Paper to be presented at

DRUID15, Rome, June 15-17, 2015

(Coorganized with LUISS)

Capturing Innovation from Collaborative Relationship Building: Applying a process based approach to evaluating collaborative doctoral research training

Fumi Kitagawa
University of Manchester
Manchester Business School
fumi.kitagawa@mbs.ac.uk

Abstract

There has been an increase in the number of doctoral students who interact with firms, receive funding from firms and work in the private sector after graduation, arguably enhancing innovation in organisations. There has been growing policy interest in collaborative doctorate schemes between academia and industry. The operation and impacts of collaborative doctoral training programmes are complex due to the diverse stakeholders involved including industry partners, the public funding body, university research units, academics involved in the programme, and the students who bridge academia and industry. Building on insights from the research literature, this paper aims to develop conceptual frameworks to capture the processes of innovation from these collaborative relationships and multiple forms of engagement. Empirically, this paper examines the impact of the Engineering Doctorate (EngD) scheme in the UK, a publicly supported doctoral training scheme with industry, differentiated from conventional academic PhD programmes. Recognising the challenges of fully capturing all effects of such academic-industry interactions, the study focuses on impacts on industry partners and doctoral graduates? career trajectories. Methodologically the study adopts mixed qualitative methods, using a sample of 18 doctoral centres examining the impact of the scheme over 20 years. The paper identifies different organisational forms of knowledge exchanges via highly skilled human capital, institutional mechanisms of S&T human capital formation and cross-boundary mobility between science and innovation. These factors and processes constitute interactive innovation processes, which then affect the overall demand environment. Management and policy implications are discussed.

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Key words: doctoral training, industry engagement, impact, knowledge exchange, innovation; human capital

1. Introduction

Doctoral students are deemed to be crucial to the conduct of research and innovation and thus doctoral education and research training has attracted policy attention across industrialised countries. Many studies show an increase in the number of doctoral students who interact with firms, receive funding from firms and work in the private sector after graduation (for a review of literature, Thune 2009; see also, Mangematin, 2001; Cruz-Castro and Sanz-Menéndez, 2005; Lanciano-Morandat & Nohara, 2006; Borrell-Damian et al., 2010; Thune, 2010; Herrera and Nieto, 2013; Lee and Miozzo, 2014). Recent policy also seems to support a "redefinition of researcher training" where broader skills and relevance for careers outside the university sector is seen as central for doctoral research training (Thune, 2010). Consequently, there has been growing interest in "collaborative doctorate" schemes between academia and industry in different national contexts (see Thune, 2009; Borell-Damian, 2009).

Over the last decade, the quality and impact of publicly funded research, including doctoral research training, has become a major policy agenda for governments, research funding bodies and universities (e.g. Salter and Martin, 2001). Recent innovation studies literature have pointed to a wide range of channels of communication between academia and industry (Perkmann and Walsh, 2007; Howells et. al., 2012). There are "relationship-based" activities between university and industry (Perkmann and Walsh, 2007), also known as "academic engagement" activities (Perkmann et. al., 2013); for example, collaborative research, commissioned research, consultancy, equipment sharing, advisory roles, joint supervision, joint publication and student placements. Other scholars have demonstrated that transfer mainly occurs through other means, for instance through softer or open channels such as publications and consultancy activities (Cohen et. al., 2002; Perkmann and Walsh, 2007), student placements and generally the production of graduates. Close relationship fostered by staff and student mobility between academic and industrial contexts (Perkman and Walsh, 2007) is believed to reduce the "inherently high levels of uncertainty in knowledge transfer" (Gertner et. al., 2011) between university and industry.

The nature of innovation processes through the collaborative doctoral training programmes is complex due to the diverse stakeholders including industry partners, the public funding body, university research units, academics involved in the programme, and students, who work as "triple helix workers (Thune, 2010). In this light, this paper examines one of the collaborative doctoral training schemes in the UK. The Engineering Doctorate

(EngD) Centres was established 20 years ago, following the recommendations from the Parnaby report (1990). Similar to the PhD, the EngD is a postgraduate research (PGR) programme.[1] It differs from a conventional academic PhD programme in that it expects doctoral students, who are called Research Engineers (REs), to work on projects which are industry-based. The recent review of business university collaboration in the UK commends the EngD not only for mechanisms for knowledge exchange but also for "skills development by engaging employers in collaborative research" (Wilson, 2012).

This study therefore starts by asking: In what ways can the interactive and multi-dimensional nature of innovation processes of the EngD scheme be best captured? Methodologically the empirical pilot study adopted mixed qualitative methods. There is a dearth of empirical data on the collaborative doctoral schemes. One of the objectives of this study is to identify available data-sets and appropriate methodologies for analysis. By triangulating data from different sources and through different research methods, the study aims to enhance understanding of the evolution of the scheme and the interactive nature of relationship building over the years from multiple perspectives.

The rest of the paper is structured as follows. Following this Introduction, the next section introduces the policy context of the study - the R&D policy and historical evolution of the EngD scheme over the past 20 years in the UK and discusses conceptual frameworks in order to better understand the effectiveness of collaborative doctoral research training as innovation policy instrument. The third section identifies the gaps in existing approaches and frameworks and presents the methodological framework adopted in the current study. The following sections present research findings from different data sets collected - the industry partner interviews, the EngD graduates interviews, and preliminary findings from the EngD graduates' destinations data and three exploratory case studies. The paper discusses the challenges and possible frameworks to capture the processes of innovation - different forms of and routes, and factors that condition the innovation. It concludes with suggestions for future studies and implications for policy and funding of research training.

[1] The REs are affiliated to the EngD Centres based at a university, but they spend majority of time within industry (about 75% of the 4 year EngD programme). The REs take taught modules on industry relevant skills, and build industry based research experiences.

2. Research contexts and policy development

2.1 Literature review

There are different organisational models for industrial engagement in doctoral training with a variety of public support mechanisms. This may reflect a "variance in terms of research organisations, national career structures and individual career paths" (Nedeva, 2013, p. 222) grounded in national resources for science, innovation and the rules for their exchange with private organisations. In Europe, "specialised industrial PhD" programmes have been developed in different national contexts (e.g. the Industrial PhD-programs in Norway and Denmark, the Industrial Research Schools in Sweden, the Industrial CASE studentships in the UK, CIFRE in France), and more recently at the European level (see -----, 2014). In the USA and Australia, and increasingly in the UK, industry engagement in doctoral training has been promoted through multidisciplinary "research centres" (Rogers et al, 2012; Gray et al., 2013; Manathunga et al., 2012).

Recent international research policy trends include growing interest in "Science and Technology Human Capital" (STHC) (Bozeman and Corley, 2004) approach combined with "open innovation" (Chesbrough, 2003) and concentration of R&D resources to a few selected organised research units (Gray et al., 2013). It is contended that when concentrating R&D and human and material resources into a critical mass, "research centers" increase the chances of better policy outcomes such as commercialization of research, enhanced innovation or skills development (Rip, 2004; Rogers et al., 2012; Wigren-Kristoferson et al., 2011). Externally, the formation of the organisational boundary may shield "autonomy at an organisational or institutional level" (Smith et al., 2011, p. 1376). Internally, these centres help the formation of scientists' professional identities including "familiarisation with the institution to accredit new knowledge, standards, procedures and norms, against which "claims for innovative contributions" (Heinze et al., 2009) of scientific knowledge are assessed.

As a "people-based partnership" (Butcher and Jeffrey, 2007) and "research centre" based scheme, one of the unique characteristics of the EngD scheme derives from interactive relationships built between academia and industry, and the tacit nature of the knowledge flows across organisations. Doctoral students 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, this provides the key challenge in measuring and evidencing the impact of the scheme over the years. Collaborative doctoral training schemes produce highly qualified graduates with a number of other engagement and knowledge exchange activities between academia and industry (see Abreau et al 2009; Perkmann et al 2013), including a broad spectrum from "soft" activities (e.g. advisory roles, consultancy, industry training, secondment, sharing facilities and equipments), as well as "hard" commercial initiatives such as patenting, licensing and spin-off activities (Philpott et al.; 2011). The nature of multiple co-existing collaborative R&D relationships, forms of engagement and interactions need to be captured, which would require an approach going beyond an outcome-based approach to impact (see Lowe, 2013; Upton et al., 2014).

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).

2.2 An evolution of R&D knowledge dissemination and doctoral research training eco-systems in the UK

Recent studies on R&D collaborative partnerships and university-industry collaborative relationships in the UK point out that a number of routes from research to impact (see Table 1). One of the routes comes through "innovation processes" as part of a broader R&D collaborative environment (PA Consulting Group/SQW Consulting, 2007; DTI, 2007). It is also pointed out that often major breakthrough in innovation in such collaborative partnerships occur from informal interactions (CBI, 2010; Howells et al., 2010). Capturing impacts from these informal interactions is often seen as the most difficult part of measuring impact and outcomes.

Impact from academic research and research training also occur through the "movement of skilled researchers" from academia into industry or to other research organisations (Lee et al. 2010). Other studies demonstrate "networks and linkages" that are catalysed by the university-industry sponsored collaborative schemes (PA Consulting Group/

SQW Consulting, 2007; Gertler et al., 2010). Recent evaluation studies also show that research impact may occur due to the “behavioural additionality” (Buisseret et al., 1995; Gok and Edler, 2011). Collaborative R&D partnerships and university-industry collaborative training schemes lead to human capital development, with different types of skills and knowledge as outcomes. Graduates bring into industry an “attitude of the mind” and a “tacit ability” to acquire and use knowledge in useful new ways, which are highly valued by industry (Senker, 1995). Analytical problem-solving of doctoral graduates is a desirable skill which is recognised by business communities (Demeritt and Lees, 2005).

In the UK, the government policy objectives to enhance closer links between academia and industry has been transforming “the political and cultural economy of university research” (Demerrit and Lees, 2005, p. 129) including the nature of doctoral training (Lee and Miozzo, 2014). Public policy initiatives include several “people-based partnership” programmes at the doctoral level that bring the academia and industry together as doctoral students as “bridging agents”. These include the Industrial CASE PhD (Demeritt and Lees, 2005), PhD incorporating Knowledge Transfer Partnerships (KTP) (Gertler et al., 2010), the EngD as well as other collaborative R&D programmes where doctoral students conduct their research in industry settings. The Industrial CASE PhD and the EngD scheme both have more than 20 years’ history.

The evolution of the EngD scheme has taken place over the past 20 years. The earliest EngD Centres started in 1992 with pilots at Universities of Warwick, University of Manchester Institute of Science and Technology (UMIST) and Swansea, joined by Brunel, Surrey and Cranfield in 1993. In 1997, the EngD scheme was expanded and centre themes were introduced. There were further cohorts of EngD Centres created under the subsequent calls for funding from the EPSRC. The EngD Centres provided the EngD programmes as an “educational, training and research” activity, and the universities award the EngD degree rather than PhD. Since 2004, the EPSRC changed the doctoral training funding mechanisms, and the scheme continued to grow. The EPSRC review in 2007 evaluated the impact of the EngD programmes positively: the EngD programmes were meeting “real business needs”, and many of the REs were having “a major impact on business performance”, and the scheme was making a valuable contribution to UK knowledge generation and transfer into industry, while satisfying its goals in terms of scholarship and publication (EPSRC, 2007).

In 2009, the major changes were made to the doctoral training funding mechanisms in the UK. 19 Industrial Doctorate Centres (IDCs) were created as a subset of EPSRC’s new

Centres for Doctoral Training (CDTs). CDTs are now one of the three main ways by which EPSRC provides support for doctoral training, and “bring together diverse areas of expertise to train engineers and scientists with the skills, knowledge and confidence to tackle today's evolving issues, and future challenges. They also provide a supportive and exciting environment for students, create new working cultures, build relationships between teams in universities and forge lasting links with industry” (EPSRC, 2014a) . IDCs are seen as an evolution of EPSRC’s EngD Centres (EPSRC, 2011), and they provide EngD programmes for “Industrial Doctorate” as “an alternative to the traditional PhD for students who want a career in industry” (EPSRC, 2014b). The aim of the IDC is to provide postgraduate engineers with “an intensive, broadly based, research programme incorporating a taught component, relevant to the needs of, and undertaken through, sponsorship with industry” (EPSRC, 2011).

As of 2011/12, £19 million was invested into 29 IDCs. The number of EngD students trained under the IDC amounts to about 1,400 and the number of company partners under the scheme amounts to some 600 over time (Golby, 2012). In the autumn of 2012, the new call for funding for CDTs was open, and there is a strong expectation about the “user engagement” in doctoral training in general. The IDC has now been integrated as part of the main CDT call (EPSRC 2013a). Some IDCs now have both PhD and EngD students working alongside. The EPSRC acknowledges that some of the CDT characteristics including having cohorts of doctoral students and integrating taught modules into the research programme originate from the previous EngD scheme (EPSRC 2013b).

3. Methodology

3.1 Gaps in knowledge and the context of the pilot evaluative study

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. The impact of the EngD scheme has been evaluated over years through several channels including experts’ reviews and externally commissioned studies (e.g. EPSRC, 2007; Strategic Marketing Associates, 2006). There have been attempts to identify quantifiable “financial benefits” and “economic impact” of collaborative schemes including the EngD and other publicly funded collaborative research schemes (PA Consulting Group/SQW, 2007; see also DTZ/EPSRC, 2011). These studies are based on earlier EngD Centres, not including the recent IDCs. There was also recognition among the AEngD steering committee that whilst the unique benefits of the EngD scheme is widely recognised by both academic and industry stakeholders, impacts deriving from the interactive nature of collaborative relationships are not captured through hard evidence.

Gaps in existing studies can be explained using the framework of the Bozeman (2000)'s "Contingent effective model". The evaluation approaches adopted by earlier studies commissioned by the public funding bodies are mostly based on Market Impact and Economic Development criteria, sometimes drawing on Political Reward approaches. Some of the indicators used by the EngD Centres and IDCs in their reporting to the EPSRC include the number of trained EngD graduates or the IP generated through EngD projects as output measures (Out-the Door approach) with little systematic understanding of behavioural changes of individual graduates, academic and industry supervisors, and organisational and institutional spill-over effects. Within the scheme, interactive and collaborative relationships and mechanisms of knowledge flows are promoted. A recent study on manufacturing research for example argues that EngD doctoral researchers work at the frontiers of "innovation, substantial and varied industry problem-solving experiences, and insights into future challenges (and opportunities)", and the scheme contributes to training and developing "the next generation of science and technology leaders" (O'Sullivan, 2011). Whilst the STHC dimension is widely acknowledged as the main objective of the collaborative scheme, evidence of processes of STHC development, its impact on industry partners and relationship with innovation processes has not been systematically captured and presented in the existing evaluation studies.

3.2 Research methodology

As already mentioned, methodologically this study adopted mixed qualitative methods. The choice of mixed qualitative methods is justified based on the following reasons. Firstly, interactive and collaborative relationships and mechanisms of knowledge flows may lead to "S&T Human Capital" (Bozeman and Corley, 2004) and various forms of impacts within industry partners that cannot be easily captured by quantitative economic impact analysis. This would require contextual understanding of interactive processes between actors as well as changes in the organisational and individual behaviour (Rogers et al., 2012). Secondly, as illustrated above, the nature of the funding and governance of the EngD scheme has been changing over the past 20 years, which requires historical and contextualised understanding of policy changes and changes in funding mechanisms that have affected the ways in which the programmes and the Centres are organised and evaluated over the years.

Data sources for the pilot study included mid-term self-evaluative documents (submitted to EPSRC as of May 2011) provided by 18 IDCs funded under the call in 2009. Semi-structured interviews were conducted with 35 individuals who have direct experiences of the EngD programmes, including 20 EngD alumni and 15 industry partners (see Annex for an overview). 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. In order to supplement interviews, the destinations of the EngD graduates was analysed 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.

Interviews were conducted between June and August 2013 with 35 individuals who volunteered to share their views and experiences on the EngD projects and programmes (see Annex). The interview findings provided evidence to the conditions, forms and routes to the impacts which supplement the findings from the documentary analysis. Interviewees are drawn from those who have direct experiences with the EngD scheme, from different EngD Centres and IDCs, with variety of industry experiences and field of work. The findings are limited in terms of representativeness and generalisability, and the interview results may have some biases. For example, most of the industry interviewees are from large firms, which give certain bias to the study. However, for this pilot study, the small scale qualitative set of data provided some advantages. It gives contextual understanding of the diversity of the IDCs, individual experiences and perceptions of the EngD projects and various forms of impact over time, which were not captured in the existing reviews and documentary analyses. To validate the findings from the small scale study, further evidence is required in order to make the findings more generalisable.

Additional case studies of three selected IDCs are presented, illustrating micro-dynamics of the EngD graduates' career trajectories and mobility. The case studies represent three EngD programmes with different disciplinary areas set in different industry sectors. The centre level case study approach enables the author to examine micro-dynamics of career trajectories of individuals over time, going beyond the snap shot presented in the DLHE data. 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. The three centres were chosen based on the following criteria:

a) they received funding under the 2009 IDC call and exist as of 2014, and

b) the case study centres were all initially established under the 2001 EngD Centre call, covering the periods of being the EngD Centres and IDCs.

In order to see micro-dynamics of how different factors and processes influencing the mobility and career trajectories under specific sector and organizational contexts, further investigation is sought by looking at three selected IDCs as illustrative case studies (see Yin, 2003). 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 anonymised. The sponsoring firms and the destinations of the EngD graduates were identified from the IDC Centres' websites and annual reports, and individual career trajectories were examined manually by collating web-based information including, Linked In for career trajectories, and ISI Web of Science for publication records and affiliation.[2]

4. Empirical findings

4.1. Industry perspectives based on interviews

Firm interviewees include Head of academic liaison, Head of Technology, those who have supervised EngD projects as industry supervisors, and those who manage collaboration with universities, including projects involving EngD, PhD and post-doc researchers. Many of the industry respondents have had close engagement with IDCs/EngD Centres, for example, being an active member of the advisory board of these Centres. According to the interviews with the industry sponsors, the EngD programme is seen as a unique scheme and supported by the industry partners because of:

[2] Methodologically, the use of data in the public website domain combined with personal professional social media such as Linked in, may need further discussion.

1) the “portfolio of the projects” compared to the specialised nature of the PhD;
2) the time REs spend within the industry, which is much longer than the PhD and
3) the direct contacts and control industry partners have over the nature of the project.

One of the industry interviewees argued that different centre types of doctoral training complement the R&D activities across the industry sectors covering different scopes of technology and different types of skills needed for the future leadership and technical research in industry. As the interviewee put it:

> *“Distinctive advantage of EngD is* the fact that it is applied in nature. The EngD allows much closer interactions, closer support system than the PhD. However, this is one model – the spectrum of models – *both PhD and EngD are needed.”* (Energy sector)

From the industry’s point of view, the collaborative R&D of the EngD scheme is characterized by the access to excellent academic research and interactive opportunities, combined with a variety of forms of engagement, including the use of facilities at the universities, opportunities to consulting senior academics, and access to wider research networks as part of the EngD/IDC programme. The nature of the EngD projects are mostly applied in nature, and often based on industry problem solving. Direct and face to face relationships and spatial proximity (e.g. use of facilities) seem to matter in certain collaborative contexts.

It is important to position the EngD scheme and programmes as part of the broader R&D eco-system and understand the reason why the industry partners choose to participate in the EngD programme amongst all the other collaborative R&D programmes. The nature and the aim of each EngD project differs according to the motivations and objectives of the sponsoring firms participating in the programme, which would shape their perception and evaluation of the “impact” of the EngD within their expected time scales. For instance, sponsoring firms often act as a potential employer as well as a research sponsor. Several of the industry partners interviewed [e.g. manufacturing, pharmaceutical, water management] use the EngD programme as a tool for employing key talents, where the impact of the EngD programme is seen as mid to long-term. Some of the industry sponsors emphasise the importance of the EngD/IDC scheme as a “deliberate mechanism by the sector” in developing the next generation of scientists and engineers [e.g. water management, nuclear engineering]. Some firms have integrated doctoral students as part of their human resource management through reward and recognition mechanisms [e.g. energy, water management].

On the contrary, some sponsoring firms [e.g. retail] use the EngD project to solve a specific and immediate business problem they are facing and/or to gain state of art research expertise. In these cases, they said that they do not intend to recruit the EngD graduates when they complete the projects. One industry partner clearly separates the EngD from their recruiting processes. They see the EngD projects as "direct solutions to the industry problems". They have highly appreciated the impact from the projects and immediately rolled out the impacts. Within two years, one of the projects resulted in the development of "modelling tools for calculating energy consumption of buildings." The new modelling tools have been implemented in the company's UK stores, as well as its overseas stores, resulting in "substantial cost savings of nearly £5 million." However, they don't see the REs as future employees as the areas of the EngD projects are specific and not the core part of their business.

The EngD programmes provide broader learning opportunities for the participating firms. Several industry respondents [e.g. Pharmaceutical, Consumer Goods] commented that they send some of the staff to part of the EngD short taught programmes as professional development. Some of the IDCs take a strong sector-based approach. Sponsoring companies sometimes work together to solve the sector-wide problems by identifying common issues and co-sponsoring EngD projects.

The impact of the EngD is recognised as sector-wide, beyond individual projects and technologies. For example, through one IDC, two sponsoring companies started to work together leading to a new collaborative funding of the EngD project. One company provides an industry problem and another company funds the project where their commercial tool gets validated. The RE will spend 50% of their time at each of the companies. This is seen as "a real synergy and an added value of the IDC [for the sponsoring company]". Some IDCs have developed networks and relationships between firms, acting as the "core part of the R&D supply chains", by providing technical expertise, sharing equipment and providing training courses.

Whilst the findings of the interviews are not generalisable, they provide views of the firms with experiences of the EngD projects with certain diversity in industry sectors. It is generally difficult to capture the long term impacts and financial impact of the EngD project. For instance, it may take several years before the technology gets commercialised. Especially when the RE has left the sponsoring company after the completion of the EngD, it is difficult to track the impacts of the EngD project within the firm, apart from the immediate and short term outcomes.

4.2 EngD alumni career paths based on interviews

Career paths and progression of the EngD graduates indicate the direct impact of the EngD in terms of STHC – including human capital and skills development as well as social ties and networks as part of their career trajectories. Interviewees cover a wide range of cohorts including those who have just completed EngD programme, and those from the first cohort who completed the EngD in the mid 1990s. Typology of the EngD alumni and their career trajectories was made based on the interview findings. In terms of prior experiences:

1) those without (or less than one year) industry working experience (fresh graduates),

2) those who had had working experiences in industry prior to the enrolment of the EngD (RE experienced).

In terms of destinations after the completion of the EngD,

3) those who stayed on at their sponsoring companies as an employee, and

4) the REs who left the sponsoring companies at the end of the EngD and found jobs in the same industry or in a different sector.

Almost half (9 out of 20) alumni had had more than two years' industry experiences prior to the EngD programme, of which 3 had more than 10 years industry work experiences prior to the EngD enrolment. Of those who were fresh graduates (11 out of 20), most of them had some kind of industry experiences, ranging from summer work experiences to 1 year industry placement, as part of the first degree. Those RE alumni interviewed commented that their previous industry experiences probably helped for the EngD RE selection process even if the areas were not the same.

In the interviews, alumni were asked to choose from a list of suggested 'motivations' – why they launched on the EngD programme. They were asked to choose multiple answers from the list of 'motivations' and 'expectations' as below. Most (18 out of 20) alumni said their main motivation for joining the EngD programme was "the opportunity to work with the industry whilst conducting academic research." The commercial aspects and industry-based nature of the scheme are also recognised as main motivations as commented by the EngD graduates.

"I had never considered a PhD; it never crossed my mind to do a doctorate because I wanted to get commercial experience.... the thing about the EngD is that you are getting that commercial experience. ... that kind of experience to *put in my CV is what I was looking for."*

Another former RE points out the value for the industry in engaging with academic research through EngD scheme:

"The thing about EngD ... is that you can research something that can be used by the company afte*rwards. It's not just general research; it's something that the company can be interested in and take up in the near future. I think it's important to have this application side of it. ...Having courses like this as a more cost*-effective way for industry to *engage with academics for research is really good."*

Interviews with the EngD alumni highlighted the benefits of the EngD programme particularly for "experienced" REs, who had industry career before the doctoral training. Many of them expressed concerns they had had over returning to education in the midst of their career. The EngD, they believe, is the right channel to help them maintain their positions within the industry as there will be arguably no hiatus in their career ladder, compared to taking on a purely academic PhD. One of the experienced RE commented:

"I like that the EngD programme requires REs to spend time in the company. *You'll benefit from having a position in industry rather than doing pure* academic research. This is important for people who are already in the *industry (because) it's hard for them to go back to academia."*

Another experienced RE put the reason for choosing the EngD as follows:

"While I was working (in industry) I started thinking about doing a doctorate. I started researching online for industry-based doctorates.... I enjoyed being in university but I *didn't enjoy the academia. So I decided to do the EngD."*

The EngD qualification with a business/management related qualification seems to advantage their professional status within the labour market, especially when they work in industry. In particular, the business qualifications and training have helped broadening REs' career choices; for example, expanding from purely technical backgrounds to more managerial roles:

"It was the management courses (in the EngD programme) that encouraged me to *pursue a management career in the company, rather than a technical one"*

The EngD programmes seem to help graduates obtain further professional qualifications. Those EngD alumni who already obtained the Chartered Engineering status believe the process had been aided and accelerated by the EngD qualification. Quantitative data on destinations and career development of the EngD graduates and information about further professional qualifications such as the Chartered status need to be systematically collected and analysed.

Of the 20 REs interviewed, all of them were able to secure employment right after the completion of their EngD programmes. 15 of the 20 former REs who were interviewed secured employment within the sponsoring firms where their EngD projects were hosted. This number seems to be relatively high and needs to be compared with a broader data of EngD/IDC alumni destinations. For those interviewed who were not employed by their sponsoring firms, the majority seems to have stayed within the same industry sector related to their EngD projects. Some individuals, mostly fresh graduates, have ventured into completely different sectors. In addition to tangible qualifications, former REs have benefited from broad range of skills and competences gained through the EngD programme including technical, analytical, transferable and business related skills, as well as working experiences during the programme embedded within industry. One former EngD student commented on her career development after EngD programme (Manufacturing) moving into a banking sector.

> *"Personally EngD gave me confidence to look into different industry* – far reaching different job opportunities. *....tangible skills, project* management experiences, maturity, overall exposure to business environment, finance management, operational management, working with different people, working on commercial goals; all useful *to advance my career."*

Many of the RE alumni positively link the EngD experiences to their employment, as the programme allowed them to be embedded within the firm and to develop their expertise and skills, leading to employment opportunities. Some of the EngD graduates interviewed have had international career mobility after the completion of the degree. Whilst the EngD scheme/IDC is designed for those who want to work in industry, some EngD graduates move between industry and academic careers – some chose to build academic career right after the EngD programme, and others move from industry to academia sometime later during their scientific career trajectories, including senior academic positions.

From interview results with twenty EngD alumni, those who had already worked at the sponsoring firms as existing employees tend to stay on after their EngD programmes. Relatively higher number of those who had prior industry experiences somewhere else and enrolled on the EngD seem to secure the job at the sponsoring company after the EngD programme than the EngD graduate without prior industry experiences. Those EngD graduates who entered into the programme straight from university degrees seem to have more diversified career pathways, sometimes moving sectors. In terms of career progression, the interviews with the EngD graduates show that upon the completion of their EngD programmes, 8 out of 20 REs (40%) continues to stay within technical roles, and have since been promoted into more senior roles within the technical fields. Another 8 REs (40%) has made a career change towards more managerial roles.

4.3 Destinations of the EngD graduates – the DLHE survey preliminary analysis

In order to better understand the factors and processes that influence the STHC development, destinations and career trajectories of the EngD graduates were examined, through national data-sets available under the UK DLHE survey data. As mentioned earlier, 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. For the purpose of the study, the EngD graduates' records were provided by the EPSRC and matched by the HESA with the DLHE survey data of doctoral graduates. Due to the consistency of the data, the EngD graduates data available is limited – 125 graduates over the three academic year combined (2008/9-2010/11).[3] Data on three cohorts of students (2008/09-2010/11 academic years combined) was matched and made available for the pilot study. An equivalent set of data on Industrial CASE PhD graduates funded by the EPSRC was also made available. There are 125 EngD graduates across the three cohorts and 201 Industrial CASE graduates for the same period.[4] Some of the preliminary findings from the analysis of the DLHE data are presented here. Where appropriate and possible, references are made to the Industrial CASE PhD graduates and other PhD graduates. [5] The main purpose of the analysis is not to compare these different types of doctoral programmes, but to illustrate

[3] The survey fields are somewhat different prior and after this period, which makes the comparison across years difficult.

[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 organisation. The time spent within industry is significantly shorter than that of the EngD.

[5] Where appropriate, the HESA DLHE data on overall PhD graduates across all disciplines (total number 20,795; 2008/09-2010/11 academic years combined) is stated. In addition, where possible, the DLHE data was sorted by "Principal subject" and 14,453 graduates' data with the "Principal subjects" A-K was extracted, which broadly correspond with the subjects of doctoral students funded by the EPSRC EngD and Industrial CASE schemes.

various contexts of impacts related to the doctoral programmes with varying forms of industry collaboration.

For the three year cohorts examined, EngD graduates' destinations demonstrate some of the characteristics of the scheme and the nature of the impact that are distinguished from those of other science and technology PhDs and the Industrial CASE, also funded by the EPSRC. In terms of the employment six months after qualifying from the course, 91.2 % of EngD graduates are in Full-time paid work (including self-employed). This compares favourably to Industrial CASE graduates (79.6%), Other PhD (all disciplines) (73.9%) and Other S&T PhD (principal subjects A-K) (78.8%).

There is a question in the DLHE "How did you find out about this job?" Relatively higher number of the EngD graduates found their jobs through "Personal contacts, including family and friends, networking" or "Already worked there". 24% of the EngD graduates found a job as they "already worked" there (including but not necessarily the sponsoring firm), which is higher than Industrial CASE graduates (10%) and Other PhD (all disciplines) (16%). This could be a result of the different lengths and extents to which the students are engaged with the future potential employers during their doctoral training forming networks and social capital.

In terms of the sectors of the employment, 85% of the EngD graduates work in non-Education sector - 32 % of EngD graduates work in "Manufacturing", 27 % in "Professional, scientific and technical activities", 15% work in "Education" sector. Whilst the EngD scheme primarily intends to train students who want to work in industry, the career dynamics of the EngD graduates illustrate the inter-linked STHC formation processes across multiple boundaries - between academia and industry, between industry firms, between sectors, and sometimes between national boundaries. In terms of the graduates' geographical destinations and sectors of employment after the EngD programmes, there is a regional variation. In London and South East the EngD graduates work in a broad range of sectors including "Professional, scientific and technical activities" "Information and communication" "Human health and social work activities" as well as "Education" whilst majority of graduates in East Midlands are employed in "Manufacturing" sector, reflecting the industry characteristics of each of the region.

Salary data in the DLHE is limited in terms of the size of the samples available. It is difficult to draw a general conclusion from the salary data presented here and careful interpretation is required when using the information. From the preliminary analysis, the findings suggests positive impact for the EngD graduates - for those who are in full-time employment, 33.3% of the EngD graduates earn more than £35K per year. This compares favourably to other PhD graduates. An earlier study (PA Consulting Group/SQW Consulting, 2007) also demonstrates that the EngD graduates earn higher salary than the comparable PhD graduates. Further comparative information could be sought on salary benefits between EngD alumni and cohorts of otherwise identical individuals (e.g. those who hold PhDs instead of EngD post graduate qualifications; those who had worked in industry over 4 years after undergraduate qualifications or Masters qualifications) (see PA Consulting Group/SQW Consulting, 2007).

In sum, the analyses of the DLHE survey (2008/9-2010/11) seem to demonstrate the impact of the EngD graduates in terms of the advantage in employability, that compares favourably to PhD graduates in comparable subject areas (see). In addition, the EngD graduates tend to gain higher salaries than PhD students in comparable subject areas (see and also see PA Consulting/SQW Consulting, 2007). However, the number of DLHE data available for the EngD graduates is limited and a careful interpretation and understanding of the variety of institutional contexts of each of the Centre is needed.

4.4 Cross-boundary mobility of the EngD graduates

Individual EngD graduates choose their destinations according to a number of factors, opportunities at the sponsoring companies or the firms in the same industry sector, or wider and longer career perspectives, often based on personal reasons. All these factors affect their career trajectories and geographical mobility, leading to different forms of “S&T human capital” development. In this section, a short summary of the findings from the DLHE survey is supplemented by the case studies of three IDCs, in terms of the patterns of career trajectories, mobility and knowledge flows with the EngD graduates in different industry sectors.HESA DLHE survey data provides systematic information on the career destinations of the UK HE leavers six months after the completion of their studies, and highlights certain characteristics of the EngD graduates and their career patterns.

In order to illustrate a variety of 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-organisational 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”.

CASE 1 Optics and Photonics Technologies (Heriot-Watt University with Universities of Glasgow, Straghclyde 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 (previously, also in the US and South Africa), nearly half of the EngD graduates between 2005 and 2014 are located in areas surrounding Edinburgh and Glasgow. 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.

There seem to be local scientific-technical labour market operating. 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 IDC, over years, have facilitated inter-sectoral knowledge flows and a variety of forms of industry collaboration. 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).[6]

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 EngD graduates got Charted Engineer status soon after the EngD graduation, and another is working towards it (source, EngD alumni profile on the University website).[7] 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 take 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 entrepreneurial opportunities abound (Lawton Smith et al., 2014). In particular, UCL seems

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[6] http://www.birmingham.ac.uk/schools/chemical-engineering/postgraduate/eng-d/index.aspx [12/12/14]
[7] http://www.birmingham.ac.uk/schools/chemical-engineering/postgraduate/eng-d/alumni.aspx [12/12/14]

to provide opportunities for research-oriented creative entrepreneurs to be part of the academic environment. One of them has taken up institutionalised 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.

5. Discussion

It is suggested that innovation requires more human capital and high skills, whilst there has been growing perception of mismatches betwen the supply and demand of doctoral graduates (Lee etal., 2010). In order to reduce such mismatches, collaborative doctoral training schemes are supported by public funding in different naitonal contexts. It is expected that these schemes will help bridge the gap between science and innovaiton. The empirical focus of this paper is on the impact and 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, mechanisms of S&T human capital formation, and interactions between research and various forms of individual social practice, including graduates' career destinations and mobility.

Industry partners' perceptions of the impact of different public schemes and doctoral training schemes (e.g. PhD, EngD, Industrial CASE PhD, and KTP) would have significant policy implications. Different conditions and contexts of collaborations need to be distinguished, including mechanisms of funding and the time required to spend within industry. In this paper, some of the characteristics of the EngD and Industrial CASE schemes are mentioned. Whilst these schemes are not technically comparable (i.e. funded under different policy objectives and conditions), differences in terms of the factors and processes of STHC development of the two schemes could be investigated further.

This paper is illustrative and exploratory in nature, and is limited in terms of explanatory power. Further 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 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 S&T human capital formation, which seems to be distinctly conditioned by disciplinary areas and industry sectors. Micro dynamics of individual career pathways and mobility can be further investigated as a form of social practice within the wider social systems individuals belong to.

The EngD Centres/IDCs have acted as the connecting nodes for the development of R&D skills, entrepreneurial resources, S&T 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 have led to knowledge generation, knowledge exchanges and exploitation with diverse spatial implication – connecting the local, national and international knowledge flows, skills, R&D and sometimes, entrepreneurial career pathways.

The short illustrative cases of the three IDCs highlight different patterns and micro-dynamics of the graduates' mobility after the graduation and impact arising from the collaborative relationships. The EngD graduates are "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) through the collaboration between academia and industry. 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 methodology adopted in this pilot study has a number of limitations and the findings need further verification. Interviews were limited in terms of scope and representation. It should be emphasised that the intangible and interactive nature of the relationship building through the EngD scheme and capturing long term impacts from such relationships provide fundamental methodological challenges to the evaluation of the collaborative scheme, especially in terms of a quantifiable outcome-based measurement. Conceptually, this study contributed to the process-based understanding of the innovation. For the university, the EngD model illustrates the interactions and synergies between research, teaching/training, academic engagement and other knowledge exchange activities (see Perkmann et al., 2013). Existing data on the career destinations and progression of collaborative doctoral graduates is limited in order to understand the processes of STHC development.

Other data sets such as the number of co-publications, co-patent applications, combined with social network analysis may provide more information and analytical tool in order to identify and track career trajectories as well as the variety of collaborative relationships formed through the collaborative doctoral training scheme (see Youtie, et al 2013). Some of the impacts such as networks and continuing informal collaboration may not be quantifiable. Detailed case studies of EngD alumni and their career pathways in different discipline areas, industry sectors, and different types and sizes of sponsoring firms would add more value in order to enrich our understanding of impacts of specific collaborative doctoral programmes.

The collaborative and interactive nature of cross-border relationships provides fundamental methodological as well as conceptual challenges to the evaluation of the collaborative scheme, interactive nature of relationships building for all the stakeholders concerned, including the universities, funding bodies and for the industry partners. This paper highlighted the cross-border mobility of individual graduates who bridge the gaps between science and innovation by presenting qualitative and illustrative case studies from different industry sector contexts. Further lessons could be drawn from international comparative studies across different sectors and across different programme types as well as longitudinal studies on career pathways of scientists and R&D professionals at various career stages.

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Annex

Table 1: Impacts from research and training – summary of literature

Innovation-related impact	A number of routes from research to impact come through "innovation processes" as part of a broader R&D collaborative environment (PA Consulting Group/SQW Consulting, 2007).
	Innovation processes are influenced by broader R&D environments, including demand for innovation, knowledge exchange efficiency and other framework conditions (DTI, 2007).
	It is pointed out that often major breakthroughs in innovation in such collaborative partnerships occur from some of the most informal interactions, and capturing these interactions is often the most difficult part of measuring impact and outcomes (CBI, 2010).
People-based partnership scheme and Spill-over effects from the collaborative relationships	People-based partnership schemes including the EngD and the CASE studentship/Industrial CASE focuses on the use of doctoral students as "agents of change," who are able to realise the benefits of cooperation, hence, creating spill-over effects from the collaborative relationships (Butcher and Jeffrey, 2007).
	Graduates and doctorates act as *knowledge networks* between public and private sectors – "raising absorptive capacity and assisting the dissemination and deployment of research results" (PA Consulting Group/ SQW Consulting, 2007).
	Such networks are actively promoted by the Research Council through different collaborative doctoral schemes (Demeritt & Lees, 2005). There are other collaborative schemes such as Knowledge Transfer Partnerships (KTP) (Gertler et al., 2010), which could be combined with a PhD study.
Skills development and Future S&T leaders	Graduates bring into industry an "attitude of the mind" and a "tacit ability" to acquire and use knowledge in useful new ways. Such abilities are highly valued by industry (Senker, 1995).
	Specific knowledge of recent research training and techniques are complemented by more generic skills; the ability to solve complex problems, the skills to perform research and the ability to develop new ideas (Martin & Tang, 2007). It is reported that employers value those with STEM skills, not only for their subject specific knowledge, but for their wider knowledge base (DIUS, 2009).
	These students and researchers enhance the capacity for "problem–solving" - through "knowledge manipulation and analytical skills enhanced through graduate training" (PA Consulting/ SQW Consulting, 2007). Analytical problem-solving is a desirable skill which is recognised by business communities (Demeritt & Lees, 2005).
	Training and developing *the next generation of science and technology leaders* is also recognised as the impact of such schemes, where doctoral engineers work at the frontiers of "innovation, substantial and varied industry problem-solving experiences, and insights into future challenges (and opportunities)" (O'Sullivan, 2011).
Behavioural changes	Research impact may occur due to the behavioural changes, so-called *behavioural additionality*, rather than stimulating additional research inputs (input additionality) and associated increases in research outputs (output additionality) (Buisseret et al., 1995).

Table 2 Industry interviewees

Sector/nature	*No of Interview participants*
Manufacturing	3
Pharmaceutical	1
Engineering Consultancy	2
Energy	2
Water management	2
Nuclear member organisation	1
Public research organisation	1
Consumer Goods	1
Retail	1
Geoscience	1
Total	*15*

Table 3 Alumni interviewees; years of industry experiences before EngD

IDC Sector	*No of Interview participants*	*Before EngD Fresh graduate*	*Before EngD with more than 3 years Industry experience*
Manufacturing	**9**	5	4
Sustainability	**2**	2	
Systems/Engineering Consultancy	**1**		1
Construction	**1**		1
Nuclear manufacturing	**2**	1	1
Water management	**1**	1	
Micro and Nano Materials	**1**	1	
Optics and Photonics	**2**		2
Formation engineering /Consumer goods	**1**	1	
Total	***20***	*11*	*9*