found that blending flipped learning with digital laboratories reduced cognitive load and improved preparedness for physical laboratory work (Portillo et al, 2024). These approaches also appear to encourage deeper learning and greater confidence among students.

However, successful implementation of CDIO principles and SCL within a laboratory setting requires careful design and support. Studies highlight that insufficient guidance can hinder learning, as seen in peer-teaching models where outcomes depended heavily on preparation and instructor support (Dosoftei & Alexa, 2024) Furthermore, while SCL offers clear benefits, questions remain about the optimal balance between independence and structure, and whether these approaches should supplement or replace traditional methods.

FORMAT OF THE CURRENT LABORATORY PROGRAMME

Although the School of Mechanical and Aerospace Engineering in the authors' institution has a strong and longstanding integrated CDIO ethos, with multiple design-build-test (DBT) experiences embedded at every programme level, a traditional engineering principles laboratory programme based on commercially available teaching equipment has also been retained for stage 1 students. Some of the typical laboratories are outlined in table 1 below.

Table 1. Typical laboratories on course

Subject area	Laboratory detail
Dynamics	Vibrations: Measuring moment of inertia of a flywheel Gyroscope: Demonstrating gyroscopic effect and measuring gyroscopic couples Static and Dynamic Balancing: Four-mass system balancing, both statically and dynamically
Fluid Mechanics	Bernoulli Demonstration: Waterflow through convergent-divergent tube Reynolds Demonstration: Laminar and turbulent flows, critical velocities, Reynolds number
Thermodynamics	Marcet Boiler: Pressure-temperature relationship of saturated steam Piston Compressor: Design and operating behaviour of compressed air generation plant
Materials	Tensile Test: Properties of different materials Hardness Test: Hardness properties of different materials
Structural Mechanics	Truss Analysis Beam Analysis

Various structures have been implemented over the years, with the programme originally running for many years with the individual laboratories aligned closely with the associated taught modules. While this was beneficial from the perspective of clearly linking theory with practice at the appropriate time, it was logistically very difficult to manage the availability and timing of the laboratories particularly as student numbers rose. A decision was made to decouple the laboratories from the modules and run dedicated laboratory weeks instead. This was much more efficient to coordinate and run but proved to be a poor learning experience for students who felt that there were too many laboratories to complete in a short time, that they did not have enough time to fully understand the principles behind each lab, and that they were not effectively learning from the laboratories. Staff marking laboratory reports at that time also reported that there was a fundamental lack of understanding by students of some of the basic theory in the laboratories, indicating a loss of integration within the curriculum. It was therefore decided in the 2023-24 academic year that the laboratory programme would be stretched over a full semester, and fewer laboratories would be undertaken by each student, but that they would spend more time in each laboratory and have more hands-on experience of each experiment. This has been an improvement in terms of student experience and learning, but further enhancements could be made.

RESEARCH OBJECTIVE

Despite extensive CDIO literature on integrated and project-based laboratory models, there is comparatively little evidence on how students themselves perceive the value of traditional, standalone laboratory experiences within otherwise CDIO-rich curricula. The focus of the present study is therefore not the laboratories per se, but an exploration of students' views on what benefits these traditional labs still offer, how they complement their DBT activities, and what enhancements students believe would make the laboratory programme more effective.

The first aim of this initial study was to understand what aspects students value in laboratory work, what they see as lacking in current provision, and the types of activities that they think they would benefit from. The second aim was then to map current provision and gaps in this provision to the CDIO syllabus areas to identify areas for improvement.

METHODOLOGY

A group of sixteen second-year students who had recently completed the laboratory programme were asked to voluntarily take part in a workshop to provide an insight into students' experiences of the laboratory programme and what they would like to see from it. They were prompted to generate some ideas for engaging laboratory structures. The workshop lasted for approximately 90 minutes. Students were arranged into four groups and provided with flipchart paper, sticky notes and markers and then asked to carry out the activities outlined in table 2. To avoid influencing the comments and ideas generated by students, the workshop made no reference to CDIO. The flipcharts produced by the students were collected and analysed. Comments on the areas that students see as valuable in the current laboratory programme, and suggested areas of improvement were tabulated, grouped into themes and then categorised into the appropriate sections of the CDIO syllabus with which they aligned. Finally, the laboratory ideas generated by the students were summarised and described, and common features across the four groups were identified.

Table 2. Workshop instructions given to students

Workshop activities and timing	Instructions provided
What is valuable about doing laboratory work as an engineering student? (15 minutes)	Value in laboratory-based work could include learning critical skills, knowledge and attributes that enhance student experience. Take 5 minutes individually to write down on individual post-it notes the key values that engineering students can obtain from laboratory-based learning. Then, take 10 minutes in teams to discuss these values and why they are important. Categorise similar post-it note ideas into groups.
How might we make the laboratory experience more engaging? (15 minutes)	Consider how a laboratory experience can be more effective and engaging whilst still teaching the values discussed. Take **15 minutes** in teams to brainstorm how to implement the discussed skills and attributes in an engaging way, whilst considering what specific limitations might be, and any possible solutions.
Laboratory Concept (20 minutes)	With consideration to everything discussed so far, create a concept for a laboratory-based learning experience. Each team will be given one of the following themes: Gas Laws; Material Properties; Newton's Laws of Motion Take **20 minutes** in teams to brainstorm a concept.
Reflection (5 minutes)	How does your design concept compare to any laboratory-based or hands-on learning you have experienced? Is the design concept more engaging? Does the design concept teach skills and knowledge more effectively? Take **5 minutes** to discuss this.
Presentation (30 minutes)	Present your design concept to the rest of the group! Take **10 minutes** to finalise your concept with your teams, outlining what skills, knowledge and attributes the concept teaches, how the experience is engaging for students, constraints considered with possible solutions, and how the concept may compare to previous experiences. Each team will have **5 minutes** to present.

RESULTS

On collating and analysing the data, it was noted that the students produced 67 comments on valuable aspects of the laboratory programme, and 57 on aspects that could be improved. Four separate laboratory activities were proposed.

What do Students Value in Laboratory Work?

The comments that students provided on the areas that they see as valuable in laboratory work were grouped into similar themes and these themes then mapped to the relevant areas of the CDIO 3.0 syllabus as presented in table 3. The percentage of comments related to each CDIO syllabus section are shown in figure 1.

Table 3. Areas of laboratory work valued by students

Theme	No. of Comments	CDIO Syllabus section
Knowledge and understanding	7	1 Fundamental Knowledge and Reasoning
Data Presentation and Analysis	6	2 Personal and Professional Skills and Attributes
Learning experience	4	
Practical experimentation skills	11	
Problem solving	1	
Professional Skills	3	
Time Management	2	
Communication	12	3 Interpersonal Skills: Collaboration, Teamwork and Communication
Team working	7	
Putting theory into practice	14	4 Conceiving, Designing, Implementing and Operating Systems

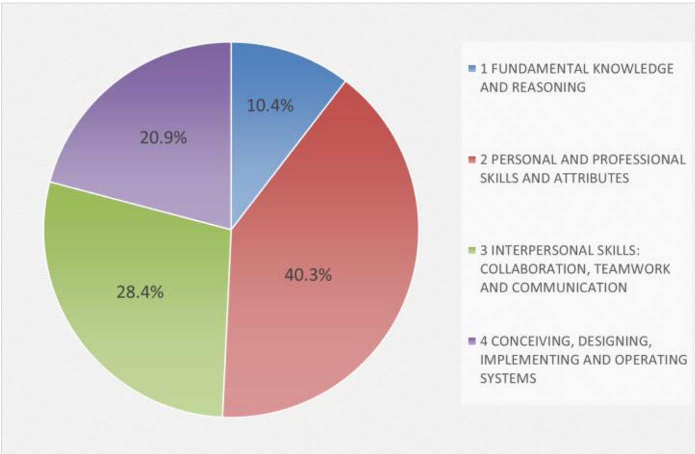


Figure 1. Distribution of comments on the perceived value of laboratory work across the areas of the CDIO syllabus

Valuable Aspects linked to CDIO Syllabus Section 1: Fundamental Knowledge and Reasoning

Just over 10% of the comments (7) from students related to a gain in knowledge, this included reinforcement and application of knowledge, and to extension of knowledge beyond that which is gained in taught lectures to allow students to stretch their learning.

Valuable Aspects linked to CDIO Syllabus section 2: Personal and Professional Skills and Attributes

The highest percentage of positive comments, approximately 40%, relate to section 2 of the syllabus, this included 11 comments about the value of practical experimental skills including learning how to follow instructions, set up experiments, gain familiarity with equipment, follow good experimental practice, and gain hands on experience. Six comments related to learning how to record, analyse and present data correctly. The benefits of active and engaging learning provided by laboratory work were also valued by students (4 comments), while students also noted skill development opportunities in time management (2 comments), professional skills such as understanding their responsibilities relating to Health and Safety and accepted industrial practices (3 comments) and one comment on problem solving skills.

Valuable Aspects linked to CDIO Syllabus section 3: Interpersonal Skills: Collaboration, Teamwork and Communication

Just over 28% of comments related to section 3 of the syllabus, with 12 relating to communication. Students highlighted report writing skills, verbal communication, presentation and listening skills as valuable aspects gained from laboratory work. The remaining comments related to this section (7) referred to improvements to skills in team working, networking, delegating, managing group work and resolving conflicts.

Valuable Aspects linked to CDIO Syllabus section 4: Conceiving, Designing, Implementing and Operating Systems

Approximately 21% of comments related to this section of the syllabus, with 8 of these comments using a close variant of the term "putting theory into practice" and the remaining 6 mentioning visualising theory in a real-world context being of great benefit.

Identified Areas for Improvement

As with the comments relating to the perceived value of laboratory work, the comments relating to suggested areas for improvement were themed and then matched to the appropriate area of the CDIO syllabus. Here the students made nine comments related to Fundamental Knowledge and Reasoning, four related to Personal and Professional Skills and Attributes, one relating to Interpersonal Skills, and, most notably, 39 relating to Conceiving, Designing, Implementing and Operating Systems. The breakdown of themes is presented in table 4, with the percentage of comments relating to each CDIO syllabus area in figure 2.

As stated above, by far the highest number of comments relating to areas of improvement were aligned with syllabus section 4, with over 68% of comments in this area. The majority of these relate to wanting more student involvement in the design, set up, and operation of the laboratories. Suggestions for reducing laboratory group sizes to provide more time for individuals to have more active involvement or changing the timing and structure of laboratories to achieve the same goal were proposed. Students also suggested that increasing the complexity of the laboratories and including other aspects into the laboratories such as design and manufacturing would be of value.

The next highest number of comments related to syllabus section 1, where students highlighted the desire to improve their understanding of concepts and stretch their learning with experience of theory and knowledge outside of that gained in taught modules. There were only a few comments about improvements required that mapped to syllabus section 2 or 3.

Table 4. Areas identified for improvement

Theme of comments	No. of comments	CDIO Syllabus Section
Improve understanding of concepts	1	1 Fundamental Knowledge and Reasoning
Provide stretch learning	2	
Link lab more closely to lectures	6	
Learning experience	2	2 Personal and Professional Skills and Attributes
Report writing	2	
Teamwork	1	3 Interpersonal Skills: Collaboration, Teamwork and Communication
Linking theory with practice	1	4 Conceiving, Designing, Implementing and Operating Systems
More manufacturing	1	
Link to industry	2	
More design based	3	
Complexity of practical tasks	5	
More hands on	27	
Other	4	Other (general comments)

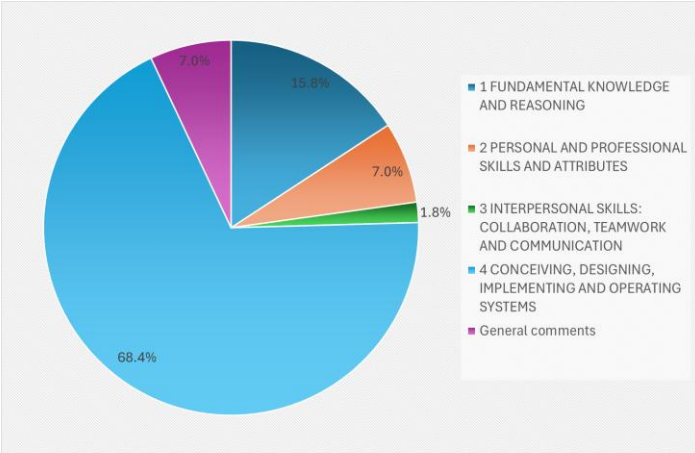


Figure 2. Distribution of comments on suggested areas for improvement in laboratory work across the areas of the CDIO syllabus

Student Proposed Laboratory Concepts

In the final phase of the workshop the students were challenged with developing laboratory concepts that they felt would be more engaging and improve their learning experience. The concepts were roughly sketched out by each group and then the students presented their ideas verbally in more detail to the room. A summary of these is given in table 5. Notably, all student-generated concepts involved a design and manufacturing aspect, followed by testing, and analysis of results. All were multi-step laboratories where students spent several sessions working on their initial concepts, learning how to use equipment, designing components and carrying out experimentation. Much less emphasis was placed on standard teaching laboratory equipment and instead focused on students learning through doing, through hands-on projects and iterative design, which resonates strongly with CDIO and SCL principles.

The current learning outcomes for the laboratory programme are drawn from the general learning outcomes for the UK Engineering Council AHEP4 standards. These are presented in table 6, along with their alignment to the CDIO syllabus sections. The same table outlines some suggested ways in which the student generated ideas could align with required learning outcomes. It can be seen that any of the proposals can be readily shaped into structured activities that meet the programme requirements, and hence further development of this process could be used to give students meaningful autonomy while remaining within the structures of accreditation requirements and the CDIO framework.

CONCLUSION

This initial study highlights both the strengths and the shortcomings students perceive in current laboratory provision and maps them to the CDIO Syllabus to inform future developments. Students value laboratories most where they develop practical experimentation and data skills (Section 2), practice communication and teamwork (Section 3), and apply theory in real-life contexts (Section 4). However, the greatest identified need for improvement is also in Section 4 with students expressing a desire for more hands-on involvement in conceiving, designing, implementing, and operating experiments. Their proposed multi-session, design-and-build concepts indicate a clear appetite for authentic, iterative work that builds ownership and confidence while better reflecting engineering practice. Student generated proposals can be readily adapted to meet required learning outcomes, giving students autonomy and potentially higher motivation, while staying within required programme frameworks.

Actions arising from this for programme development will include restructuring selected laboratories into multi-session structured activities that support full design-build-test cycles which maximise individual hands-on time, with the aim of increasing the impact of the laboratories on student learning and skill development, aligned with CDIO and SCL principles.

Table 5. Student laboratory concepts

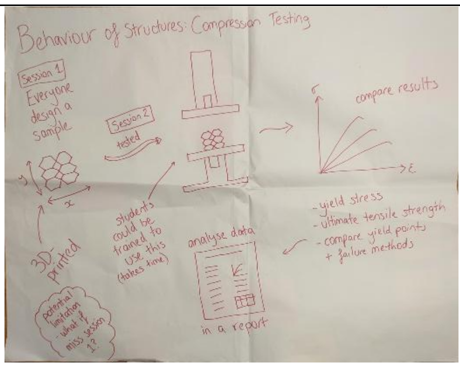
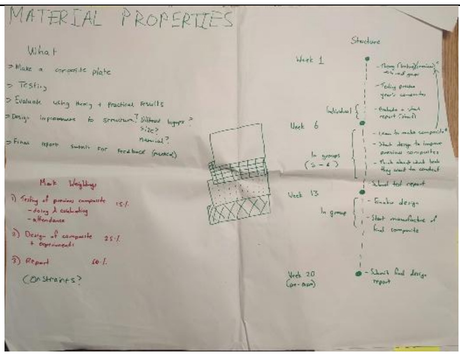
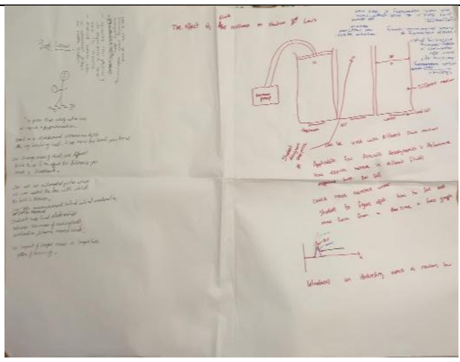
Group	Sketched Outline	Laboratory detail
1		STRUCTURES Multi-step laboratory incorporates student design of a structural component, manufacture by 3D printing, training on test equipment, testing of component, analysis of results (comparing results across group) and reporting findings.
2		MATERIALS Semester-long laboratory activity incorporates initial benchmarking and evaluation of composite panels made by students during the previous year. Students would then learn how to manufacture a composite panel, and then develop an improved design, manufacture it and test it. Finally, they would produce a technical report.
3		NEWTON'S LAWS The group had two suggestions: The first laboratory relates fluid resistance and motion of an object in different media to Newton's Laws. A student-led design element is introduced through design and manufacture of the drop piece. Students would take measurements, produce graphs and compare them with theory. Student physical interaction activity, investigating effects of mass and other variables on motion.
4		NEWTON'S LAWS Students design and manufacture a model vehicle which is course-specific e.g. for Mechanical or Aerospace. They then investigate the effect of variables on motion such as mass, friction, and surface gradient. Students suggested incorporating additional aspects such as material properties and failure mechanisms.

Table 6. Alignment of AHEP LOs with CDIO Syllabus and student proposals

Current AHEP learning outcomes on laboratory module	CDIO alignment	Group 1	Group 2	Group 3	Group 4
Apply knowledge of mathematics, statistics, natural science and engineering principles to the solution of complex problems. Some of the knowledge will be at the forefront of the particular subject of study	1.1, 1.2, 2.1, 2.4	Structures and materials theory, statistics	Composite theory, structures	Dynamics, fluid mechanics	Forces, motion, energy
Select and apply appropriate computational and analytical techniques to model complex problems, discussing the limitations of the techniques employed	2.1, 2.2, 2.3	Beam/plate models, FEA, comparison of results/theory	Use modelling tools and compare with test data	Compare experimental data to theoretical fluids models	Make predictions about motion
Select and evaluate technical literature and other sources of information to address complex problems	2.2, 2.4	Material datasets, standards, background information	Research layup strategies, failure modes	Literature search on drag, typical models	Research friction coefficients, small vehicle dynamics
Apply an integrated or systems approach to the solution of complex problems	2.3	Consider geometry, materials, printing parameters, test methods etc	Consider material, manufacturing, design, testing	Interactions between geometry, fluid medium, measurement apparatus	Consider vehicle, contact surfaces, test conditions
Use practical laboratory and workshop skills to investigate complex problems	2.2, 4.4, 4.5, 4.6	Hands-on printing and testing	Hand lay-up, cutting, testing	Manufacture of test piece, experimentation	CAD and 3D printing, assembly, testing
Select and apply appropriate materials, equipment, engineering technologies and processes, recognising their limitations	1.2, 2.1, 4.4, 4.5	Justification of material choices, printing parameters	Choose resins, fibres, moulding techniques	Choose geometry, manufacturing method, material	Choose materials, bearings, wheels
Function effectively as an individual, and as a member or leader of a team	2.4, 2.5, 3.1, 3.2	Team based	Team based	Team based	Team based
Communicate effectively on complex engineering matters with technical and non-technical audiences	3.2	Lab report, presentation	Technical report, presentation	Lab report, presentation	Technical report, presentation

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BIOGRAPHICAL INFORMATION

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Angena Panaser completed her MEng Aerospace Engineering degree at QUB in June 2024, and then worked on a research project related to Student Centered Learning in laboratories during the subsequent academic year. She is now undertaking PhD research at the University of Birmingham in Experimental Fluid Mechanics.

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