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Conceive-Design-Implement-Operate (CDIO) as an Effective Learning Framework for Embedding Professional Skills*

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Engineering education requires the development of professional skills alongside technical expertise. Active, project – and problem-based learning have all been shown to be an effective method for learning and teaching and the CDIO (Conceive-Design-Implement-Operate) framework is internationally recognised for this. The aim of this study was to evaluate the effectiveness of our CDIO approach to undergraduate Mechanical Engineering degree programmes through analysis of student confidence in a variety of professional skills. Two questionnaires were given to students at the start (QNR1 n = 109) and end (QNR2 n = 117) of their final year of study in 2016/17, 2017/18, and 2018/19, including a list of key skills for students to rate their confidence levels. Results showed that students were highly confident in a number of professional skills including "problem solving" (4.20/5), "communication" (4.08/5) and "teamwork" (4.13/5), and that almost 90% of students used the CDIO process during their Final Year Project (FYP). Students recognised the importance of their academic advisors in the development and completion of their FYPs, particularly in areas such as defining the project aims (mean 85% agreement of importance), but also accepted that responsibility was predominantly their own or shared in all areas of the project. Only 5.4% and 11.1% of students thought it was the advisors responsibility alone to "Implement the Project" and "Define the Project Aims" respectively. This is a positive indication that CDIO is an effective methodology for giving students confidence in the professional independent and team working skills required post-University.

Keywords: engineering education; skills; CDIO; active learning; project-based learning; problem-based learning

1. Introduction

The student journey through a degree programme is largely shaped by the structure of the learning experience i.e. the modules, activities, assessments, and projects that they undertake. Their skills, experience, behaviours, thoughts and confidence depend on these elements, as well as how they are delivered and received. Integrated learning and teaching, where students problem solve in active learning settings, has the benefit of students developing both skills and knowledge at the same time [1]. Active learning has been shown to be an effective learning method for increased student performance in STEM subjects [2], and research has shown that students will remember course content and information better if learned in an active learning environments [3].

One strategy for integrated, active learning is CDIO, which can be considered to incorporate active learning in a systematic and integrated way. CDIO is a framework for engineering education, providing students with the opportunity to Conceive-Design-Implement-Operate (CDIO) solutions to real world problems, developing both technical and professional skills, with a syllabus that can be adapted to suit the needs of the provider and student population [4]. It was created in response to the industry need for engineering graduates to have better professional as well as technical expertise [5], and can be described as both project-based and problem-based in its approach to learning, and the nature of this is down to the higher education providers and how they implement the framework. The syllabus is regularly reviewed in line with other practices, standards and requirements [6], and the CDIO international community shares best practice and developments regularly via forums and conferences, for example.

Implementation of the CDIO framework into a degree programme is very possible and has been demonstrated in a range of institutions internationally (e.g., Queen's University Belfast MEng in Mechanical and Manufacturing Engineering [7]). By following the CDIO standards and learning from other institutions who will share their experiences, becoming a CDIO member institute is extremely accessible. There are over 180 institutions listed on the CDIO website (cdio.org). A survey in 2014 [8] reported that of the forty seven institutions who responded, CDIO had been applied to over ten different disciplines in the field of engineering. And although the CDIO framework was designed for engineering programmes initially, it has since been implemented in a number of non-engineering programmes (e.g., mass media [9]). An explanation and

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series of case studies for implementation of CDIO in non-engineering programmes was presented by Malmqvist et al. in 2016 [10].

The CDIO framework was implemented at Aston University, a UK Higher Education Institution, in 2010 [11] in the Mechanical Engineering and Design Department, and follows the 12 CDIO standards [12]. It has been implemented at curriculum level for a number of programmes, including Mechanical Engineering (BEng and MEng), Design Engineering (BEng), and Product Design programmes (BSc).

Students studying undergraduate Mechanical Engineering and Design have a unique learning and teaching environment, where the CDIO philosophy is discussed, and the acronym employed by staff and students from week 1 of study. CDIO is also used as the key design and problem solving process that is put into place for students to work through and apply in a series of team-based exercises that build into four major PBL modules over the first two years of study. PBL study has been demonstrated to give students an effective way of building their communication and team working skills [13]. Our PBL modules involve students working in groups of between 3 and 12, and going through the design-build-test of products ranging from healthcare devices to wind turbines, for example. Associated smaller modules run alongside these PBL modules, feeding in technical theory and understanding. The aim of using CDIO in this way is to not only develop their theoretical knowledge, but also practical and professional skills, including problem solving, teamwork, and communication.

In the final year of study, students work individually on their own Final Year Projects (FYPs), with an academic advisor to help guide them. This gives students the opportunity to use the skills developed in earlier years in an individual setting, and to steer them towards becoming successful engineers for the future. The layout and credit value of these modules is shown in Fig. 1.

A review by Chen et al. [14] summarises the approaches of both project and problem-based learning (PBL), and also the challenges faced by both staff and students. Some of the key challenges faced by students are the need for greater self-learning skills, and the ability to transfer skills between different learning environments [14]. Anecdotally, it has been noted that students do not always link different modules or years of study, something that project-based learning aims to challenge by bringing different topics and tools together within the student activity.

The aim of this research study was to analyse the effectiveness of the CDIO philosophies embedded

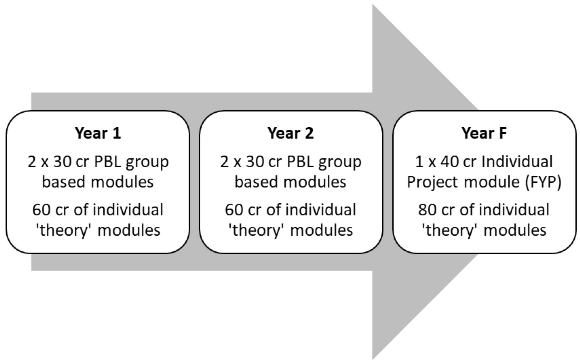

Fig. 1. Student journey through Years 1, 2 and Final (F), showing the number of credits (cr) spent on the different module types i.e. theory and project-based-learning (PBL). Note – there is also an optional industrial placement year between years 2 and F however this is optional and so not displayed.

in the learning and teaching for our engineering programmes, through the examination of student awareness and confidence across a range of professional skills, including time management and the ability to be a self-directed learner. We also wanted to gauge the students' ability to use the CDIO framework as a problem solving tool when not directed to do so.

By understanding more about the effectiveness of our curriculum for embedding key skills, we can identify strengths and weaknesses, as well as areas for development in our programmes.

2. Presentation

2.1 Methodology

Gathering the attitudes and opinions of engineering students is a useful way of evaluating courses and their impact [15]. For this study, we wanted to explore and understand what skills students were more confident with as they progressed through the course and into their final year projects (FYPs). We also wished to evaluate their understanding of independent work, but also their role in a team with their academic advisor.

In order to achieve this, two questionnaires, QNR1 (n = 109) and QNR2 (n = 117), were created and given to three cohorts of final year students over the academic years of 2016/17, 2017/18, and 2018/19. These will be referred to as Cohort 1, Cohort 2 and Cohort 3, respectively.

QNR1 was delivered at the beginning of the academic year of study and at the start of their FYPs, and QNR2 towards the end of the year following completion of the FYPs. These were delivered via paper copies of the QNRs, with an offer for all FY students to complete them during quiet times of classroom activity, or in their own time in order to minimise any potential negative impact on their learning time.

Questions and topics for the QNRs are shown in Table 1. Also collected were data around student factors such as gender, student status, and age.

The list of skills used in the QNRs were derived from the 12 CDIO standards, and the implementation of the CDIO philosophy at Aston University. They comprised of the following key areas:

- Apply engineering science in design-implement projects.
- Communication.
- Consider regulations during product development.
- Consider technology during product development.
- Consider wider concepts during a project (e.g., enterprise, business and society).
- Create designs, i.e. plans, drawings, and algorithms.
- Creative thinking.
- Critical thinking.
- Define customer needs.
- Develop business plans.
- Develop conceptual plans.
- Develop technical plans.
- Engineering reasoning.
- Knowledge discovery.
- Leadership.
- Problem solving.
- Professional ethics.
- Project Management.
- Scientific thinking.
- Self-awareness of knowledge and skills.
- System thinking.
- Teamwork.
- Transform a design into a product, process, or system.
- Work to professional standards in an organisation.

Once data was collected and processed, statistical analysis was performed using a combination of Excel (Microsoft Ltd., Reading, UK) and SPSS (IBM Ltd., Portsmouth, UK). Ethical approval for this study was gained from the local ethics committee at Aston University, and informed consent was obtained from all participants.

2.2 Results

Table 2 displays the number of students that answered each QNR in relation to the student population size in each year group.

Table 3 displays data gathered around student identity. Due to the low number of female respondents, data was not analysed by gender. There was also a low number of EU/International student respondents in this study, meaning that no useful analysis could be undertaken based on student status.

The aim of the study was to analyse the effectiveness of our CDIO framework in embedding professional skills in our graduating students. In order to measure this, the mean average scores of students' answers to 5-point Likert scale statements regarding their confidence in a variety of skills was analysed for QNR1 and QNR2. This was done across all three cohorts, and the results for this

Table 1. Questionnaire (QNR) topics, method of questioning and format of response for both QNR1 and QNR2. 5-point Likert scale: 5 = Strongly Agree, 4 = Agree, 3 = Neither Agree nor Disagree, 2 = Disagree, 1 = Strongly Disagree)

		Question Topic				
		Skills Confidence	**Student time on FYP**	**Meetings with academic advisor**	**Use of CDIO**	**Input from academic advisor on FYP**
	Method of question	5 point Likert scale	Time options	Frequency options	Extent of use scale	Scale across FYP aspects
QNR	**QNR1**	Confidence	Planned	Planned	–	Responsibility
	QNR2	Confidence	Actual	Actual	Actual	Importance

Table 2. Numbers of students completing QNR1 and QNR2 in each cohort as well as total size of student population in each year group and the percentage of students (to 0 decimal points) who answered each QNR from that student population

	Cohort 1	**Cohort 2**	**Cohort 3**	**Total**
QNR1	37 (44%)	27 (26%)	45 (43%)	109 (37%)
QNR2	36 (43%)	38 (37%)	43 (41%)	117 (40%)
Student population	84 (100%)	103 (100%)	105 (100%)	292 (100%)

Table 3. Percentage demographics of students answering QNR1 and QNR2 (to 1 decimal point)

	Male	**Female**	**UK**	**EU**	**International**
QNR1	90.5%	9.5%	84.0%	3.8%	12.3%
QNR2	93.7%	6.3%	85.7%	5.4%	8.9%

data are broken down by cohort and shown for QNR1 and QNR2 in Figs. 2 and 3, respectively.

In order to identify the skills that students were most confident in, responses where the mean confidence level was four and above were calculated. This cut-off point was chosen because this figure clearly represents that the majority of students indicated a "Confident" or "Very Confident" answer on the QNR. The list of skills above this cut off across all cohorts was as follows:

- Apply engineering science in design-implement projects.
- Communication.
- Consider regulations during product development.
- Create designs.
- Critical thinking.
- Develop conceptual plans.
- Develop technical plans.
- Engineering reasoning.
- Knowledge Discovery.
- Leadership.
- Problem solving.
- Professional ethics.
- Project management.
- Scientific thinking.
- Scientific thinking.
- Self-awareness of knowledge & skills.
- Teamwork.
- Transform a design into a product, process or system.
- Work to professional standards.

In a number of instances, there was high confidence in a particular skill across all the cohorts, indicating a level of consistency across the cohorts, and at the time point in the FYP at which QNRs were deployed. For example, across all three cohorts, and both QNRs, "Problem Solving" was rated consistently high. In QNR1, between 87 and 92% of students across the cohorts indicated they were "Confident" or "Very Confident" in this skill.

As previously stated, QNR1 was implemented at the start of the students Final Year (FY) of study, and QNR2 at the end. The FYP undertaken by students is an individual assignment and, though using the same skills as in previous years, is both new and unique to the student. In order to determine if there was an effect on the students' confidence in their skills across the FY, the statistical difference between QNR1 and QNR2 data for each cohort was analysed using a two-tailed Mann-Whitney U test. This non-parametric test was used because the data did not meet the assumptions required for parametric tests, as it is neither continuous in nature, nor normally distributed.

Cohort 1 showed no statistically significant dif-

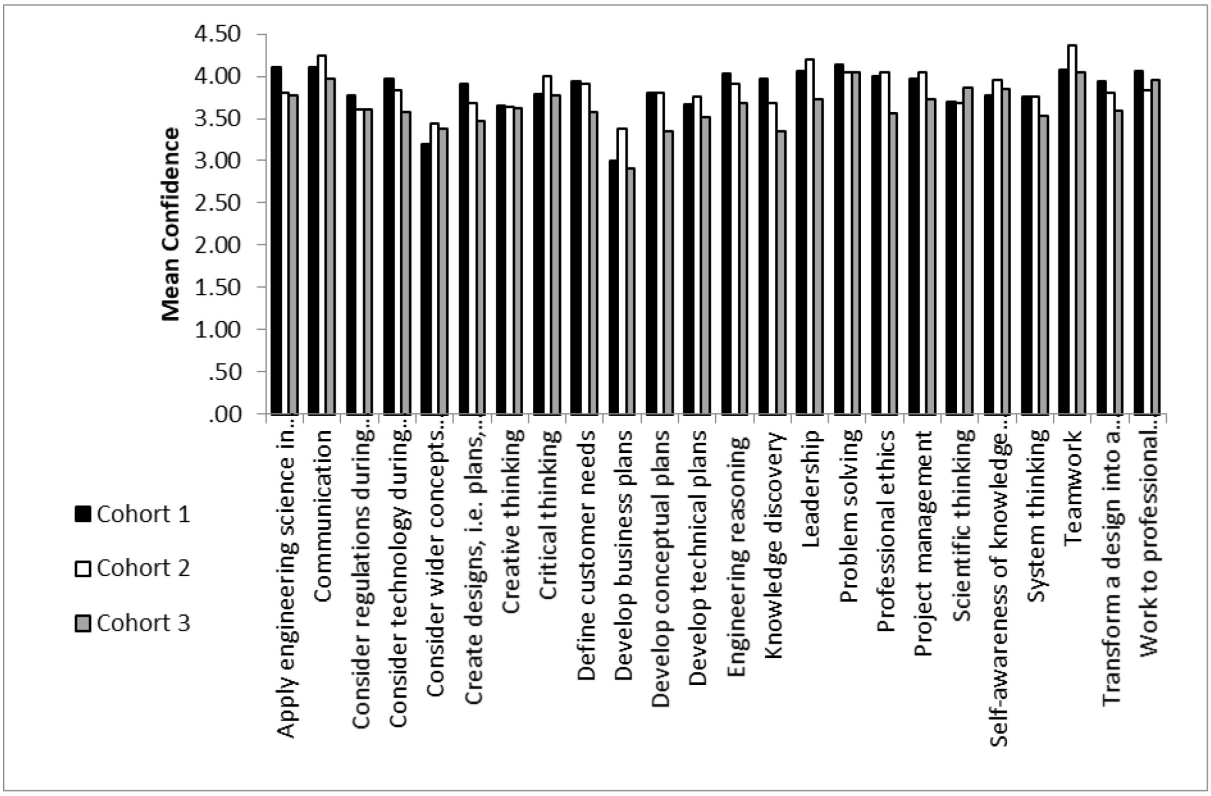

Fig. 2. Mean confidence ratings for the skills in QNR1, for each cohort.

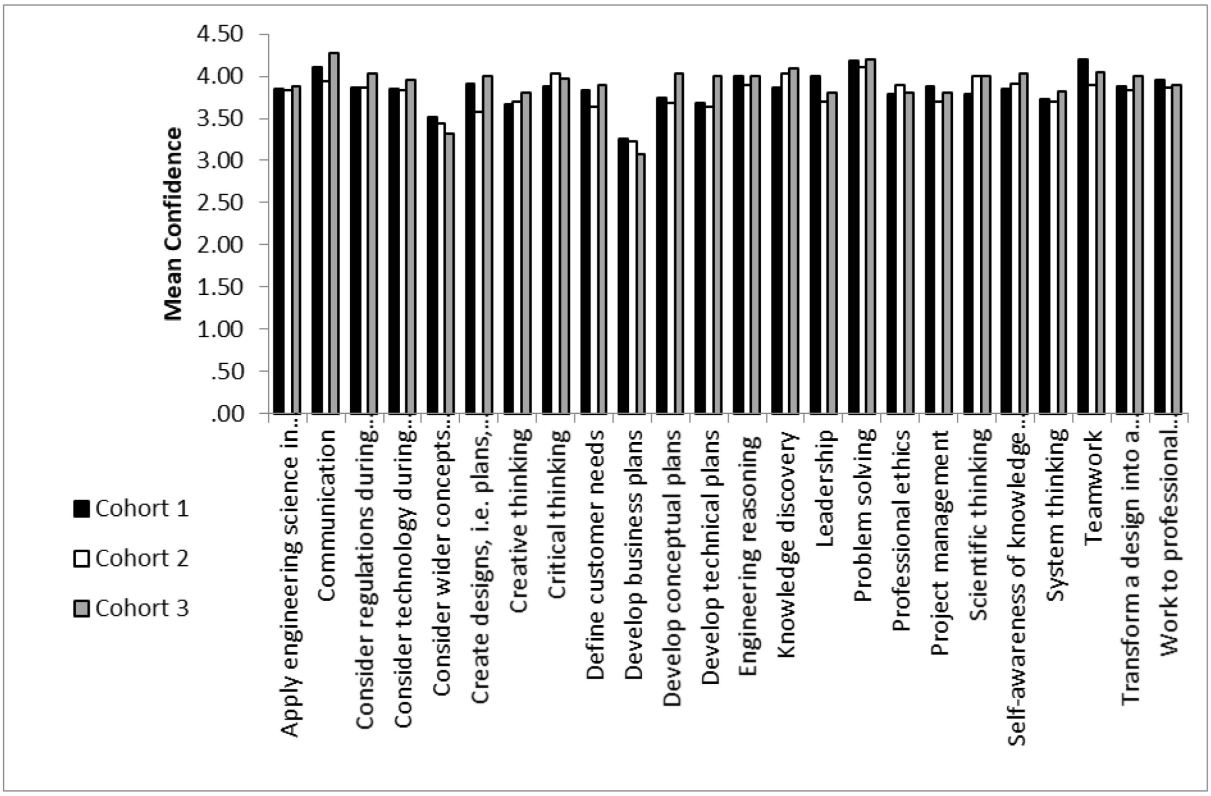

Fig. 3. Mean confidence ratings for the skills in QNR1, for each cohort.

ferences between QNR1 and QNR2 skills data. Cohort 2 showed a statistically significant increase in confidence for two skills, and a statistically significant decrease in confidence for two skills. Cohort 3 data showed a statistically significant increase in confidence for seven skills, and no statistically significant decreases. The relevant Mann-Whitney U data is shown in Table 4, including the mean ranks, N, U, z, and p values.

Another key skill that underpins the work of engineering students, especially as they undertake their FYPs, is time management. In order to explore whether our students were developing this key skill appropriately, students were asked about the time they expected to spend in each TP on their FYP in QNR1, and then the time they actually spent in each TP in QNR2. Though there are some differences between the planned and expected time spent, overall, the majority of students indicated that they spent a similar amount of time in each period as was planned, suggesting they had good time planning in place, as well as reasonable expectations of

Table 4. The results of the Mann-Whitney U test to determine any statistically significant differences between skills in QNR2 compared to QNR1 for each cohort

Cohort	Skill	Direction of change	Mean rank QNR1	Mean rank QNR2	U	z	p
2	Knowledge Discovery	Increased	26.54 (N = 25)	34.10 (N = 36)	338.5	–2.287	0.022
	Scientific Thinking	Increased	26.44 (N = 25)	34.17 (N = 36)	336.0	–1.988	0.047
	Teamwork	Decreased	36.78 (N = 25)	26.99 (N = 36)	305.5	–2.292	0.022
	Leadership	Decreased	36.38 (N = 25)	27.26 (N = 36)	315.5	–2.188	0.029
3	Knowledge Discovery	Increased	33.18 (N = 44)	53.54 (N = 41)	470.0	–4.318	0.000
	Consider technology during product development	Increased	37.31 (N = 45)	49.40 (N = 40)	644.0	–2.580	0.010
	Develop conceptual plans	Increased	34.71 (N = 45)	52.33 (N = 40)	527.0	–3.567	0.000
	Develop technical plans	Increased	36.67 (N = 45)	50.00 (N = 40)	620.0	–2.696	0.007
	Consider regulations during product development	Increased	36.54 (N = 45)	50.26 (N = 40)	609.5	–2.772	0.006
	Create designs	Increased	36.43 (N = 45)	50.39 (N = 40)	604.5	–2.778	0.005
	Transform design	Increased	36.23 (N = 44)	49.40 (N = 40)	604.0	–2.718	0.007

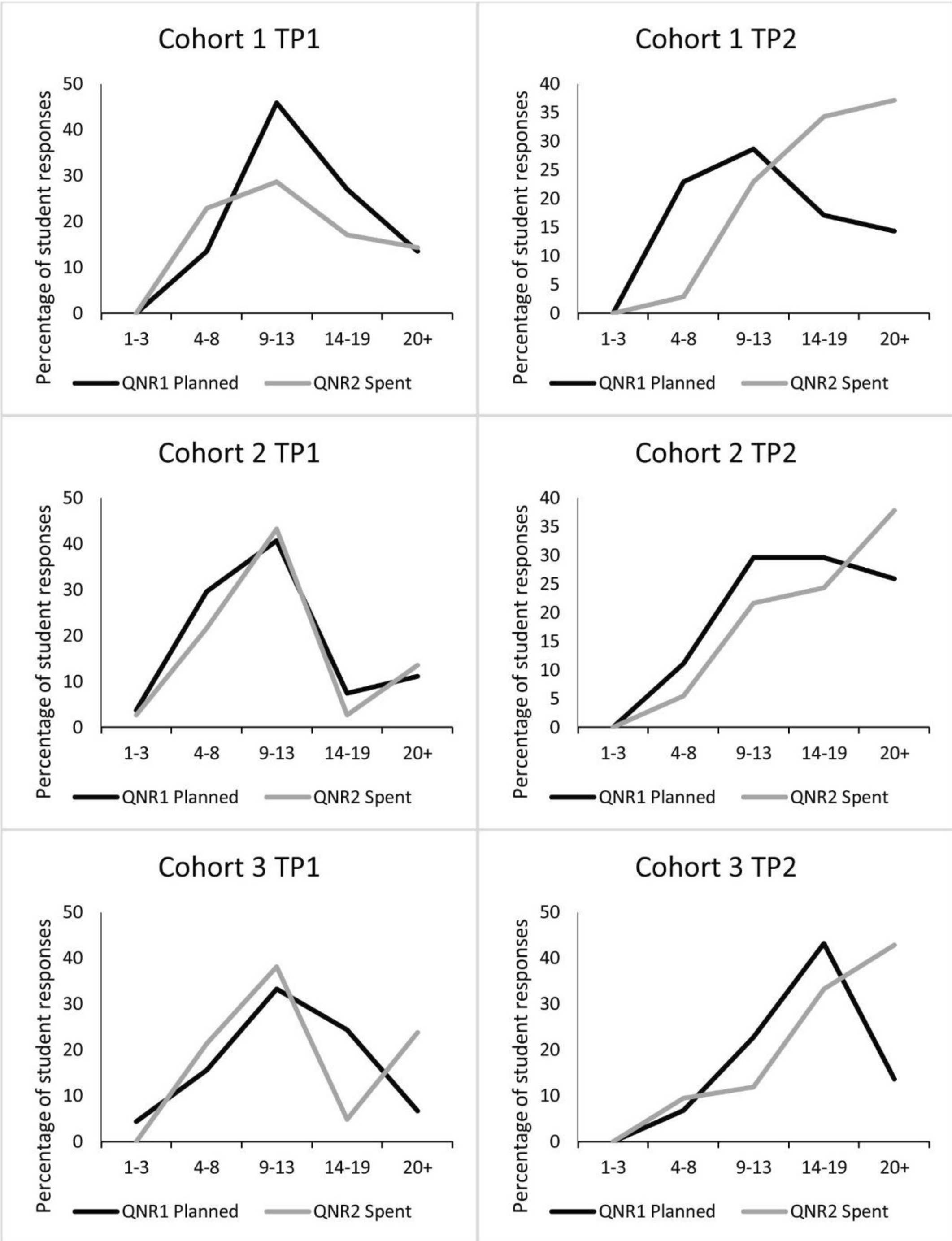

Fig. 4. Time expected (QNR1) versus time spent (QNR2) on the FYPs for each cohort in each teaching period (TP). Results show a good consistency between planned time and time spent, with some under expectation of the time in TP2.

their workload. There does appear to be an element of under-planning of time spent in TP2, which is particularly noticeable in Cohort 1 (see Fig. 4).

In order to further explore the learner-centred journey and skills of our students, we asked them in QNR1 who they thought had responsibility for the various aspect of their FYP; the student, the advisor, or both. In QNR2, we then asked the students to retrospectively rate the importance of their FYP advisor in the same aspects of the FYP.

When responding to questions around the responsibility for various aspects of their FYP, the majority of students felt that it was the students sole responsibility for all aspects of the FYP, aside from ‘Defining the Project Aims’, which the majority of students felt was both the responsibility of the student and the advisor combined. Very few stu-

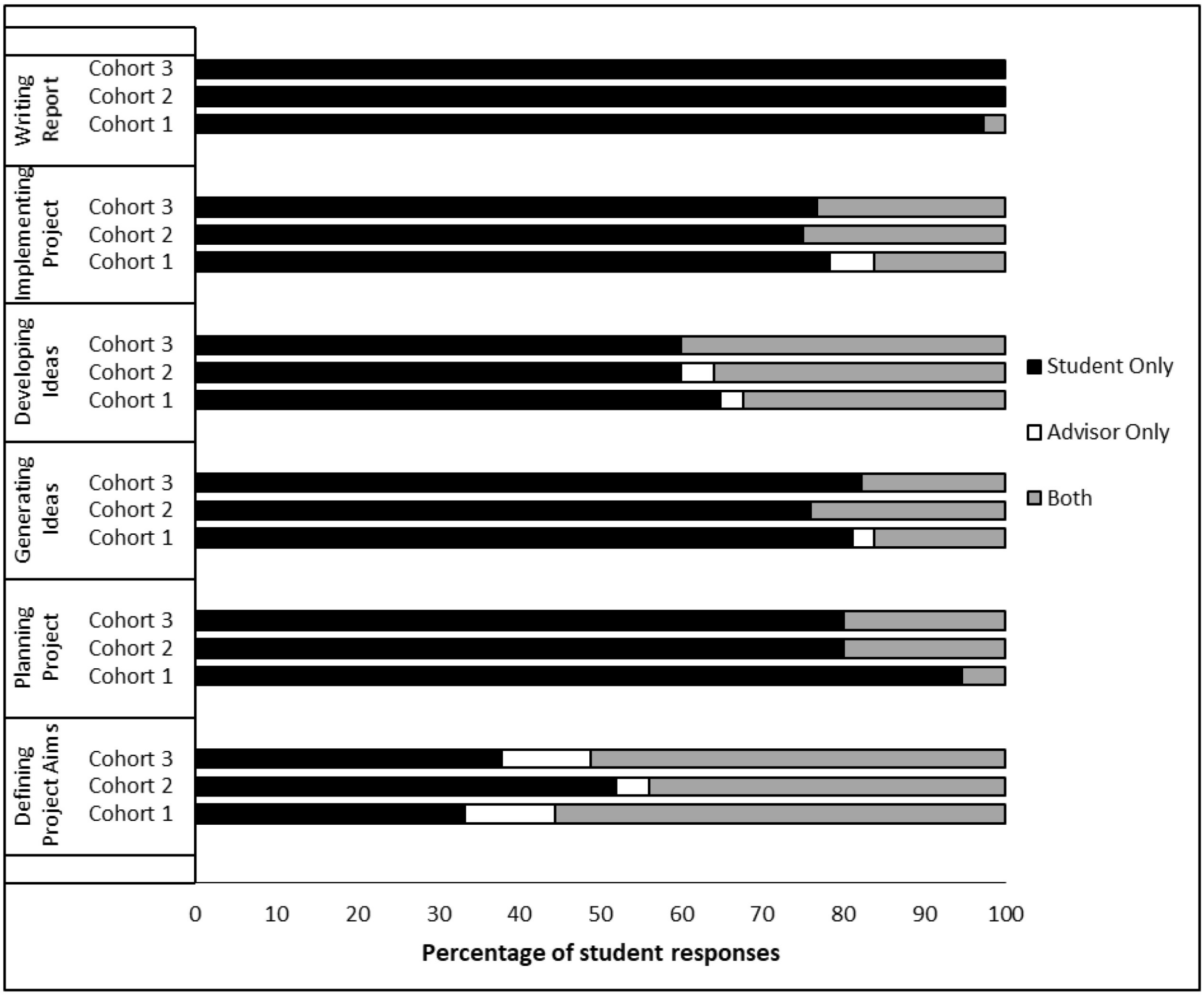

Fig. 5. The percentage student response when asked who is responsible for various elements of the FYP in QNR1.

dents felt that any of the aspects of the FYP would be the sole responsibility of their advisor. Results are shown in Fig. 5 for all cohorts.

When asked in QNR2 how important they felt their advisors had been in their FYPs, the majority of students stated their advisors were important to some extent (either "Quite Important" or "Very Important") in most aspects of the project. Full results in Fig. 6.

The results from QNR1 and QNR2, which explore the responsibility and importance of the FYP advisor, links the leadership skill with the teamwork skill, both of which are important attributes for an engineer.

As previously mentioned, Aston University is in the minority of CDIO institutions that openly and directly employs CDIO as an acronym in its teaching and delivery to students, and actively encourages students to use this framework in problem solving during the PBL modules in years 1 and 2. In this study, we wanted to explore whether students saw value in the CDIO framework through their individual FYPs by asking them about the extent to which they actively employed the Conceive-Design-Implement-Operate model in their work. Of the students surveyed in QNR2, over 88% of students in every cohort indicated that they used CDIO to some extent during their FYP. Fig. 7 shows the breakdown of these results in more detail.

2.3 Discussion

The CDIO teaching principles and philosophies centre around creating engineers who can apply technical knowledge to real-world problems [16]. There are a range of skills that we aim to develop through the Mechanical Engineering and Design programmes at Aston University, by using the CDIO philosophies. The aim of this study was to explore the effectiveness of these programmes through measurement of students' confidence in these key skills, and their use of the CDIO principles. Teamwork models and tools, as an example, have been assessed in other studies to examine their effectiveness in providing students with teamwork

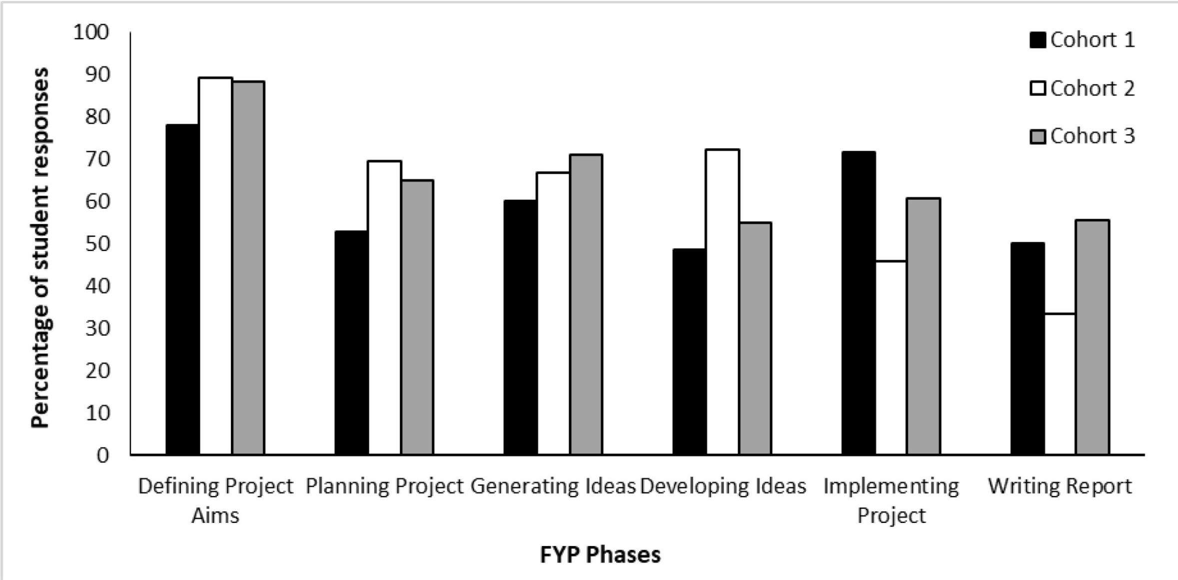

Fig. 6. Percentage of students who rated their Advisor as "Important" in the different elements of their FYP in QNR2. Results show that the majority of students found their advisors role was important in nearly all aspects of the FYP.

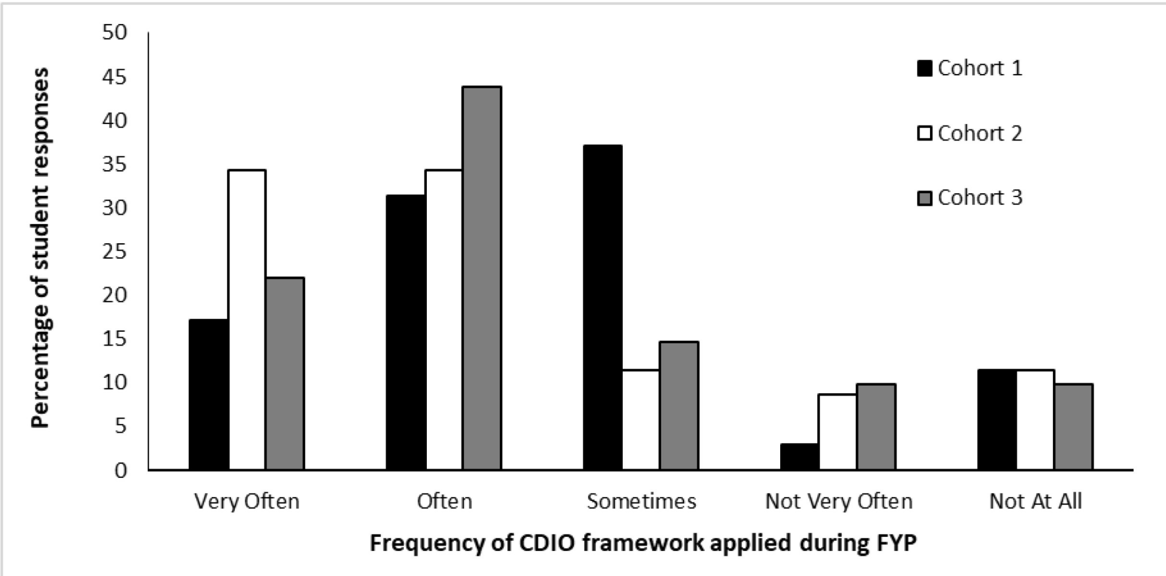

Fig. 7. The percentage of student responses when asked how often they used CDIO in their FYPs. Over 88% of students responded to say that they used CDIO to some extent in each cohort.

skills and understanding [17]. We wished to do the same with our programmes in order to understand effectiveness, and also identify areas that could be improved in this novel CDIO-based teaching approach where CDIO is actively discussed and used with students.

Results from across the QNRs and cohorts show there were a number of skills in which the vast majority of students felt confident, as well as a high proportion of students across all professional skills. That the professional skills were rated so highly in this study is a positive indicator of the usefulness of CDIO as a programme tool for developing employable graduates, and that the CDIO philosophy embedded within our teaching curriculums is providing students with an integrated experience of both knowledge and skills development.

Other studies have also shown that 'CDIO students' rate these skills highly. For example, in a study by Malmqvist et al. [18], students and alumni who had been through a CDIO Mechanical Engineering programme at Chalmers University were found to have higher confidence in skills than other alumni (non-CDIO programmes), including skills such as teamwork and communication, as well as technical skills. Their current students also expressed that they were well prepared when working in teams, and felt that CDIO had prepared them for being professional engineers and strengthened their employability.

As well as specific professional skill development and confidence, developing the skill for independent, self-directed learning is critical in the development of engineers, and has been well discussed in the UK higher education sector and beyond [19]. Previous research has shown that students struggle with the transition from School to University, particularly in terms of their ability to learn independently [20] and they have high expectations of the levels of academic support in their learning [21]. Being able to self-direct their own learning provides students with the ability to adapt to different projects with their transferable skills.

One element of self-directed learning is a student's ability to manage their own time. In this study, students were asked to plan their time and then report their time as spent on their FYPs. Though there were some differences between the time planned and time spent, overall there was a consistency to the time management of students. Time management in engineering students has previously be shown to be a skill that can be addressed through group design projects [22], and, in the case of the students in this study, has been integrated into the four PBL modules in years 1 and 2, and effectively employed by the students in their FYPs.

Another element of students' abilities to self-direct and lead their own learning was explored through the perceived responsibility and importance of their FYP advisor. In this study, both before and after the FYP, it appears that students recognised both their own responsibility but also the value of working as a team with their academic advisor. Previous studies show that students who have been through project-based-learning (PBL) education develop their professional skills during this learning journey [23], including skills such as teamwork and communication [24]. The recognition of the team, as well as their own responsibility and independence, suggests that though the transition may be difficult, the recognition of the skills required and the ability to work with an advisor is a positive learning experience for the students.

Aston University is one of the few CDIO providers that openly and explicitly uses the 'CDIO' terminology during teaching, with many providers using the CDIO processes but without discussion of this terminology with the student cohorts. Our research shows that almost 90% of students indicated that they employed the CDIO process in their FYP. This suggests that they have learned a process for tackling problems and projects, and can adapt that process for new projects that are independent as opposed to the group environment in which they were previously applied.

The limitations of this study are the relatively low numbers of participants (109 and 117 for QNR1, and QNR2, respectively), and that no qualitative data was obtained. This could have allowed for deeper interpretations of results, and more detailed discussion about what the research findings mean. Focus groups were conducted as part of this study, but participation was very low, and it was not deemed appropriate to include the opinions of just a few students as part of discussing overall trends. Another potential limitation of this research is the differences between student cohorts, their individual personalities, learning styles, and individual experiences. Also, the potential changes in teaching each year, and the individual nature of the FYPs, which are unique for each student, mean that the results are potential influenced by numerous factors outside the scope of the study.

A further observation is that confidence may not be matched by competence, something shown in previous studies of technical skills [25]. Though competence in this study was not directly measured, the style of active learning, as used here in our CDIO programmes, has been shown to increase student performance [2].

3. Conclusions

The aim of this research was to analyse the effectiveness of the CDIO philosophies embedded in the learning and teaching in our programmes, through student awareness and confidence across a range of professional skills.

The novelty of this work is in both the way CDIO is used at Aston with an open understanding and use of both the CDIO terminology and process for problem solving and design-build activities by the students. Whilst there are numerous articles around CDIO, skills development and curriculum design, we could not find any examples of where CDIO is actively discussed, described and used as terminology with the students as it is at Aston University. By surveying students who have this understanding of the CDIO philosophy, we have developed a unique understanding of the students confidence in skills purposefully embedded in our CDIO lead programmes.

Our findings support the argument that our programmes are successfully developing numerous key skills and principles for our engineering students, many of which are considered in the CDIO standards, as well as highly desirable professional skills which are valued within industry. Our work demonstrates that the use of CDIO terminology gives students a known framework by which to solve problems and plan projects, and the use of group and individual work gives them the flexibility to adapt and apply their skills to different projects. Time management, though perceived well by students in this study, could be improved.

Future work includes a comparison of confidence with competence in order to explore whether the two are linked, as well as improving the student experience to increase confidence in the other skills identified as being core to employability and effectiveness as an engineer. In addition, further qualitative research will be conducted in coordination with quantitative work, which will add richness to any further data analysis.

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