INTERNATIONAL SYMPOSIA FOR
NEXT GENERATION
INFRASTRUCTURE

Next generation doctoral training for future infrastructure and built environment

Niamh Gibbons
Department of Engineering, University of Cambridge, United Kingdom

Janet Lees
Department of Engineering, University of Cambridge, United Kingdom

Abir Al-Tabbaa
Department of Engineering, University of Cambridge, United Kingdom

Abstract

Urbanisation, population growth, scarcity of resources, climatic change, rapid technological development, and the globalisation of both construction and engineering design are driving the pace of change within the construction industry. There is a clear need for engineering education to evolve alongside these changes. Specific challenges facing the construction industry include the delivery of large complex construction projects, creating complex underground spaces and the ramifications of extreme environments. At a doctoral level, there is a need to provide training that reflects both modern research practice, facilitating multi-disciplinary and industry collaborations, and the need for industry leadership in order to drive innovation and entrepreneurship. There is also a shortage in skills to address the complex and multi-sector challenges facing future construction.

We have been advocating a new philosophy for training doctoral students which will deliver the next generation of PhD graduates who are equipped with the deep technical skills needed to address future challenges in Engineering, but who will also become future leaders capable of thinking outside current norms and with a strong sense of social responsibility. To achieve this aim, a new MRes/PhD programme was established. From the outset, one striking feature has been the range of disciplines outside of civil engineering that the students on the programme come from including architecture, town planning, applied mathematics and physics, information and computer engineering, manufacturing engineering, mechanical engineering, and materials science. This has introduced challenges in terms of ensuring that a sound civil engineering technical basis is established across the cohort during the MRes year. However, it has greatly enriched the diversity of the cohort and promoted the importance of the role of multiple disciplines to successfully address 21st century engineering challenges in new and innovative ways.

This paper discusses and reflects upon the achievements to date, the pedagogical and structural approaches taken, the practicalities of implementing this vision and shares the lessons learnt to date. Selected contributions to doctoral training are highlighted through a series of case studies in the context of the development of a T-shaped skill set, providing breadth of knowledge with depth of specialist expertise, and the delivery of multi-disciplinary research with significant industry engagement. The case studies illustrate how these aims have been implemented through project work, focusing on multi-disciplinary aspects of large infrastructure projects and commercial feasibility of nascent technologies.

Key Words

engineering education, doctoral training, industry-academia collaboration, multi-disciplinary engineering

1 Introduction

The PhD was first introduced to Britain in 1917[1]. One hundred years on, what has changed? This paper gives an overview of a programme for doctoral training at the University of Cambridge, currently in its early stages, for graduate students in Infrastructure and the Built Environment. The programme was set up as an Engineering and Physical Sciences Research Council (EPSRC) funded Centre for Doctoral Training in Future Infrastructure and Built Environment (FIBE CDT) in 2014 and, at present, is in its third year of student intake.

The aim of the FIBE CDT is to develop world-class, technically excellent, multi-disciplinary engineers equipped to face current and future infrastructure and built environment challenges. The approach taken to achieving this aim has involved a significant shift away from the traditional model of doctoral-level education, focusing primarily on research skills outcomes and a contribution to knowledge as embodied by a thesis, towards the development and training of engineers with "T-shaped knowledge". The concept of the T-shaped skill set, as illustrated in Figure 1, is a core element of the FIBE CDT model and combines a breadth of knowledge, encompassing personal skills, professional practice and commercial appreciation, with specialist training set out in the context of civil and other engineering disciplines and further cognate fields.

As highlighted by Park[2], who identifies a number of key policy documents which called for increased provision of research skills training in the UK since the mid-1990s[3], [4], [5], a focus on skills and training at doctoral level is not new; however, there is at present a pressing need to integrate research with industrial application. The UK Government's announcement of the Industrial Strategy Challenge Fund earlier this year[6], [7] sets out a clear objective to place research and innovation at the centre of the Government's Industrial Strategy and "aims to bring together the UK's world leading research with business to meet the major industrial and societal challenges of our time".

This sets out a need for training that integrates research and industry, which supports the above strategy and the associated investment. In addition to the provision of both technical and transferable skills training to support the development of researcher skills, key aspects of the CDT philosophy, illustrated in Figure 2,

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[1] Simpson R. *The development of the PhD degree in Britain, 1917-1959 and since: An evolutionary and statistical history in higher education*. (Lampeter, Edwin Mellen Press, 2009).

[2] Park C. New variant PhD: The changing nature of the doctorate in the UK. *Journal of Higher Education Policy and Management*. **27(2)**, 189-207 (2005).

[3] Dearing R. *The national committee of inquiry into higher education: Higher education in the learning society*. (National Committee of Inquiry into Higher Education, Leeds, 1997).

[4] Harris M. *Review of postgraduate education.* (Higher Educational Funding Council for England, Bristol, 1996).

[5] Roberts G.G. *SET for success: the supply of people with science, technology, engineering and mathematics skills.* (HM Treasury, London, 2002).

[6] HM Government. *Building Our Industrial Strategy, Green Paper*. (HM Government, London, 2017).

[7] Department for Business, Energy and Industrial Strategy. *Business Secretary announces Industrial Strategy Challenge Fund investments, press release 21 April.* (Department for Business, Energy and Industrial Strategy, London, 2017).

are to integrate industry needs directly with research via the co-creation of PhD research projects, and, crucially, through the involvement of industry in the training, project work, and seminars delivered as part of the programme.

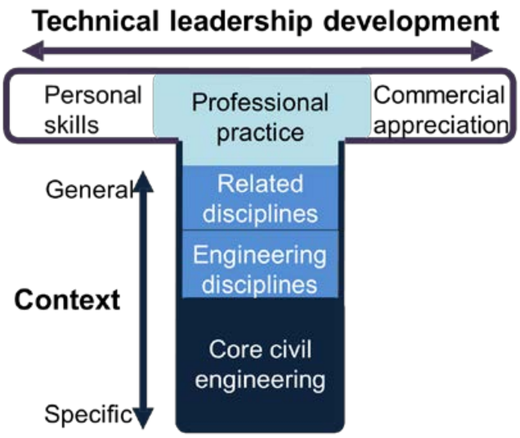

Figure 1: T-shaped skill set.

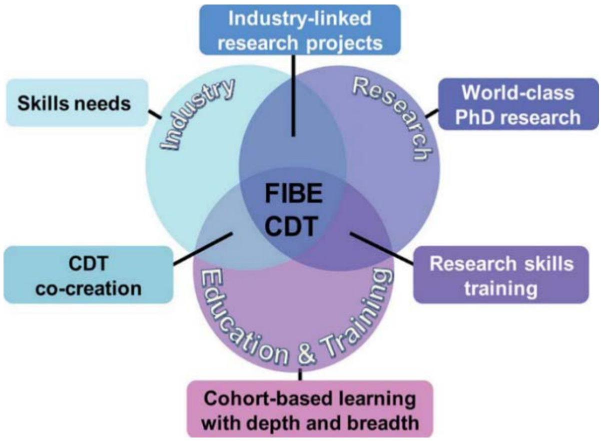

Figure 2: Philosophy of programme.

2 Pedagogical and structural approach

The programme is structured as a one year MRes followed by a three year PhD. A broad cohort-based MRes education undertaken the first year covers core civil engineering topics, specialised modules, and research and commercial skills training. The subsequent 3 year PhD training embraces a diverse range of topics grouped around nine core research themes including: future energy infrastructure; construction design and technology; innovative construction materials and waste minimisation; infrastructure resilience against natural hazards; asset management, transportation infrastructure and building environment; sustainability and urbanisation, risk and resilience in infrastructure; building physics; water and waste; and digital applications.

The MRes year is divided into three components consisting of a taught component, a project work component and a research component. The taught component consists of four core modules covering civil engineering theory, civil engineering research methods, multidisciplinarity in civil engineering, and transferable skills training. The taught component also includes elective modules, which are selected from a wide range of multiple disciplines to either support or explore the research interests of individual students. The project work component consists of a desktop study, a mini-project and an emerging technology (ETECH) project. The research component consists of a master's level research project. An additional aspect of the FIBE MRes research project is that it is intricately linked to a PhD proposal. This involves significant student-led input into scoping and defining the research project and the MRes project proposal is carved out of and defined relative to a preliminary PhD proposal. A one page PhD proposal, in which the objectives of the MRes project are outlined, is submitted at the outset of the MRes research project. Then, in parallel with the MRes research, a more detailed PhD proposal is developed and submitted alongside the MRes thesis.

Cohort-based training is central to the ethos of the programme and is implemented through cohort-led study tours, peer-to-peer learning, the development of entrepreneurial solutions to industry-led challenges, group project work and student-led outreach, with the aim of inculcating a sense of collaboration and cohort identity within a societal and construction industry framework.

3 Academic background of the students

When the programme was initially established, it was envisaged that applicants would be primarily from a civil engineering background. However, the programme has attracted a much greater number of applicants from cognate disciplines than anticipated at the outset. Nearly a third (31%) of current students are from cognate disciplines including architecture, town planning, applied mathematics and physics, information and computer engineering, manufacturing engineering, mechanical engineering, and materials science. In addition to the above, students for next year's cohort have also been recruited from construction and project management, aerospace and aerothermal engineering, design engineering, and energy technologies. Amongst the students who have a civil engineering background, just over a quarter (28%) have either undertaken further study, conducted research or gained professional experience in fields including nuclear engineering, oil and gas, biomedical engineering, finance, and sustainable development.

The mix of experience and background is clearly in line with the research themes and multi-disciplinary ethos of the programme; however, this has had implications for the course design. The need to balance the interests and development of such a mixed cohort has been most notable in the core Civil Engineering Theory module, which aims to provide a graduate-level integration of the relevant fundamental principles of structures, dynamics and geotechnical engineering, focussing on the contributions to Civil Engineering that have been made from within the Department of Engineering at the University of Cambridge. This provides the benefit of utilizing the Department's existing expertise; however, even for students from a civil engineering background, this adds an additional difficulty in balancing the level of interest of the students, as graduates of the home institution have had greater familiarity with the preliminaries of the material covered.

The approach taken to balancing these disparities has been to tailor both the coursework and assessment to the background of each student (such an approach is, however, clearly dependant on small cohort numbers, the largest of which to date has been twelve). A portfolio-style approach has been taken to the coursework and assessment incorporates a viva voce examination with multiple academics. This serves two purposes: it better facilitates assessment of individual progression from a highly varying baseline and it assists in transitioning away from manuscript-based assessment, more typical at undergraduate level, towards more interactive presentation and interview-based assessment methods used to assess graduate level research, prior to conducting a significant piece of research.

4 Case studies

The overarching goal of the programme is to train engineering leaders and deliver industry relevant research within a multidisciplinary context. In order to achieve this, the following expected skills and outcomes at the end of the MRes course have been prioritised in the design and delivery of the course: a basic grounding in civil engineering; an improved technical background in an area of interest; exposure to current research activities; graduate-level research and communication skills; development of independence and creativity; an ability to proactively scope and progress a project; an ability and willingness to engage outside partners; and the development of a research culture and habit of mind.

The following case studies are provided to illustrate how these aims are implemented through the project work in particular, focusing variously on: the direct immediate needs of industry, the future challenges of delivering large multi-disciplinary infrastructure projects, and the entrepreneurial considerations for brining nascent technologies to market.

4.1 Case study 1: Desktop study on grouted anchors

The desktop study is the first item of project work undertaken in the MRes year and serves as an introductory individual project of limited scope, proposed by and undertaken in partnership with an industry partner and undertaken over a six week period. The desktop studies are proposed by industry partners on the basis of their own current needs and they serve as preliminary exploratory studies which give an overview of the existing state of affairs or state-of-the-art, provide some preliminary analysis and give a view of avenues for further exploration. Depending on the individual project, meetings, office visits or site visits with the industry partner are used to progress the project, and industry partners are then invited to an interim presentation session (Figure 3) in order to provide feedback to be incorporated into a final report. The training and development aims are to work collaboratively with an industry partner, gain an industry perspective on an area requiring further research, identify practical or implementable findings, and to conduct a literature review which includes industry-focused documents. Topics which have featured heavily to date have included projects in the areas of sustainable urban drainage and flood risk, the implementation of building information modelling, the impact of autonomous vehicles, timber construction, asset management for a range of infrastructure, and prefabricated design.

In 2015, the relevant British code of practice for grouted anchors, BS 8081[8], was revised in order to align with the Eurocodes. The Construction Industry Research and Information Association (CIRIA) saw this as a timely opportunity to review current methods of inspection, monitoring, testing and maintenance of grouted anchors and to produce a good practice guidance document for the industry. As a member of CIRIA, Mott MacDonald, an engineering consultancy and industry partner with the FIBE CDT, were involved in a proposal to incorporate guidelines on condition monitoring and assessment processes that can be used for the classification of grouted anchors in service, as well as the risk strategies to be adopted as part of their sustainable maintenance and management[9]. Mott MacDonald put forward a desktop study project to support the development of the CIRIA proposal. The desktop study aimed to identify the changes between the 1989 and 2015 editions of BS 8081 in relation to anchor maintenance and to understand

[8] British Standards Institution. *BS 8081:2015, Code of practice for grouted anchors*. (British Standards Institution, 2015).

[9] Construction Industry Research and Information Association. *CIRIA proposal: P2618 Grouted (Ground) Anchors - condition appraisal and remedial treatment.* (Construction Industry Research and Information Association, London, 2015).

current maintenance practice in the UK through stakeholder interviews, with a view to formulating more detailed guidelines on anchor maintenance.

As part of the desktop study, a survey of 17 UK projects undertaken by 8 major companies was undertaken in order to document current practice and identify areas to focus on for both procurement of new anchors and management of existing anchors (Figure 4). The survey identified significant variation between projects due to emphasis on "mission criticality" in maintenance decisions; fragmentation of maintenance regimes due to reliance on other standards; contract arrangements which give responsibility to client, but for which specialist contractors are better suited; the rediscovery of old anchors which are subsequently added to maintenance plans; and that standardisation is desired by most stakeholders. The main conclusions of the report were that there should be a portfolio of standard anchor maintenance plans, allowing each project team to choose a different plan depending on the mission criticality of its anchors; the procurement model of anchors should shift towards an arrangement that assigns long-term maintenance responsibilities to the specialist contractor rather than the client; and that the focus of maintenance activity should move away from load testing and towards anchor head protection and accurate record-keeping. The desktop study project was highly successful in working directly alongside industry to identify the current state-of-the-art and identifying implementable findings and recommendations for future work and the outcomes of the study were reported by CIRIA and circulated to its members[10].

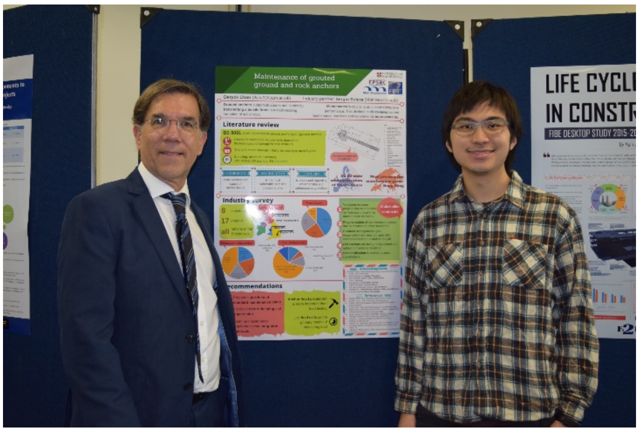

Figure 3: Desktop study presentation to industry partners, image courtesy of Paula Block.

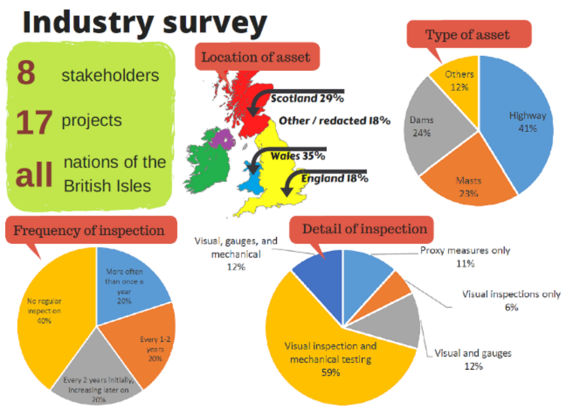

Figure 4: Summary of results of industry survey for desktop study on grouted anchors[10].

4.2 Case study 2: The evolution of the FIBE CDT mini-project

The mini-project examines a major infrastructure project from a number of different perspectives, in order to develop a multi-disciplinary view of the overall project and to consider how non-design factors (e.g. politics, markets, environment, public perception, economics, planning, policy, strategy and contracts) impact project decisions. The development and scoping of the project is student-led and much more

[10] Chan, D. & Solera, S. Maintenance of grouted ground and rock anchors. Desktop Study Report, University of Cambridge (2016).

involved than the desktop study and is a key aspect of the training and development aims. However, this has developed somewhat over the first three years of the course, and its evolution is discussed below.

In the first year, an overall project theme was allocated to the cohort for the mini-project, examining a major mixed development site in northwest Cambridge. This was then developed into individual sub-projects examining provision of social infrastructure and its role in accommodating the needs of different population; social, environmental and functional requirements; network analysis of urban patterns; assisted waste collection; the utilisation of roof space; sustainability frameworks for environmental impact assessment; and selection of structural building materials.

In the second year, the cohort requested greater autonomy in selecting the overarching infrastructure project to be studied and a project on the Swansea Bay Tidal Lagoon was democratically chosen from a number of cohort-generated proposals. As the cohort had selected a highly topical project, they were also able to attend a public debate on the project, which assisted them in developing contacts with industry to support their project which they used to host a workshop and seminar (Figure 5) to help scope and define the sub-projects that they would investigate individually including a comparison of tidal with other renewables, the potential for tidal lagoon power across the UK, identification of community priorities for Swansea Lagoon via analysis of public consultation submissions, drainage and landscape design, environment impact assessment, coastal processes and sedimentation, and factors influencing turbine selection. At the time the cohort had completed their mini-project report, a call for evidence for an independent review of tidal lagoons[11] was open to which they submitted their report.

The student-led approach for identifying a mini-project developed a very strong sense of ownership and pride in the project, which assisted the project greatly when obstacles were encountered, for example in obtaining suitable data for a currently proposed project. The student-led approach was then further developed in the third year, mimicking to a certain extent a preliminary tender design competition. A longer lead time for the project was introduced, and at the very outset of the year, the cohort developed and presented preliminary project proposals to industry partners at a mini-project scoping workshop, in order to help identify areas of particular interest within the project, identify points of contacts within the industry partner organisations, receive recommendations for literature or identify sources of data, and hear directly from the organisations involved what major constraints and considerations have had an impact on the project development. Following on from this workshop, projects were selected for further development, conducted as a team exercise, with the presentation and submission of a group project proposal consisting of inter-related individual sub-projects. As there are twelve students in cohort three, it was felt that the group size might be too large to ensure individual and group engagement across a mini-project with twelve different sub-projects. Therefore two mini-projects were taken forward.

The first project was on the proposed Lower Thames Crossing, a multi-disciplinary infrastructure project directly in line with the stated aims of the mini-project. The second mini-project departed somewhat from the prescribed approach and investigated a multi-disciplinary infrastructure theme as opposed to an infrastructure project, examining aspects of the future of nuclear power in the UK including the strike price

[11] Hendry, C. *The Role of Tidal Lagoons. Final Report*. (Department for Business, Energy and Industrial Strategy, London, 2017).

(Figure 6), build costs of nuclear in the UK, the siting of small modular reactors, health and safety, nuclear waste management and the structural design of nuclear power plants. The individual sub-projects were then developed with the support of both individual meetings and group workshops with industry, prior to compilation of a joint report. Both types of project, a multi-disciplinary infrastructure project and a multi-disciplinary infrastructure theme, were very successful in terms of industry feedback and in terms of meeting the training aims of developing, scoping and progressing a project with an external partner. As a result the newly trialled approaches of developing the project with industry at a mini-project scoping workshop and the possibility of taking on a multi-disciplinary infrastructure theme will also be continued in future. The current structure for the project focuses strongly on team work in the early scoping stages of the project, prior to conducting research for the individual sub-projects which is carried independently. The final stage of the project, where students compile their joint report, is intended to return to the team work format, but it is evident that in the absence of specifically allocated project time and support in advance of the project deadline, that this activity becomes neglected. This is an area that requires some further refinement and will be the focus of structured development in future years.

Figure 5: 'Swansea Bay Tidal Lagoon' mini-project workshop, image courtesy of Paula Block.

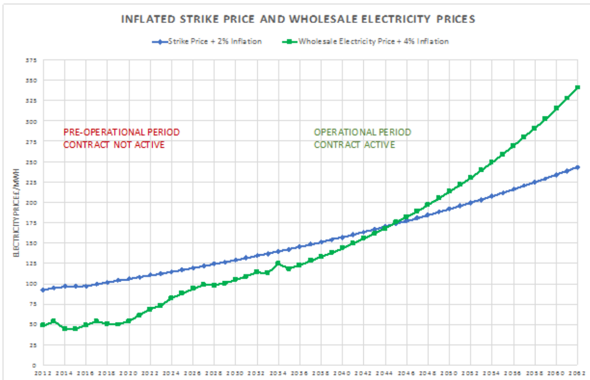

Figure 6: Comparison of electricity prices based on varying inflation estimates[12].

4.3 Case study 3: Emerging technology (ETECH) project on Smart Roads

The FIBE CDT emerging technology (ETECH) project is a group project which runs over an 8 week period for which a market feasibility study is conducted for a real-world nascent technology that is market- or near-market-ready. The ETECH project is run by the Judge Business School at the University of Cambridge and is supported by an intensive week long "Introduction to Entrepreneurship" module. The project is intended to provide the students with an understanding of the entrepreneurship, the commercialisation process, opportunity recognition, intellectual property, market and industry assessment, routes to market, technology-centred business models, selling an idea/pitching to investors, and team building (including a day of simulation on how a startup works). The technologies considered for the FIBE CDT ETECH projects are ones which have either been proposed by FIBE CDT industry partners or have their origins in research

[12] Fryer, B. Is the strike price for the Hinkley Point C Contract for Difference justifiable? Mini-project Report, University of Cambridge (2016).

spin-outs at the University of Cambridge and a major aspect of the project is to gain the practical experience of evaluating a real opportunity.

In 2014-2015, the concept of a "Route to Smart Roads" by was proposed by Costain, to involve a potential link-up of Costain with Vodafone and IBM. It assessed the feasibility of introducing Radio Frequency Identification technology on the road network to improve traffic management and road safety through vehicle-to-vehicle communication and vehicle communication with the Cloud (Figure 7).

The cohort's final recommendation, presented to Costain (Figure 8), was to form a spin-off company in partnership with IBM and Vodafone, in which Costain had an equity stake. It was recommended that initially the technology should be introduced in a closed-loop, e.g. airports, and then rolled out to the UK road network. The conclusions were made through primary and secondary research which assessed the technology, stakeholders, acceptability of the technology, business model, financial projections, and the risks to the project.

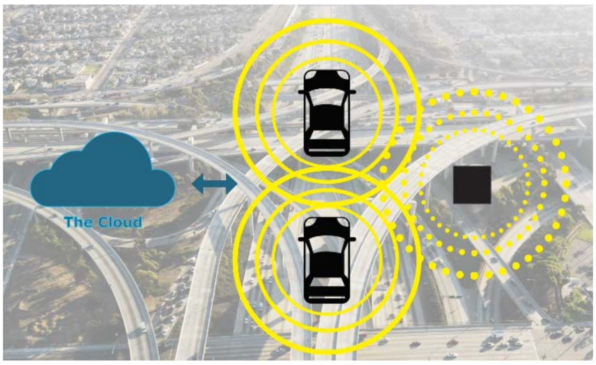

Figure 7: Visualisation of smart roads technology[13].

Figure 8: ETECH project presentation to industry partner Costain for market feasibility study of smart roads.

The project highlighted a potential multi-million-pound business opportunity, and at the conclusion of the project, Costain used the final report[13] as supporting evidence submitted to the board of directors as a valid reason to purchase a company, which would enable Costain to take part in this new market. The board decided in favour of the acquisition in July 2016 of Secure Sockets Layer (SSL), specialists in the development of traffic monitoring technology such as speed cameras and tunnel control systems. The project was also showcased in a recent EPSRC document[14] highlighting how centres for doctoral training are building leadership and skills.

5 Discussion and conclusions

A cohort-based approach has been central to the success of much of the project work and course work, and a cohort mentality is cultivated through a number of supporting activities undertaken throughout the

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[13] Baker, H. *et al.* Smart Roads / Vehicles: RFID sensors and tags. Emerging Technology Report, University of Cambridge (2015).

[14] Engineering and Physical Sciences Research Council. *Building skills for a prosperous nation: EPSRC Centres for Doctoral Training* (Engineering and Physical Sciences Research Council, Swindon, 2017).

programme, including group study tours and site visits, peer-to-peer learning (in which each student teaches the cohort about an area within their own expertise), outreach activities, student-led organisation of workshops and seminars, inter-cohort events and indeed social activities.

Co-creation of research with industry is another key component of the programme, and the professional networks and ideas generated in the project work, have a strong influence on the direction and involvement in subsequent research interests and projects respectively. The development and management of research projects within the programme builds on this and has also taken a more novel approach, although this not discussed in detail here, but has included: an I+ scheme with a year in industry prior to commencing the MRes year; industry-academia road-mapping of research themes; academic co-supervision arrangements across multiple disciplines; and an open "club" based approach to collaboration and secondment with industry.

Furthermore, the landscape for training and supporting doctoral students is also developing outside of the university environment. To date, there have been four FIBE CDT students who have undertaken a year in industry with an industry partner as part of the I+ programme. Two students undertook a year in industry with Laing O'Rourke on a dedicated research and development project[15] in a sequential programme, with the work of one student being carried forward by the next. A further two students worked with Costain, who support doctoral training of their employees through a range of MRes+PhD, PhD and EngD programmes. As a result, Costain have developed their own internal cohort-based programme to support and integrate this broad range of doctoral students who sit across a variety sectors within their organisation. The support provided in relation to the doctoral training programme has been unique to each organisation and would provide an interesting area for further study in itself.

The case studies presented above highlight some examples of how the FIBE CDT ethos and philosophy is implemented pedagogically in the programme and how the research undertaken is influencing industrial applications. The project work is intended to serve as a platform to develop skills beyond typical research training in order to foster independence and creativity and develop leadership and team-working skills for the delivery of successful projects requiring multi-disciplinary skills and engagement with numerous partners. However, as illustrated by the second case study on the mini-project, it has been and will continue to be an evolutionary process.

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[15] Edwards, H., Locke, A., Jackson, A. Manufacturing power stations. *Ingenia*. **69**, 31-34 (2016).