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# **Crossing Boundaries between Science and Innovation – Career Mobility and Impacts of Graduates of the UK Industrial Doctoral Centers (IDCs)**

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## **Abstract**

The mobility of individuals represents a crucial mechanism through which knowledge flows across organisations, in the labour market and between places. There has been an increasing policy attention to the mobility of scientific researchers at various stages of their careers, especially for doctoral students and doctoral graduates in bridging the gaps between science and innovation closer. This paper focuses on one of the collaborative doctoral training schemes between academia and industry – a case of the Engineering Doctorate (EngD) scheme in the UK as a distinct model from the traditional PhD. The paper presents the mobility of EngD graduates based on the illustrative case studies of three Industry Doctorate Centres (IDCs) for the period between 2001 and 2014. The EngD graduates' career paths and mobility suggests knowledge dissemination and exploitation with diverse spatial implication – the talents are collocated in specific industry locations with local, national and international knowledge flows, skills, R&D and innovation activities.

## **Key words**

Collaborative doctorates; university-industry relationships; cross-border mobility; knowledge exchange; human capital

# **Crossing Boundaries between Science and Innovation – Career Mobility and Impacts of the Graduates of the UK Industrial Doctoral Centers (IDCs)**

## **1. Introduction**

It is argued that doctoral students provide a large scientific input into creating the competitive advantage in R&D with potential long term consequences on economic growth (see Stephan et al., 2004). The recruitment of doctoral graduates and/or placement of doctoral students during their studies represent one type of knowledge flows through people mobility (e.g. Cruz-Castro and Sanz-Menéndez, 2005; Herrera and Nieto, 2013). The mobility of individuals represents a crucial mechanism through which knowledge flows across organisations (Dietz and Bozeman, 2005; Bozeman and Mangematin, 2004), in the labour market (Crespi et al. 2007; Mason and Nohara, 2010; Lawton Smith and Water, 2011). In particular, doctoral students and doctoral graduates who are highly trained skilled researchers may help industry in reducing uncertainties in innovative activities and raising “absorptive capacity” by acquiring, assimilating, transforming and exploiting external knowledge (Zahra and George, 2002).

However, the mechanisms through which such flows and transformation of knowledge occurs are not well understood. This paper aims to fill this gap in existing knowledge by looking at the career mobility of individuals as a mechanism of dynamics between science and innovation. The mobility in the form of career trajectories of doctoral graduates reflects the nature of scientific labour markets, the transition of researcher into the world of work, and the nature of training within the university system. By examining micro-dynamics of the EngD doctoral graduates’ career trajectories and mobility, the paper aims to provide a better understanding of the relationships between skills formation, innovation and the dynamics of knowledge flows across organizational boundaries. Theoretically, the paper contributes to the development of micro-level understanding of the institutional processes (Powell and Colyvas, 2008).

Empirically, this paper investigates the nature and the impact of the mobility through one of the collaborative doctoral training schemes between academia and industry – with a case of the Engineering Doctorate (EngD) scheme in the UK – as a model of an industrial collaborative doctoral scheme distinguished from that of the conventional academic PhD programmes. The mobility of individuals trained through the doctoral programmes would illustrate interactions between “research and various forms of social practice” (Benner and Sandstrom, 2000, p. 294) between industry and academia. In this light, this paper identifies organisational forms, mechanisms of skills

development and human capital formation. Such knowledge would provide an important insight for policy and institutional practices as well as guide individuals in selecting and building new “competencies in a scientific career” (Rip, 2004, p.157) in a specific system of “competence building and innovation” (Lam and Lundvall, 2006).

The rest of the paper is structured in the following way. After this introduction, the Second section provides a review on the literature on collaborative doctoral schemes encompassing the spheres of industry and academia, and the roles of public policy in building collaborative relationships and mobility across organisational boundaries. The Third section introduces the Engineering Doctoral (EngD) scheme as a case of collaborative doctorate research training, illustrating the policy contexts in the UK. The Fourth and Fifth discuss and the methodological approaches adopted and findings from illustrative case studies of three Industry Doctorate Centres (IDCs). The paper highlights differences in career pathways and a variety of mobility patterns from different centres, as distinct routes to the impact from the collaborative doctoral research centres. It concludes with implications for further studies and stakeholder communities.

## **2. Collaborative Doctoral training – Review of literature and research agendas**

There are contested views about the models of doctoral training - some of the recent studies emphasize the diversity and flexibility of the existing PhD structures that respond to diverse career trajectories and emerging demands, whilst other scholars argue that new “hybrid models” of research training are needed with distinctive degree structures that cross disciplinary and organizational boundaries (see Enders, 2005). Models of “specialized industrial PhD programmes” (Thune, 2010) or “collaborative doctoral programmes” (Borrell-Damian 2009) seem to have been created in different national contexts to explicitly promote such hybrid models as public policy tools.

Collaborative doctoral training typically involves research supervision by both academic and industry supervisors (Borrell-Damian, 2009). There are different approaches to “collaborative doctoral programmes” including initiatives from industry (e.g. large firms, R&D intensive SMEs), university-led initiatives, and structured public-private partnerships supported by governments (Thune, 2010). These schemes have taken different shapes in different national contexts with variety of outcomes (see Borrell-Damian, 2009), depending on policy objectives and historical institutional forms and structures. Industry organizations that participate in collaborative R&D relationships through doctoral training are important stakeholders that influence the nature of the projects and the programmes, as well as the impacts of such collaboration.

In previous studies conducted on the collaborative doctoral training, several characteristics of the collaborations, such as “firm characteristics, type of organization,

resource exchange and routines developed during the course of collaboration”, have been investigated and found to have an impact on students’ interaction experiences (Thune, 2010; Butcher and Jeffrey, 2007). These organizational characteristics need to be investigated further in light of the nature of the collaborative R&D projects including technology trajectories, market readiness and industry maturities, within the industry sector characteristics.

Collaboration between academia and industry are also conditioned by the nature and perceived “quality” of research, influencing firms’ choice of research collaboration partners (Perkmann et al., 2011). The industry’s perception of the geographic distance and choice of academic partners for the specificity of industry projects need further investigation (see Laursen et al., 2010). The availability of new doctoral graduates and post-doctoral researchers from local universities may also have an effect on firms’ choices – for example, “local availability of skilled and talented problem-solvers may induce higher rates of industry exploitation of university research for their innovative activities” (Laursen et al., 2010, p.520).

Doctoral research students who work in such collaborative relationships play “boundary spanning” roles (Aldrich and Herker, 1977) across organizational boundaries. In other words, through the collaboration between academia and industry, these students act as “bridging scientists” (Subramanian et al, 2013) who mediate between the two systems of knowledge production, balancing between the different expectations and governance mechanisms associated with “open science” versus “proprietary science” (Dasgupta and David, 1994). In light of the existing literature on collaborative doctorates reviewed above, this paper asks the following question –in what ways do the collaborative doctoral programmes influence the cross-border mobility of individuals, knowledge flows and industry impacts?

### **3. Policy and institutional contexts of collaborative doctoral schemes in the UK**

Different forms of collaborative doctoral schemes have been developed over the last two decades as part of the national innovation and S&T policy objectives as well as research and higher education policies (Kitagawa, 2014). In the UK, in the fields of engineering and physical sciences, several distinctive types of collaborative industrial doctoral schemes were established in early 1990s and have co-existed with different funding streams and objectives. For example, the Engineering and Physical Sciences Research Council (EPSRC) have funded the Engineering Doctorate (EngD) and Industrial CASE studentships, both of which have significant industry collaboration through doctoral training (see Demeritte and Lees, 2005; Butcher and Jeffrey, 2007).

The EngD scheme was created in 1992 designed as a unique four-year full-time engineering doctoral programme for those who want a career in industry. The scheme

has been supported through a series of funding from the EPSRC. The EngD scheme has evolved over the past twenty years as part of the national research system, but the core nature of the scheme remains: the EngD is seen as work-based research degree, an alternative to traditional PhD, at least “equivalent to the intellectual challenge of a PhD” (EPSRC, 2011, pp. 3–4).

The Industrial CASE scheme provides funding for “industrially relevant PhD studentships that are jointly supervised by the academic and industrial partners” where “businesses take the lead in arranging projects with an academic partner of their choice” (EPSRC, 2013). The Industry CASE students need to spend at least 3 months of their 3.5 year project working in a non-academic setting with the collaborating organization. The time spent within industry is significantly shorter in the case of the Industry CASE than that of the EngD. In this paper, the primary focus is on the EngD scheme but the Industrial CASE scheme is referenced as appropriate. The main purpose of the analysis in this paper is not to compare these two schemes, but to illustrate various contexts of impacts related to the doctoral programmes with varying forms of industry collaboration.

The EngD students are called research engineers (RE), who work on the research project based on industry relevant problems. The doctoral students are supervised by both academic and industrial supervisors and spend most of their time (around 75% during their programme – about three years) within the industry sponsor (EPSRC, 2011, p. 4). The EngD programmes also provide taught provisions both in business and management areas, and technical fields. The EngD programmes were provided at the EngD Centres. The initial five EngD Centres were created in 1992 and 1993 at the following universities: Warwick, University of Manchester Institute of Science and Technology (UMIST), Swansea/Cardiff, Cranfield and the Surrey/Brunel consortium.

In 2009, the major change was brought to the EngD Scheme when 19 new Industrial Doctorate Centres (IDCs) were created as “an evolution” of the EngD scheme (EPSRC, 2011)<sup>1</sup>, expanding the scope of the EngD scheme. The aim of the IDC scheme is to provide postgraduate engineers with “an intensive, broadly based, research programme incorporating a taught component, relevant to the needs of, and undertaken

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<sup>1</sup> “...in 2009 EPSRC decided to both expand the scope of the previous EngD scheme (to cover the entire remit of EPSRC) and to seek to refresh the portfolio of Centres being supported (to allow new priority areas to be identified and supported - in energy for example). Thus, the cohort of 19 IDCs represents a mixture of new Centres and continuations (albeit in an evolved form) of a number of EngD Centres”.

<http://www.epsrc.ac.uk/skills/students/coll/idc/> accessed 15/09/14; In 2011, five IDCs were funded all focused around manufacturing themes.

through, sponsorship with industry” (EPSRC, 2011). The IDCs are described as “user-oriented centres” that provide the same training environment and features as the new Centres for Doctorate Training (CDTs) where PhD students are trained, whilst IDCs are also incorporating a strong industrial focus at both firm and sector levels.

In the autumn of 2012, the new call for funding for Centres for Doctoral Training (CDTs) was open, with a strong expectation about the “user engagement” in doctoral training, and the IDC scheme was integrated as part of the CDT call in 2013 (EPSRC 2013). The EPSRC acknowledges that the key features of the current doctoral training centres originate from the previous EngD Centres (EPSRC, 2013).

As a result of changes in the scheme and series of rounds of funding with different priority areas, the institutional landscapes of EngD Centres/IDCs have become rather complex. Only one EngD Centre created in 1993 still exists as the IDC as of 2014. Six of the EngD Centres created in 1999 and 2001 still exist as IDCs. The EngD scheme has evolved over the past twenty years as part of the national research system. The core nature of the EngD/IDC scheme has remained: proportion of time spent in industry and engagement from industry sponsors differentiates the EngD scheme from other collaborative doctoral schemes such as Industrial CASE PhD scheme or other collaborative industry placement as part of the PhD.

#### **4. Research Methodology**

This study originates from a pilot evaluative study designed and conducted in 2013 in collaboration with the Association of the Engineering Doctorates (AEngD) and the EPSRC in order to develop a conceptual framework and identify methodological approaches that help capture the impact of the EngD scheme (see Kitagawa, 2015). Building on the pilot study, methodologically this study adopts mixed qualitative approaches.

The choice of mixed qualitative methods is justified based on the following reasons. Firstly, interactive and collaborative relationships and mechanisms of knowledge flows between academia and industry cannot be easily captured by quantitative economic impact analysis. This would require contextual understanding of interactive processes between actors and the mobility of researchers. Secondly, in terms of human capital development based on the EngD graduate career pathways, mobility and destinations, there are constraints in the availability and comparability of existing quantitative data. The changes of the scheme itself and the centres funded under the EngD scheme over the past 20 years have constrained the consistency of the graduates data across centres over time. This has constrained the understanding of the patterns of mobility of graduates. Therefore, this study aimed to build on a small scale of both qualitative and quantitative data made available in the pilot study, by collecting

additional data sets in order to gain contextualized understanding on the micro-dynamics of individual career trajectories and mobility.

Data sources for the initial pilot study included mid-term self-evaluative documents provided by 18 IDCs funded under the call in 2009 (submitted to EPSRC as of May 2011). Semi-structured interviews were conducted with 35 individuals who have direct experiences of the EngD programmes, including 20 EngD alumni and 15 industry partners. Whilst the data-sets collected in the interviews were relatively small, efforts were made to include the diversity of the contexts to be represented in the study – industry sectors and different types of IDCs across the UK. Firm interviewees included Head of academic liaison, Head of Technology and those who have supervised EngD project as industry supervisors, those who manage collaboration with universities, including EngD, PhD and post-doc staff.

In order to supplement interviews, the destinations of the EngD graduates were analysed in the pilot study using the Destination of the Leavers from Higher Education (DLHE) survey available from the Higher Education Statistical Agency (HESA). The DLHE survey collects data of the UK and EU domiciled graduates from the UK higher education institutions (HEIs) six months after qualifying from their higher education course. The data on EngD graduates was initially obtained from the EPSRC, which was matched and integrated into the HESA DLHE data of all doctoral graduates. Data on five cohorts of students (2008/09-2010/11 academic years combined) was matched and made available for the pilot study. The HESA DLHE survey data, despite its limitation in the data consistency over time, provided systematic information on the career destinations of the UK HE leavers six months after the completion of their studies, indicating overall characteristics of the EngD graduates and their career patterns.

In order to understand micro-dynamics of factors and processes influencing the mobility and career trajectories of the EngD graduates, further investigation was sought by looking at three selected IDCs as illustrative case studies (see Yin, 2003). In this paper, additional case studies of three selected IDCs are presented with different disciplinary areas set in different industry sectors. The case studies were built on insights gained from interviews with industry partners and alumni of the EngD programmes, as well as other secondary data sources accessed as part of the pilot study conducted in 2013, including the HESA DLHE data (see Kitagawa, 2015).

The three centres were chosen based on the following criteria:

- a) received funding under the 2009 IDC call and exist as of 2014, and
- b) initially established under the 2001 EngD Centre call, covering the periods of being both EngD Centres and IDCs. The three IDCs were chosen because of the similar history under the scheme (established as an EngD Centre in 2001, and got funded as an IDC in 2009). Since the establishment as the EngD Centres in 2001, each of the



centres has about 20-36 EngD graduates completing the programmes between 2005 and August 2014. All personal information is anonymized and treated confidentially. The sponsoring firms and the destinations of the EngD graduates were identified from the IDC Centres' websites and annual reports, which are publicly available. Individual mobility and career trajectories were further examined manually by collating web-based information including, "Linked In", and ISI Web of Science in order to identify publication outcome records and affiliations.<sup>2</sup>

## 5. Mobility and career trajectories of the EngD graduates

In this section, short case studies of three IDCs, with details of the patterns of career trajectories, mobility and knowledge flows with the EngD graduates in different industry sectors are presented. In order to illustrate institutional contexts of the graduate career trajectories and mobility patterns in a variety of industry sectors, case studies of three selected IDCs are briefly presented below. Brief illustrations of each of the Centres below aim to highlight:

- a) the nature of the technology and industry sectors,
- b) geography of collaborative relationships and cross-organizational linkages developed through the EngD/IDCs, and
- c) career pathways and knowledge flows between academia and industry.

Each of the case study centres covers multi-disciplinary fields with the so-called "emerging technologies": "Optics and Photonics Technologies"; "Formulation Engineering"; and "Virtual Environments, Imaging and Visualisation". The following sections illustrate each of the case study centres - geographical locations of the Centre and their industrial sponsors (where the REs work), the nature of collaboration between university and industry, destinations of the EngD graduates, and their characteristics of the careers. Table 1 presents summarises the key features of the three IDCs. The data was collected in December 2014.

### **CASE 1 Optics and Photonics Technologies (Heriot-Watt University with Universities of Glasgow, Strathclyde and St Andrews)**

The IDC in Optics and Photonics Technologies demonstrates geographical clustering of graduate employment locations - 16 out of 32 EngD graduates are employed in the area near Edinburgh and Glasgow, where the IDC lead and partner universities are located. Whilst the industry sponsors are spread across the UK as well

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<sup>2</sup> Methodologically, the use of data in the public website domain combined with personal professional social media such as LinkedIn, in understanding the micro-dynamics of individual careers and interactions, may need further discussion (e.g. Papacharissi, 2009).

as in the US and South Africa, nearly half of the EngD graduates between 2005 and 2014 are located in areas surrounding Edinburgh and Glasgow. In response to the pilot study interviews conducted in 2013, one of the industry interviewees who has had links with this IDC commented that “geographical proximity” to the IDC is particularly important for them for sharing equipment and research collaboration.

Two large industry sponsors in the area near Edinburgh and Glasgow send their long-term employees repeatedly to the EngD programme. After completing the EngD, five out of six of them remain at the same employers. The IDC provides training of professional R&D personnel for firms in the local area. Heriot-Watt and Strathclyde universities seem to act as part of the local labour market for the EngD graduates, some move on to industry jobs whilst a few remain as post-doctoral researchers. There are two cases of EngD graduates starting up technology based ventures.

The career pathways and mobility of the former REs reflect close collaboration between academia and industry partners, and their individual employment pathways are sometimes international (e.g. move from South Africa to the UK; move within USA; Germany). In some cases, the career mobility cuts across different industry sectors through the IDC collaboration, and there are cases of career mobility between industry and academia including different levels of seniority (e.g. professor level; researcher level).

## **CASE 2 Formulation Engineering (University of Birmingham)**

The case of the IDC in Formulation Engineering demonstrates different types of career mobility of its graduates. IDC in Formulation Engineering is located in the School of Chemical Engineering at the University, and involves industry sponsors from several different industry sectors – food, health, consumer goods, bio-engineering and manufacturing. Industry sponsors are spread across the UK, and some are in Europe (Germany, Netherlands and Belgium). Some large firms have hosted multiple EngD projects, demonstrating the strong links between the university research and industry application (e.g. Unilever has hosted 12 projects; Rolls Royce has hosted 9 projects; P&G has hosted 7 projects).<sup>3</sup>

Out of 36 EngD graduates, upon completion, 12 of them stayed at their industry sponsor firms. Some graduates move between different sectors, which reflect the interdisciplinary nature of the application areas of the technology. One former RE comments that he left the sponsoring company at the end of the EngD programme, but continues to work with them as part of the supply chain and develops technology from his EngD studies in his current job. Over 70 % of the EngD graduates are still employed in the field of Formulation Engineering, contributing to the technology sector. Two of the

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<sup>3</sup> <http://www.birmingham.ac.uk/schools/chemical-engineering/postgraduate/eng-d/index.aspx> [12/12/14]

EngD graduates got Chartered Engineer status soon after the EngD graduation, and another is working towards it (source, EngD alumni profile on the University website).<sup>4</sup> There is no case of existing employees carrying out the EngD sent by the employers.

The career pathways of the graduates demonstrate the regular and institutionalized knowledge flows between academia and industry. Five EngD graduates took up post-doctoral positions after the EngD, one of which was funded by the industry sponsor. The EngD graduate destinations reflect geographical concentrations of each of the industry sectors both nationally and internationally. Some of the graduates continue to work at the sponsoring firms in Europe and South Africa.

### **CASE 3 Virtual Environments, Imaging and Visualisation (University College London)**

The IDC in Virtual Environments, Imaging and Visualisation (VEIV) encompasses a broad range of portfolio of projects, namely “system interactions”, “animated bodies”, “dynamic environments”, “enhanced vision” and “intelligent materials” (VEIV, 2013). The IDC shows unique career pathways and mobility patterns of their graduates.

Out of 20 EngD graduates identified between 2005 and 2014, six of them work full time as academic, researcher or academic manager job, another four of them have set up their own businesses also having an affiliation to universities or have part time university jobs. Another three has set up their technology companies, and another one is self-employed in design area. There are several EngD graduates who work as Hardware design engineer, Head of Applied research, and Senior programmer in corporate settings, including electronic and game industry. Many of them are located in London and South East region, where academic entrepreneurial opportunities abound (Lawton Smith et al., 2014). In particular, UCL seems to provide opportunities for research-oriented creative entrepreneurs to be part of the academic environment. One of them has taken up an institutional position as an interface such as University Knowledge Exchange fellowship.

The career patterns of the VEIV graduates are diverse including higher number of graduates’ entrepreneurial start-ups than other IDCs. There are close inter-connection between the entrepreneurial individuals being employed in the academia, including part-time affiliation, mostly concentrating in London. The IDC seems to provide a space where technology, entrepreneurial resources and skill development in visual and creative industry are combined.

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<sup>4</sup> <http://www.birmingham.ac.uk/schools/chemical-engineering/postgraduate/eng-d/alumni.aspx>

Table 1 An overview of the three IDCs

	IDC in Optics and Photonics Technologies	IDC in Formulation Engineering	IDC in Virtual Environments, Imaging and Visualisation
industry activities; sectors	imaging, semiconductors, medical devices, defense, security, geoscience	health, consumer goods, bio-engineering and manufacturing	visual modelling, construction, architecture, game and creative industry
Geography of career mobility	UK and international with 50% of industry sponsors collocating in local cluster around Edinburgh and Glasgow	UK and Europe, widely spread-out with concentration on where industry is located	UK with strong concentration in Greater London
Mobility and career types	Industry R&D; some cross-border career change to academia; professional development of employee of industry sponsors.	Industry R&D; Cross-sectoral mobility between different industry; high number of post-doctoral researcher with industry funding	Start-ups, self-employed with academic affiliation; interface between academia and business

The three IDCs, over years, have facilitated inter-sectoral knowledge flows and a variety of forms of industry collaboration. The mobility of the EngD graduates suggests scientific-technical labour market is at work at multiple levels, including local, national and international.

## 6. Discussion – Cross-border mobility and knowledge flows

The EngD scheme not only produces highly qualified graduates but also contributes to a number of other engagement and knowledge exchange activities between academia and industry (Abreau et al 2009; Perkmann and Walsh, 2007), with a broad spectrum from ‘soft’ activities (e.g. advisory roles, consultancy, industry training, sharing facilities and equipments), to ‘hard’ commercial initiatives such as patenting,

licensing and spin-off activities (Philpott *et al.*; 2011). These forms of knowledge exchanges occur through intersections of research, teaching and training and through the individual REs working within the industry settings.

The short illustrative cases of the three IDCs highlighted different patterns, micro-dynamics of the graduates' mobility after the graduation, indicating different forms of impacts arising from the collaborative relationships. The EngD graduates play "boundary spanning" roles (Aldrich and Herker, 1977) across organisations, connecting between the university and their sponsoring firms. Sometimes the sponsoring firms send their existing employees as professional development. Newly graduated EngD alumni often get recruited by the sponsoring firms or other firms participating in the IDCs. Whilst the scheme intends to train students who want to work primarily in industry, the career trajectories of the EngD graduates often include mobility between industry careers and academic careers. Throughout the three IDCs the career mobility of the EngD alumni illustrate the S&T human capital formation processes across multiple boundaries - between academia and industry, between industry firms, between sectors, and sometimes between national boundaries. The nature of technologies, disciplines and the types of industry sectors define the career patterns of the graduates with a diverse variety across the IDCs. Longitudinal and systematic data analysis is needed in order to understand the mobility and impacts of the EngD graduates in terms of career development and progression.

The organization of the EngD scheme based at autonomous EngD Centres, and more recent IDCs, has been another unique feature of the EngD scheme which distinguished the EngD from other collaborative doctoral schemes such as Industrial CASE or other PhD placements, based at existing academic units. The organizational forms of collaborative relationships take different shapes for IDCs working in different discipline areas and industry sectors. Recently the "research centre" model is becoming a key feature of the doctoral training funding in the UK, which seems to be the international trends (Rogers *et al.*, 2012). However, somewhat ironically, some of these unique features of the original EngD Centres have become less distinctive, as these are spreading further through the new CDTs.

## **7. Conclusion**

It is suggested that innovation requires more human capital and high skills, whilst there has been growing perception of mismatches between the supply and demand of doctoral graduates (Lee *et al.*, 2010). In order to reduce such mismatches, collaborative doctoral training schemes are supported by public funding in different national contexts. It is expected that these schemes will help bridge the gap between science and innovation. The empirical focus of this paper is on the mobility through one

of the collaborative doctoral training schemes between academia and industry – with a case of the Engineering Doctorate (EngD) scheme in the UK as a distinct model from the traditional PhD. Drawing on findings from a pilot study conducted in 2013 and additional illustrative case studies of three Industry Doctorate Centres (IDCs), the paper identified different organisational forms of knowledge exchanges via highly skilled human capital, and interactions between research and various forms of individual social practice, through graduates' career destinations and mobility.

This paper is illustrative and exploratory in nature, and is limited in terms of explanatory power. Further methodological development (see for example, Feldman and Lowe, 2015; Rogers et al 2012) and empirical investigation is needed in order to identify the factors and mechanisms that influence the mobility of highly skilled researchers in scientific labour market and a variety of forms of impacts emerging from collaborative doctoral schemes. The structure and development of the labour market as well as the characteristics of the sectors and the locality, combined with firms' recruiting strategies and individual human and social capital development strategies affect career pathways and mobility of the graduates. The illustrative case studies of the three IDCs suggest different mobility patterns and career pathways of EngD graduates leading to different human capital formation, which seems to be distinctly conditioned by disciplinary areas and industry sectors they work in. Micro dynamics of individual career pathways and mobility can be further investigated. This would enrich our understanding of micro-processes of institutions through individual social practices within the wider social systems those individuals belong to.

The EngD Centres/IDCs have acted as the connecting nodes for the development of R&D skills, entrepreneurial resources, scientific human capital and R&D value chains. The case of EngD shows that the collaborative doctoral training scheme makes multiple routes of knowledge exchanges through research, training of doctoral students, continuing professional development, sharing of facilities and other relationship-based long term engagement between university and industry. The EngD graduates' career paths and mobility suggests knowledge dissemination and exploitation with diverse spatial implication (see Feldman and Lendel, 2010) – the talents are collocated in specific industry locations with local, national and international knowledge flows, skills, R&D and innovation activities.

The movement of people between labour markets, sectors and firms is seen to have important consequences for industrial functioning and innovation (De Laurentis 2006; Power and Lundmark, 2004). The collaborative and interactive nature of cross-border relationships provides fundamental methodological as well as conceptual challenges to the evaluation of the collaborative scheme, for all the stakeholders concerned, including the universities, funding bodies and for the industry partners. This

paper focused on the cross-border mobility of individual graduates who bridge the gaps between science and innovation. Allocation of funding for collaborative doctoral centres seems to have impact on the industry R&D activities, innovation processes and human capital formation.

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