CHARACTERISATION OF EFFECTIVE DELIVERY AND SUPERVISION OF CAPSTONE PROJECTS

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ABSTRACT

Delivering activities that are well aligned to the CDIO curriculum can present many challenges and often the complexity of these activities can lie outside the skill set of any single individual. Student projects at the University of Liverpool are now more complex than they were 15 years ago and it was felt that critical reflection of supervisory practice would be of benefit. This paper studies how the topic, structure, delivery and supervision of Capstone projects at University of Liverpool has evolved over the last 10 years. Several gradual shifts are noted: towards sustainability themes, towards cross-disciplinary approaches, and towards extended industrial collaboration. This paper presents an analysis of professional skills development in Capstone projects; drawing on consultation with academic faculty, current Capstone students and graduates now in employment. The prioritisation of various learning outcomes is compared across these three groups: the diversity of these outcomes suggests that academic faculty alone cannot hope to deliver them. This paper proposes that the key to effective delivery of complex learning activities lies not in developing and equipping any one individual supervisor with a never-ending skill set, but instead lies in fostering effective partnerships between a number of diverse individuals (academic faculty, technical staff, industrial partners). The paper then explores best practice in Capstone project supervision through reflection on current practice, and consultation with academic faculty supervisors, students, technicians and industrial partners/supervisors. The benefits of involving technicians and industrial partners in the development and delivery of Capstone projects is discussed; and the use of recent graduates as industrial supervisors is explored. The concept of using ‘Communities of Practice’ to guide and support Capstone supervision is presented and described. In light of our recent experience of using Communities of Practice, we also explore how this has the potential to augment faculty development initiatives, and to improve the competency of staff delivering Capstone supervision.

KEYWORDS

Capstones Project Supervision, Technicians, Industrial Collaboration, Faculty Development, Community of Practice, CDIO Standards 7, 8, 9, 10

1. INTRODUCTION

Capstone projects are fundamental to the CDIO approach to engineering education; they are an effective platform for students to “*conceive-design-implement-operate complex value-added engineering systems in a modern team-based environment*” (Crawley et al. 2014), and they are crucial to ensuring programmes can meet CDIO Standards 7 and 8. They focus not only on engineering science but on enhancing skills and experiences required of graduates entering into professional engineering.

A survey carried out by Brumm et al. (2006) shows that respondents rated the learning opportunities provided by Capstone projects second only to a placement in an engineering workplace. Students acknowledge that these activities are where they develop vital skills and demonstrate their employability. Of the students completing an MEng programme at University of Liverpool (UoL), of which Capstone projects are an integral part, 100% are in employment six months after graduating, 70% of which are employed as engineering professionals (HESA 2018). However, these can be the most difficult learning experiences to deliver; project topics can vary widely and supervisors are required to possess a range of practical, pedagogical, professional and scientific skills. It is therefore highly unlikely that any one individual instructor will possess this full skillset.

As Capstone projects at UoL have evolved to become more complex, then our supervisory practice has had to evolve to ensure effective delivery. Efforts have been made to broaden the pool of knowledge available to students by increasing the involvement of non-academic staff in the delivery of these projects. Although student surveys have shown an increase in satisfaction, and anecdotal evidence suggests that students are acknowledging the benefits of the complementary knowledge gained from other members of staff, it would seem sensible to take a more in depth look at our current practice. This paper aims to explore the assumption that a team approach to supervision can improve student learning in Capstone projects.

2. EVOLOUTION OF CAPSTONE PROJECTS AT UNIVERSITY OF LIVERPOOL

Capstones at UoL are 22.5 ECTS group design-build-test projects that run throughout the 3rd and 4th years of study. They have been a core component of 4-year MEng Mechanical Engineering programmes at the University of Liverpool for 15 years. During this time our approach to supervision and assessment has been refined; and the nature of the projects has evolved to reflect changes in the priorities of our discipline and in the interests of our students. Key developments have been:

2.1. Gradual Shift Towards Sustainable Development Themes

In the early years of Capstones most students worked on our flagship project - the Formula Student single seat petrol engine racing car (IMechE, 2022). Alongside this we ran other smaller projects such as the development of unmanned air vehicles and the laser marking of auto-body sheet aluminium. As the number of students taking the course increased (to approximately 140 per year currently) we sought to diversify our project portfolio to give students choice – reflecting their interests and the changing priorities of modern professional engineering. In short there has been a shift towards sustainability themes and Table 1 below lists the projects running from 2019-2022.

2.2. Increase in Cross-disciplinary Collaboration

In the early years of our Capstones, the projects only addressed ‘traditional’ Mechanical, Materials and Aerospace engineering themes. A weakness was that our students did not experience the cross-disciplinary collaboration that characterises modern professional engineering. Our current project themes (Table 1) have much greater interdisciplinarity, and our mechanical engineering students are therefore working every day with students and professionals from other disciplines: electrical, civil, chemical and nuclear engineering; industrial design; medicine; veterinary science; bioscience, retail. Thus, we are now better preparing our students for their lives and careers ahead.

Next year we will begin a new Capstone project in which our students will develop a cargo bike customised to allow a charity to support homeless people sleeping on the streets of Liverpool. The project team will include a group of sociology students who will explore the social and economic impact of our engineering. This is a critical development to enhance student understanding of all dimension of sustainable development, not just environmental.

Table 1: Current Capstone Project Themes

Project	Description
Formula Student Electric	International Competition
Velocipede – world human powered speed challenge	International Competition
12m land wind turbine for agricultural refrigeration in Africa	Industrial Collaboration – Siemens Gamesa Renewable Energy S.A.
Mobile vertical axis wind turbine for urban / events use	
Solar powered agricultural refrigeration in Africa	Academic Research Group Collaboration – Renewable Energy Research Group
Autonomous systems for hazardous nuclear environments	Industrial Collaboration – British Nuclear Fuels Ltd
Engineering systems for equine surgery	Industrial Collaboration – Leverhulme Equine Hospital
Automated leak detection in water supply & sewage systems	Industrial Collaboration – United Utilities plc
Systems to predict pipe corrosion and failure in hazardous chemical engineering	Industrial Collaboration – Inovyn Ltd
Autonomous vehicle for automatic detection and repair of road surface damage	Industrial Collaboration – Robotiz3D Ltd
Refillable technology for the supermarket of the future	Academic Research Group Collaboration – Hague University of Applied Science
Next generation folding bike for urban commuters	UK&I Region CDIO Competition

2.3. Enhanced Industrial Collaboration

In the early years of our Capstones, the projects were all delivered 'in-house' with academic faculty supervision and no collaboration with external professional engineers. Over the last five years we set ourselves the challenge of only introducing new projects if they are in partnership with engineering industry (whilst retaining our high-profile international competition projects) – see Table 1. Our Industrial Capstones improve student motivation and engagement with 'real world' engineering challenges; and they enhance student personal and professional development through working in partnership with practising professional engineers. The extent of industrial collaboration in our Capstone projects is at one of three levels to suit the partner company:

Industrial Project Concept: the partner company sets a current design-build-test challenge; briefs the students on the project context and background technology; and participates in periodic project reviews. See section 4.3 for an example.

Industrial Project Support: as above, but the company also assigns one or more professional engineers to act as 'consultants' to the project. These professionals are available on-demand to the students to inform, support and guide their work. In these projects the students also spend time working at the partner site.

Full Industrial Collaboration: as above, but the company also assigns one or more professional engineers to provide formal supervision and mentoring to the student team. These professionals are the primary project supervisors (supported by academic faculty) and typically hold 2-hour project meetings each week with the students. In these projects the students spend time working at the partner site and often take summer internships with the company.

Our ambition is that all new projects are based on full industrial collaboration because in this mode the students are most exposed to professional engineering practice: their professional and personal development, and ultimately their graduate employability, are most enhanced. Our current partnership with Siemens Gamesa Renewable Energy S.A. embodies this ambition: they are currently supervising two wind power projects and Figure 1 summarises the project structure and supervisory approach.

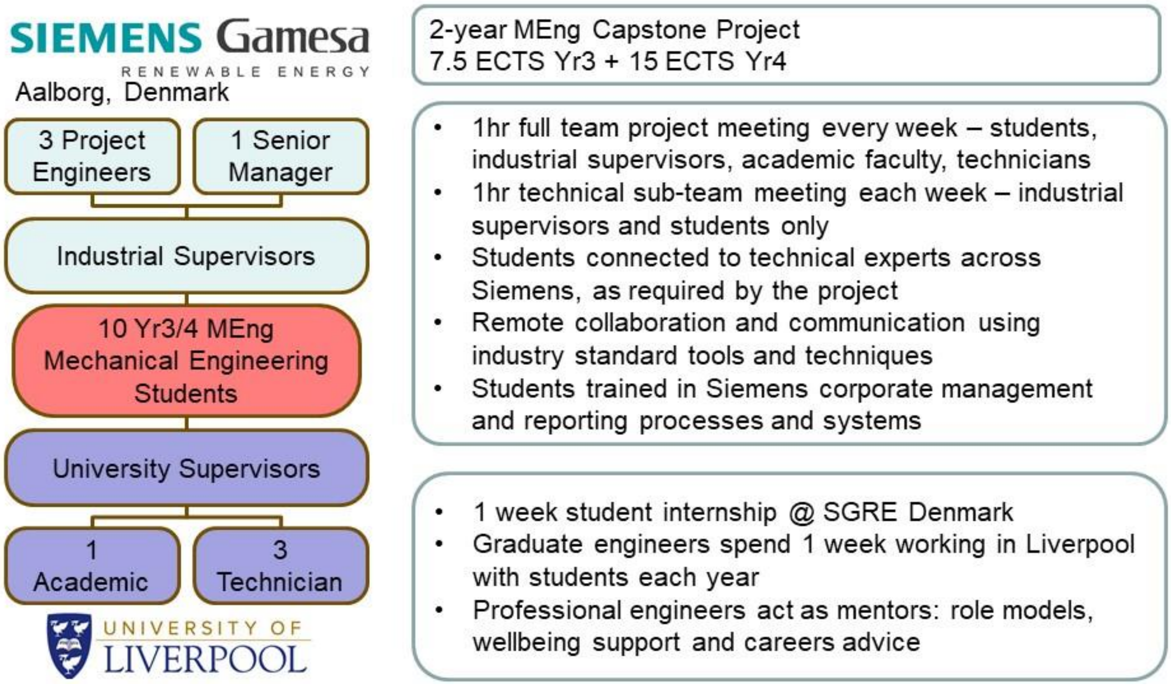

Figure 1: Project Structure and Supervisory Approach for Capstone Projects with Full Industrial Collaboration

3. REVIEW OF PERSONAL AND PROFESSIONAL SKILLS DEVELOPED IN CAPSTONE PROJECTS

In order to gain an understanding of the skill transference over the course of a Capstone project, a survey of current students and graduates was carried out. Of the ~60 individuals emailed the survey (8 graduates, ~50 students), 15 responded (5 graduates, 10 students). The survey presented respondents with a list of the published learning outcomes for the course (Table 2) and asked them to select any of the skills that they anticipated to gain, or had gained. They were then asked to rank the perceived importance of the skills they selected. Further to this survey, a consultation with academic supervisors of current Capstone projects (3 individuals) and technicians closely involved with Capstone projects (2 individuals) was carried out to gauge what skills they thought they were transferring to students and what they felt were the most important skills gained from Capstone projects. Table 3 compares the five most important learning outcomes identified by each stakeholder group, ranked by perceived importance.

Table 2: Course learning outcomes for Capstone projects (in no particular order).

Course Learning Outcomes	
Product & System Design	Communication (formal & informal)
Project planning & management	Technical record keeping
Design for manufacture, assembly, cost and sustainability	Professional reporting & progress presentation
Materials Science & Selection	Reflection on own & peer performance
Mechatronics	Problem solving
3D CAD modelling	Teamwork
Modelling and simulation	Manufacturing technology

Table 3: Professional skills gained from completing Capstone projects ranked by perceived importance

Rank	**Professional Skill**	
	Graduates (Survey)	**Current Students (Survey)**
1	Project planning & management	Teamwork & collaboration
2	Problem solving	Project planning & management
3	Design for manufacture and assembly	Problem solving
4	Teamwork & collaboration	Design for manufacture and assembly
5	Communication (formal and informal)	Communication (formal and informal)
	Academic Faculty (Consultation)	**Technician (Consultation)**
1	Teamwork & collaboration	Problem solving
2	Project planning & management	Design for manufacture and assembly
3	Application of engineering theory in system design	Communication (formal and informal)
4	Problem solving	Product & System design
5	Communication (formal and informal)	Manufacturing Technology

Although this data only represents feedback from 20 individuals, it is interesting that the selected skills are somewhat similar across all four groups. It should also be noted that the outcomes of this survey correlate well with the findings of Paul et al. (2015) on global graduate attributes (GA): specifically the desired learning outcomes of problem solving, team work, communication and ability to design (analogous to design for manufacture in our survey). We can also see that Table 3 overlaps with the skills outlined in the CDIO syllabus (Crawley et al. 2011), specifically sections; 2.1, 2.4, 3.1, 3.2, 4.4, and 4.5. The identified learning outcomes in Table 2, and the skills they overlap with in the CDIO syllabus and GAs, are difficult to deliver elsewhere in the programme so this work confirms the importance of Capstone projects and may offer insight as to why these projects can be difficult to deliver.

The survey of current students and graduates asked how Capstone students interacted with academics, technicians and industrial partners; and what they gained from these individual interactions. The responses confirmed that some skills were more likely to be gained from interaction with a particular group. Typical survey responses were:

- Academic Faculty supervisors were best placed to *"guide the project"*, offer support with "*project planning and management"* and provided *"expertise in a particular field"*;
- Technicians helped with *"design and problem solving"*, answered questions *on "the practicalities of [design] ideas"* and *gave "knowledge…on the right technology for the project"*;
- Industrial partners offered insight into professional practice of *"planning projects and presenting information".*

The survey shows that students place a high value on skills such as teamwork, communication and problem solving: skills that cannot be taught but only developed through experience. Students also appear to be learning different skill sets from different types of supervisor. In acknowledging these challenges, UoL has already moved towards a team approach to Capstone supervision where groups of individuals work together to deliver the full range of learning outcomes effectively. Efforts have been made to create proper working partnerships between academic and technical staff and these activities are now seeing a range of input from industrial partners with the aim of further increasing the educational benefit to students.

It is assumed that a team of supervisors, working in different roles, can be more beneficial than an individual faculty supervisor. To test this assumption, respondents of the survey where asked to define the ideal supervisor or supervisor team. Below are some of the comments received from both graduates and students:

- *"Ideal supervisor team would involve a mix of people with both academic skills (report writing, presentations, communication, etc.), and technical skills (DFMA, manufacturing, "hand-on" skills, etc.)."*
- *"I think a closer link with industrial partners would be really useful for more 'real world' expertise… But all individuals mentioned are important in my opinion, and bring different things to the project so make a good combination on a whole."*
- *"My ideal team would probably have academic and technicians available for support throughout the process alongside post-grads, individuals and industrial companies available during different stages where they are relevant"*

4. REFLECTIONS ON APPROACHES TO CAPSTONE SUPERVISON

The findings above confirm that Capstone students do gain some significant learner benefits from a team approach to supervision. To further explore this concept, we now reflect on our evolving approach to Capstone supervision by looking at the individuals involved in more detail.

4.1 Academic Faculty

A core component of the academic faculty role is the creation, supervision and assessment of student projects. Faculty have the appropriate technical expertise, pedagogic training and experience to supervise/assess *research-focussed* projects. Further, the Codes of Practice and quality assurance protocols of most universities require academic faculty to be the primary supervisor/assessor of all student work. Historically, academic faculty have been the sole supervisors of student projects providing scientific expertise; supporting project planning and management; teaching students formal reporting approaches; assessing and providing feedback on student work; and providing encouragement and guidance to students. Whilst Capstone projects might contain some scientific research, they are primarily group design-build-test projects and as such place more complex and varied demands on the supervisor.

CDIO Standard 9: Enhancement of Faculty Competence acknowledges that "*Engineering professors tend to be experts in the research and knowledge base of their respective disciplines, with only limited experience in the practice of engineering …*" Standard 9 also recommends that "*… Faculty needs to enhance its engineering knowledge and skills so that it can provide relevant examples to students and also serve as individual role models of contemporary engineers*". For many years CDIO collaborating schools have been seeking to develop their academic faculty competence in an effort to create the "ideal engineering educator" to supervise Capstones. For many years they have struggled.
Almost all collaborator self-evaluations against the CDIO Standards prove that Standard 9 is the hardest to make progress against.

4.2 Technicians

In our experience, Capstone project briefs designed without any input from technical staff would be more likely to falter as they progress to the Implement-Operate stage due to unrealistic expectations of in-house workshop capabilities. When technicians are involved in designing a Capstone project brief from the start, then more realistic targets can be set for the expected outcomes, ensuring that the scope of the project remains feasible. Having a proper working partnership between technicians and academics at all stages of the design and delivery of student projects is considered essential.

Technicians have a set of skills to offer that most academics do not possess; 90%+ of workshop technicians have vocational qualifications which are traditionally deemed better than university degrees for equipping people with practical engineering skills (Lewis and Gospel 2015). This skill set is invaluable to practical activities such as the ones discussed above: in fact, it could be argued that without knowledgeable technicians, students would struggle to progress their projects through the Implement-Operate phases. In their paper, Thomson and Gommer (2018) acknowledge that technicians *"are key partners in enabling these activities and ensuring successful outcomes for students."*

It is of course essential that technicians are not just involved in the design of Capstone project briefs, but also in the supervision of the projects. To help improve student understanding and project work, our technicians are now more accessible to them and more involved in the delivery and support these projects. Drop in appointments have been arranged, technicians meet with student groups at the start of the project and then meet regularly with them to review designs.

Lewis and Gospel (2015) note that a proportion of technicians are over-qualified and under-utilised; applying their skills and knowledge to a deeper involvement in the design and delivery of teaching could be a way fully realise the potential of this section staff. This reflects a growing sector wide movement to recognise the input of technicians in teaching and to encourage technicians to gain professional teaching qualifications (Bradley 2018).

4.3 Industrial Partners

Industrial partners can offer educational benefits beyond what is offered by academic and technical staff. Hurn (2016) suggests that working with industry on 'live' projects can significantly enhance student experience and improve engagement and performance. Wu (2017) notes that students can experience increased learning outcomes and points out that there is a growing trend in industry for graduates with cross-disciplinary competence and that implementing a CDIO approach to student projects could be the best way to achieve this. Engineering graduates will often be expected to work across disciplines in order to solve complex global problems (Tomkinson et al 2018) and Capstone projects can offer first-hand experience of this. A requirement of the CDIO syllabus (Crawley et al. 2011) is that students are able to work in cross-disciplinary teams and with non-technical members and teams. The UK engineering professional bodies requires that students have an ability to apply and adapt design processes and methodologies to unfamiliar situations (Engineering Council 2014).

As noted in *Section 2.3*, industrial collaboration in our Capstone projects is at one of three levels.

Concept partnerships are well suited to cross-disciplinary projects where the partner may have limited engineering knowledge.
For example, a recent project involved veterinary surgeons form the University of Liverpool Equine Hospital looking for engineering input to improve equipment used for post-surgery recovery. The partners introduced the brief, and helped the students become more familiar with surgical practice. The students gave regular updates to the partners and received feedback on the direction of their work, in the process gaining experience in communicating with non-engineers and translating design intent from non-technical explanations.

Support and Full Collaboration partnerships go further, offering an insight into professional engineering practice; and in providing a tangible demonstration of the link between scientific theory and engineering application. Eckert et al. (2013) note how important it is for the learning process to see theory implemented in practice. They go on to add that students can benefit from; a deeper understanding of company structures and routine, training in how to communicate with industry, and how to promote themselves to potential employers.

4.4 Alumni as Full Collaboration Partners

A new variation of the *Full Collaboration project* has recently started at UoL that could offer further benefits. The project brief was provided by an industrial partner (Siemens Gamesa) as usual, however the supervision team includes three graduate engineers who are alumni of Capstone projects. It was felt that having supervisors with recent experience of University education, in particular themselves having completed a Capstone project, would improve student learning by; empathising with the student project experience; offering accessible role models, wellbeing and life coaching; and employability and career support. The three alumni supervisors and their senior supervisor were interviewed as a group shortly before the start of the project, and then again after six months. Presented below is a summary of the most relevant comments made during interviews.

- It was noted how valuable the graduate supervisors found the opportunity to experience the entire CDIO project life cycle. The design of the project brief took this into account to ensure an achievable end goal that would reach the 'Operate' stage.
- They noted Capstone projects failed to pass on some of the essential soft skills they needed in their first year of employment. They hoped to include in this project more opportunity for the students to develop; project management skills, including specific project management tools; an understanding of the importance of how documentation is developed and implemented; and change management, adaptability and resilience skills.
- Graduate supervisors are currently working on their professional qualification, and are using that experience to enhance their capstone supervision and provide more structured professional development training for the students.
- The senior industry supervisor noted that it could be difficult to switch between supervising professionals and supervising students, sometimes having unrealistic expectations of the students. Having recent graduates on the supervision team helped to calibrate expectations and act as a medium between the needs of the students and the expectations of the professionals.
- It was noted that students had become more professional and organised during presentations and meetings. Students were initially disorganised and found it difficult to keep focus on the project aims but it was felt that it was necessary to allow the students to find their own way of working. Supervisors gradually introduced industry-standard project management concepts and tools which allowed the students to make a clear link between the incorporation of these tools and the improvement in their output.
- Graduate supervisors acknowledged the impact of supervising the project on their own professional development along with an improvement in their level of knowledge. In particular, supervision of this project was helping towards their professional qualification by providing management experience.

5. DEVELOPING BEST PRACTICE IN CAPSTONE SUEPRVISION

We have evidenced that different types of project supervisor can deliver different learning outcomes and benefits to Capstone students. However, to better understand how a team of supervisors could effectively work together to support students it was felt that reflection on current supervisory practice and a review of related literature was needed.

5.1. Reflections on Working Together Effectively

In considering the challenges faced when delivering these complex projects, it was useful to first reconsider what knowledge is and how it is transmitted. Northedge (2003) sets out the argument that viewing teaching as presenting items of knowledge to be internalised can create problems when faced with diverse student needs. Every Capstone project is different, every student is different and when we consider that some of the skills students value the most are teamwork, communication and problem solving, these discrete 'items' of knowledge become even more difficult to define, let alone transmit. Notrhedge goes on to argue that these challenges demand a more fluid concept of teaching which can be found in sociocultural theories of learning.

In light of this, we might then consider viewing the partnerships created between staff, industrial partners and students to work on these projects as a '*community of practice*' (CoP), defined by Wick (2000) as "*professionals that have similar responsibilities and disciplinary backgrounds that work to solve authentic problems*". Johnson (2001) notes communities of practice have roots in constructivism concepts: ill-structured problems that are authentic and complex; real-world problems that engage learners in collaborative group activities; and where leaners gain ownership of the problem through shared goals. The fundamentals of Capstone projects are similarly rooted in constructivism, it could therefore be argued that applying this sociocultural view to supervision is beneficial. Case (2008) advocates the usefulness of using CoPs as a thinking tool in engineering education, noting that it has always been implicitly present. Further adding that taking this line of thinking onboard can help these types of activities become more effective learning experiences, particularly in problem-based learning activities such as Capstones. Beckmann (2016) points out that thinking about teaching and learning in light of CoP is increasingly becoming a preferred strategy. Indeed, current practice within our School has already moved towards a CoP style of supervision, albeit an instinctive move born out of necessity rather than a conscious effort to employ these pedagogic theories.

5.2. Using a CoP Approach as a Tool to Improve Student Learning

Further benefits of operating within a CoP can be found by taking on board Northedge's (2003) perspective that knowledge "*arises out of a process of discoursing, situated within communities"* and that individuals can benefit in participating in this discourse, no matter what their level of understanding is; "*a discourse is a communal knowledge system within which all participants, in the process of participating, extend their repertoire of knowledge."* Each student within the group will have different levels of initial understanding and at the start of a project that level will be at its lowest. The specific terminology of engineering will be little understood by the student and the communication skills required to describe complex ideas and solutions may be limited. By participating in the discourse in a peripheral manner, students can begin to acquire the necessary skills. That is to say that by listening to the manner in which the academic, technician and industrial partner discuss work and the language used to answer students queries, the student's knowledge will increase. As the project progresses, student's knowledge will increase at different rates. However, *"if a course presents compelling flows of richly textured meaning, a wide range of students will be able to participate and will advance from their prior level of discursive skill."* (Northedge 2003).

By acknowledging that knowledge can be transferred as part of the group discourse and by encouraging this way of working, the supervisor can ensure that all students needs are met. This opportunity to participate in a rich CoP can also improve professional practice and employability opportunities. Northedge (2003) gives an example of a student being offered a job because they were able to *"speak the same language as the interviewers."*

5.3. Using a CoP Approach as a Tool to Aid Retention of Skills and Knowledge

This CoP approach can also offer a solution to managing the knowledge that is generated when solving discrete problems within a given project. Even though projects vary widely it is often found that the experience and knowledge gained from working on one project can be transferable to the next project. Knowledge retention becomes more vital for projects that run over a number of cycles and which focus on innovation and iteration. Wick (2000) describes how a social-centred approach to knowledge and the use of collaborative teams can be an ideal way to ensure that knowledge is captured and maintained within a department. This is particularly important in the context of supervising Capstone project; once a project is finished and the students graduate it can be easy for the knowledge and experience gained to leave with the students. If members of staff, particularly technicians who often only have limited interactions with a project, are not properly engaged and connected to the work, the knowledge that is generated can become diffuse and incomplete. By having staff fully engaged and working within a community of practice this knowledge can be retained and transferred again to new students at the formation of a new team. Gherardi and Nicolini (2000) stress the importance of this type of organisational knowledge, the knowledge and experience shared within an organisation is greater than the sum of knowledge held by its individuals. Wenger (2001) also acknowledges the benefits of employing the CoP mindset to knowledge retention, stating that *"Members of a community of practice develop a shared repertoire of resources: experiences, stories, tools, ways of addressing recurring problems – in short a shared practice"*.

5.4. Using a CoP Approach as a Tool to Improve Faculty Competency in Capstone Project Supervision.

In our experience of using a CoP approach, we have noted that working within a CoP could in itself become a form of professional development for staff. For staff new to CDIO principles or problem-based learning, working within a CoP with a more experienced colleague can help them to develop the skills needed to best support this type of learning. This 'training' is crucial to ensuring effective supervision; although using a team approach to teaching brings a net increase to the skills available, all team members should be familiar with supervising Capstone projects to improve the likelihood of successful outcomes. For example, it is common practice at UoL for more experienced staff to support less experienced staff by attending group meetings and presentations. The way feedback and guidance is given by the more experienced offers authentic examples of practice to the less experienced.

Further to this, forming effective CoPs could be a way to improve the overall competence of a department in delivering complex projects. As noted in *Section 4.1,* it is difficult to make progress in this area; the recommendations in Standard 9 can take a significant amount of time to plan, implement and fulfil. The CDIO community has presented papers that address improving faculty competence (for example; Bhadani et al (2017), Cleveland-Innes et al (2017), Marchand et al (2018), P. Papadopoulou et al (2019)) but most often they focus on the development of an individual. This can add to the difficulty in making progress as the onus is on the already time pressured individual to make personal improvements. Whilst it is important that individuals engage in professional development and have the skills to develop activities, learning outcomes and authentic assessments that align to the CDIO fundamentals, this focus can often neglect the wealth of skills and experience already available within an institute or the industrial community.

6. CONCLUDING REMARKS AND FURTHER WORK

We have confirmed our initial assumption that a team of different types of supervisors can be more beneficial than an individual academic faculty supervisor.

On reflection, the authors suggest we take a new approach to Capstone supervision: that we stop trying to create the academic faculty member with the perfect blend of skills & experience, and instead focus on proper partnership between faculty, technical staff and practicing professional engineers in the design and delivery of projects. We assert that such a team-based approach can enhance student learning and allow us to target the full range of required learning outcomes.

The paper also suggests it is time to rethink the traditional route to which faculty competence is improved, shifting away from the notion that an individual has unlimited time to continually develop and master an ever-expanding skill set, and instead focus on how to best cultivate a knowledge community (Northedge 2003) that can effectively utilise the collective skills of all staff.

Further work would explore the development of a well-defined framework, using the findings of this paper as a foundation, that would capture and codify supervisory best practice and enable this practice to be shared between partner institutions.

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REFERENCES

Beckman E.A. (2016), Forums, Fellowship and Wicked Problems in Teaching, In: *McDonlald J., Carter-Steel A., Communities of Practice,* pp 545-565 *Springer, Singapore,*

Bhadani K., Hulthén E., Malmqvist J., Edelbro C., Ryan A., Tanner D., et al, et al (2017). CDIO Course Development for Faculty in Raw Materials Programmes, *Proceedings of the 13th International CDIO Conference*

Bradley S. (2018), Recognising the contribution Technicians make to teaching and supporting students through HEA Fellowships, AdvanceHE, Available at: https://www.advance-he.ac.uk/news-and-views/recognising-contribution-technicians-make-teaching-and-supporting-students-through (Accessed on 10th January 2022)

Brumm T.J., Hanneman L.F. and Mickelson S.K., Assessing and Developing Program Outcomes through Workplace Competencies, *International Journal of Engineering Education*, Vol. 22(1), 2006, pp 123-129.

Case J. (2008), Education Theories on Learning: An Informal Guide for the Engineering Education Scholar, *An Engineering Subject Centre Guide, Higher Education Academy Engineering Subject Centre*

Cleveland-Innes M., Stenbom S., Gauvreau (2017) Technology and teaching in engineering education: A blended course for faculty, *Proceedings of the 13th International CDIO Conference*

Crawley, E., Malmqvist, J., Östlund, S., Brodeur, D., & Edström, K. (2014). Rethinking engineering education - the CDIO approach (Second edition ed.): Springer

Crawley, Edward & Malmqvist, Johan & Lucas, William & Brodeur, Doris. (2011). The CDIO Syllabus v2. 0 An Updated Statement of Goals for Engineering Education.

Eckert G., Hjelmåker M., Elmquist L. (2013), Off Campus Integrating Theory and Practice with Progression, *Proceedings of the 9th International CDIO Conference*

Engineering Council (2014), *The Accreditation of Higher Education Programmes: UK Standard for Professional Engineering Competence (UK-SPEC)*, Engineering Council, Available at https://www.engc.org.uk/ahep (Accessed 10th January 2022)

Gherardi S., Nicolini D. (2000), The Organizational Learning of Safety in Communities of Practice, *Journal of Management Inquiry, 9 (1) pp. 7-18*

Higher Education Statistics Agency (2018), Destination of Leavers from Higher Education, Survey, Available at: https://discoveruni.gov.uk/course-details/10006842/MENG_MEEN/Full-time/ (Accessed 23rd December 2020)

Hurn, K.M. (2016), Joined up Thinking? A Review of the Impact of a Higher Education and Industry Partnership on Undergraduate Product Design Students. *Industry and Higher Education. 2016;30(2):129-139.*

Institution of Mechanical Engineers (2022), Formula Student; Available at https://www.imeche.org/events/formula-student ; (Accessed 10th January 2022)

Johnson C. M. (2001), A survey of current research on online communities of practice, *The Internet and Higher Education, Volume 4, Issue 1, Pages 45-60*,

Lewis P.A., Gospel H. (2015), Technicians under the microscope: the training and skills of university laboratory and engineering workshop technicians, *Journal of Vocational Education & Training, 67:4, 421-441,* DOI: 10.1080/13636820.2015.1076502

Marchand A., Luong G., Vo T. (2018) A Case Study Designing Training Curricula to Support Implementation of CDIO, *Proceedings of the 14th International CDIO Conference*

Northedge A. (2003) Rethinking Teaching in the Context of Diversity, *Teaching in Higher Education, 8:1, 17-32,* DOI: 10.1080/1356251032000052302

Papadopoulou P., Bhadani K., Hulthén E., Malmqvist J., Edström K. (2019). CDIO Faculty Development Course – Built-in Implementation, *Proceedings of the 15th International CDIO Conference*

Paul, R., Hugo, R. J., & Falls, L. C. (2015). International Expectations of Engineering Graduate Attributes. Proceedings of the 11th International CDIO Conference

Thomson G., Gommer L., (2018), The Development of Technical Staff Competencies Via International Exchange, *Proceedings of the 14th International CDIO Conference*

Tomkinson C., Engel C., Tomkinson R. (2009). Dealing with Wicked Global Problems: An Inter-Disciplinary Approach. *Collected Essays on Learning and Teaching*. DOI: 10.22329/celt.v2i0.3199

Wick C. (2000), Knowledge Management and Leadership Opportunities for Technical Communications, *Technical Communication,* Vol. 47, No. 4 (NOVEMBER 2000), pp. 515-529

Wenger E. (2001) Supporting communities of practice: a survey of community-oriented technologies. (pp.3) Available at https://www.teluq.ca/inf6400c/module2/m2txt2_6.pdf (Accessed 13th February 2021)

Wu H. (2017), The Essentiality of Sustainability and Variety for Industry Collaborations with University Partners, *International Journal of Advanced Corporate Learning, Vol. 10, No. 2*

BIOGRAPHICAL INFORMATION

Tony Topping is a Learning Technologist in the School of Engineering and a Master of Arts candidate in Academic Practice, both at the University of Liverpool. He has a technical background, having worked as Teaching and Research Technician for 15 years, where he developed and delivered authentic learning experiences. His current work focuses on blending pedagogic and technical knowledge; and the use of technology to enhance the teaching activities of the school.

Matt Murphy is a Senior Lecturer in Engineering Design and Director of Education at School of Engineering, University of Liverpool, UK. He is a metallurgist by background with a PhD and 10-year technical research career in the additive manufacture (3D printing) of metals. For the last 14 years Matt has worked primarily on learning & teaching and has held several leadership positions in the School of Engineering, with special responsibility for curricular and pedagogic reform. Matt teaches a range of courses in materials science & manufacturing, but most enjoys leading the group design project modules. He establishes and supervises a broad range of student projects in fields such as renewable energy, urban farming, sustainable transport; veterinary healthcare; circular economy; and the local recycling of thermoplastics. In recent years Matt has focused on developing authentic learning and assessment experiences that seek to replicate industrial practice within taught programmes.

Matt has been a CDIO collaborator for 16 years; was co-Chair of the UK & Ireland Region for 6 years; and has been a CDIO Council member-at-large for 5 years.

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