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SKILLS OF PHD GRADUATES FOR OPEN SCIENCE AND OPEN INNOVATION

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Abstract

The study presents findings from the analysis of skills useful for Open Science (OS) and Open Innovation (OI). Employers both within and outside academia and employed PhD graduates and students in the Czech Republic, Ireland and Denmark were interviewed and job postings aimed at research vacancies were reviewed to identify key skillsets useful in broadly defined OS and OI environments. Five skill profiles of PhD graduates have been identified: (1) collaborative and interdisciplinary research, (2) practical applicability of research results, (3) involving the wider public in research, (4) use of Open Science tools and (5) career planning. Implications of the findings for possible interventions in PhD education systems are discussed.

Keywords: PhD education, Open Science, Open Innovation, skills

DOVEDNOSTI ABSOLVENTŮ DOKTORSKÉHO STUDIA V OBLASTI OPEN SCIENCE A OPEN INNOVATION

Abstrakt

Studie prezentuje výsledky analýzy dovedností užitečných pro Open Science a Open Innovation. Byly provedeny rozhovory se zaměstnavateli z akademické sféry i mimo ni, se zaměstnanými absolventy doktorského studia a doktorandy v České republice, Irsku a Dánsku, a byly prozkoumány pracovní nabídky zaměřené na volná místa ve výzkumu s cílem identifikovat klíčové dovednosti užitečné v široce definovaných prostředích OS a OI. Ze zjišťovaných informací a názorů respondentů vyplynulo pět profilů dovedností absolventů doktorského studia: (1) spolupráce a interdisciplinární výzkum, (2) praktická využitelnost výsledků výzkumu, (3) zapojení širší veřejnosti do výzkumu, (4) využívání nástrojů Open Science a (5) plánování kariéry. Diskuse se věnuje těmto zjištěním jakožto východiskům pro možné úpravy systému doktorského vzdělávání.

Klíčová slova: Doktorské studium, Open Science, Open Innovation, dovednosti

INTRODUCTION

Traditionally, PhD education has been designed as individual work on a long-term research project, followed by a thesis defence. The PhD mentor is the main source of feedback for the PhD candidate. Graduates tend to search for academic jobs, for which they are being prepared during their PhD education. There are, however, clear trends that indicate the need for this concept to evolve. Jobs throughout the labour market are getting increasingly complex, creating more demand for research-oriented specialists outside

the academic sector, which, on the other hand, does not have enough capacity to absorb all the PhD graduates. Academic science is evolving towards more team-based and interdisciplinary work with an emphasis on sharing data and research outcomes with collaborators and wider audiences (Ledford, 2015). Therefore, making PhD education more flexible and open to various potential careers may benefit both the PhD graduates and society.

This study aims at identifying the skills of highly qualified workers required in academic and non-academic sectors. For this purpose, semi-structured interviews with employers, employed PhD graduates or students and educators of PhD students were carried out in the Czech Republic, Ireland, and Denmark and complemented by a job posting review in these countries. The study is based on broadly understood ideas of Open Science (OS) and Open Innovation (OI), in which interdisciplinarity, teamwork and cooperation across institutions and between academia and other sectors are vital elements. It is a contribution to ongoing attempts to diversify doctoral education regarding the aims of the study, organisational forms and career outlooks of the graduates (Kosová *et al.*, 2019, 26–40; Hnátková *et al.*, 2022).

1. BACKGROUND

Globalisation and technological advances indicate that there will be changes in sectoral structure and demand for new types of skills that we are not even currently anticipating. Employment in R&D positions has been increasing rapidly (+31 % in the EU between 2011 and 2020), while the trend is driven by the business sector (+46 %) much more than by universities (+20 %; Eurostat, 2021). On the other hand, ever more people get PhD-level education: in the USA, the share of PhD graduates in the population 25–64 years grew from 1.3 % to 2.0 % in 2005–2020, and the same trend is observable in the EU (OECD, 2021). Typically, less than half of doctoral graduates will be employed in academia immediately after graduation and even less after a few more years (Boman *et al.*, 2021, p. 49). This leaves a significant majority of PhD graduates seeking employment outside the academic setting during their careers, for example in industry and non-commercial organisations, whose significance as employment destinations for PhD graduates has been rising in the past years, at least in the USA (National Center for Science and Engineering Statistics, 2019). It is therefore clear that these graduates need to possess many of the required skills for purposeful employment.

That does not apply only to non-academic jobs. In academia, international, interdisciplinary and intersectoral networks are on the increase with established researchers collaborating within and across disciplines to increase and improve innovation, creativity and knowledge (Chung, 2018, p. 77–95; James Jacob, 2015). More recently, this is being mirrored by the establishment of interdisciplinary and intersectoral doctoral research networks, the intention of which is to train PhD graduates for careers both within and outside academia and who are equipped to address societal challenges (Mountford *et al.*, 2020).

A gap has, however, been identified in current doctoral curricula. Current offerings do not always foster big thinkers and creative problem-solvers – graduate attributes our society needs (Bosch, 2018). It is recognised globally that the science and technology workforce is inadequately prepared for careers in the coming century (National Academies of Sciences, Engineering, and Medicine, 2017). The identified gaps relate not just to skills in data analysis and problem-solving, but also teamwork, interdisciplinary communication and the ability to collaborate with non-academic partners that span multiple cultures, geographic regions and time zones (Stokols, 2018). It is becoming apparent that there is a growing need to re-imagine a PhD education that incentivises doctoral students to engage with other knowledge creators and consumers, not only within their discipline but also across other disciplines and sectors to have a real societal and economic impact.

Open Science is an umbrella term that encompasses a number of key elements: open access & peer review, open software, data and research infrastructure, open educational resources, open partnerships and citizen science. It has been defined as follows: "Open Science comprises a set of institutional policies, infrastructure and relationships related to open access publication, open data and scientific resources, and lack of restrictive intellectual and other proprietary rights with the goal of increasing the quality and credibility of scientific outputs, increasing efficiency, and spurring both discovery and innovation" (Ali-Khan *et al.*, 2018). The notion of Open Science is not new, but advances in communication technologies and changing innovation policies have given the movement a new impetus in recent years. The rationale underpinning the practice of Open Science varies across its proponents and includes the democratisation of knowledge, better bidirectional citizen-scientist communication, increased research

transparency and reproducibility, decreased redundant research and more efficient scientific/economic progress enabled by open partnerships and infrastructures. However, Open Science has not yet achieved its breakthrough despite its potential. That is thought to be due to a variety of interacting factors such as research culture, academic research incentives and business models unaligned to Open Science practices, a lack of science capital among the general public and tokenistic involvement of community/indigenous groups in research. Additionally, there is no single standard for Open Science which results in different organisations, governments, and firms applying Open Science in heterogeneous ways. It is not the focus of this study to examine in depth the barriers and enablers of practising Open Science or the merits of these arguments. Rather, we are focused on skills related to Open Science in a broad sense in order to inform future education interventions.

The term "Open Innovation" was first defined by Chesbrough (2003) as a process of combining internal and external ideas as well as internal and external paths to market to advance the development of new technologies. The concept was originally limited to the level of an organisation, later the scope expanded to the level of industries, regional innovation systems and the society as such (Chesbrough & Bogers, 2014; Bogers *et al.*, 2016). The concept has expanded also in policy and practice and has been applied to several sectors beyond the development of new technologies. Open Innovation networks, characterised by open partnerships, have been described in terms of a triple helix, a quadruple helix and most recently, a quintuple helix model. The triple helix model represents trilateral networks between university-industry-government linkages for the purpose of targeted knowledge co-production and use (Etzkowitz and Leydesdorff, 2000). A fourth less institutionalised type of actor was added to the system – i.e. civil society in its manifold forms that participate as partners rather than just receivers of innovation processes, making it a quadruple helix. In the quintuple model of innovation, Carayannis *et al.* (2012) have added a fifth important element: the socioecological perspective of the natural environment. Given the prominence of sustainability in these times and considering the effects of the Covid-19 pandemic where vulnerabilities around resource use and the fragility of supply lines have been exposed, resource-producing ecologies that fuel innovation networks of the future need to be understood. Do PhD graduates of today possess the necessary "interaction competence" to

participate in networked collaboration between different skill sets, sectors, epistemologies, cultures and helices?

The recent findings of an in-depth study by Reichert (2019) described in detail the features of nine Open Innovation networks in nine European countries based on over 130 interviews. They report seven profound changes, "perhaps even paradigm shifts" in the conception and organisation of innovation:

1) from linear to nonlinear innovation;
2) from closed to open innovation;
3) from technological to systemic challenge-driven innovation;
4) from individual to collaborative and interdisciplinary innovation;
5) from spontaneous innovation to systemic innovation;
6) from exchange-based innovation to co-creation in innovation spaces;
7) from innovation projects to common innovation cultures.

The authors conclude that collaborative research, challenge-based learning projects and impact-oriented start-ups are the most important ingredients in the universities' role in regional innovation and the very fabric of innovation ecosystems. This study provides an important vista into the future through these exemplars of Open Innovation networks that span many different domains, yet exhibit many similar characteristics, as enumerated above. How PhD graduates enter these new Open Innovation networks, what attributes they value within themselves in contributing to these types of innovation networks and what skills are valued by their employers, are currently not known. The skills analysis presented in this study enables us to understand valued learning outcomes that support employment in innovative environments from the perspectives of graduates, educators and employers.

A related ecological conceptualisation of researcher education encourages 'the student [to venture] across the ecosphere of the university' (Barnett, 2018), which involves engaging with an assemblage of external stakeholders and partners, including the wider societal and cultural domains. Learning that takes place outside the disciplinary/institutional environment is valued because the interconnectivity of these learning domains is what sustains research momentum and creativity (Bengtsen, 2019). Thus, the learning spaces that PhD students navigate and integrate throughout their research journey are forms of micro-/meso-ecosystems, with some similar features to

Open Innovation networks i.e. both are complex networks of informational resources and skills that need to be assimilated and then accessed under a variety of changing situations. Gaining a deeper understanding of how one ecosystem interacts with the other, and how this can be influenced through the affordances of an open and socially connected online learning environment is what drives the novel research reported here.

The skill analysis presented in this study rests upon the above-mentioned concepts of Open Science and Open Innovation. We understand **Open Science** as practices that enhance accessibility and transparency of scientific procedures and outputs (open access, open data, open source code) and as efforts to encourage scientific cooperation within and across organisations, disciplines and individuals. We understand **Open Innovation** as a cooperation of organisations in innovating products, services, and processes, and sharing relevant valuable knowledge.

2. METHODOLOGY

The core method of the exercise was semi-structured interviews. Three groups of respondents were recruited: employers (from academic, state, business and NGO sectors), PhD graduates or students (mostly employed outside academia) and representatives of institutions that provide education in fields related to OS, OI or entrepreneurship (educators). In April and May 2021, interviews were carried out in Ireland, the Czech Republic, and Denmark, the countries involved in the international project, within which this exercise was performed. The total number of interviews reached 35, of which 18 were with employers (6 academic, 2 state, 9 business and 1 NGO), 10 with PhD students and recent graduates (up to 5 years from graduation) and 7 with educators. Interviewees in the first group were sought among companies and organisations that collaborate with other organisations in research and innovation at the institutional level and share valuable knowledge with them. Out of these, non-academic employers were to be represented by at least half of the sample to account for the diverse potential careers of PhD graduates. With the same aim, PhD students and graduates were sought only among those who worked outside academia. Representation of various industries and disciplines of the study was accounted for in the recruitment process. The complete list of the conducted interviews is in the appendix, including codes of interviews that we will

be using throughout the study. The codes consist of a country marker (IE for Ireland, CZ for the Czech Republic, DK for Denmark), a respondent type marker (EMP for employers, PHD for PhD graduates or students, ED for educators) and a number of the interview within each group of respondents within each country.

The interviews explored the following core topics:

- What transversal (field-unspecific) skills do employers active in OI / OS value the most in their highly qualified workforce
- What skills (specific for OI / OS but also other skills) do PhD-level employees lack and/or need to develop for the future
- What is employers' experience with hiring PhD graduates
- How has PhD education prepared the students and graduates for their current roles
- Where do the employers and PhD students/graduates see possibilities for PhD education to improve?

The respondents were also asked about their understanding of Open Science / Open Innovation, about activities of their organisation or their own activities within the organisations with a focus on research and innovation. Interview guides were developed to structure the interviews, based on a previously agreed framework. The interview transcripts were analysed with the use of coding of patterns and meanings that were found in them and deriving themes from them, following the principles of thematic analysis (Guest, MacQueen & Namey, 2012).

Compared to long-term research carried out by universities using institutional and grant-based public funding, the position of research in private enterprises, state organisations and NGOs is much less clear-cut and more diverse in their motivation, forms and funding. That is reflected in the survey sample of our interviews. Among the interviewed employers and the employers of the PhD graduates and students, we find research and development for own commercial use, institutional or personal links to academia (especially museums and hospitals), research projects with outputs used outside the organisation, promoting science to wider audiences and innovation consulting.

Besides the interviews, a review of job advertisements for research-related vacancies was undertaken. Academic (universities, academies of science) and other job postings, potentially aimed at PhD graduates,

academic and other job postings were reviewed for skills and tasks related to teamwork and cooperation, those associated with fields other than the focus of the positions (in search for interdisciplinarity) and other transversal skills. Vacancies were retrieved from popular job portals and the websites of academic institutions. The following keywords were used for filtering relevant non-academic advertisements: "Open Science", "Open Innovation", "PhD" (as a requirement or advantage for the candidates) and "research" (limited to university-degree jobs). In total, 443 academic and 408 other job postings from March, April and May 2021 were reviewed across the three countries. We will refer to the three country reviews as "Job postings CZ", "Job postings IE" and "Job postings DK".

3. RESULTS

Understanding and practising Open Science and Open Innovation among employers and employed PhD graduates/students

The interviewees were asked what they understood by the terms Open Science and Open Innovation. For Open Science, the first connotation was usually open-access publication of research outputs or data. That was by some respondents recognised as a generally positive phenomenon with growing promotion on the EU level, although, specific strategies in this respect are often lacking by employers, as admitted, for example, by DK_EMP_05. Among the benefits for individual researchers, the visibility of their work is the clearest one (CZ_ED_02). The same principle may be the case at the level of organisations – a Danish employer who carries out both academic and commercial research attracts potential customers by open-access publishing (DK_EMP_04). A strongly demotivating factor for researchers is the pressure to publish in high-impact publications that are usually closed behind a paywall (IE_ED_03, CZ_ED_02). Among broader concepts related to interviewees' understanding of Open Science, the democratisation of research appeared. According to the representatives of the field of digital health, the worlds of clinical and technical research should open to the needs of all societal segments that they want to serve with their solutions and so become more democratic than is currently the case (IE_EMP_08), more diverse in representation (IE_EMP_06) and allow the voices to be heard of those who are impacted by the research (IE_PHD_04). Such a trend is also seen in the field of architecture

where citizens affected by architectural developments are now given more say than in the past (CZ_PHD_01). Interviewees across sectors and disciplines spoke about the need to open the traditionally individual *"siloed"*[1] research on three levels: to immediate collaborators, to other researchers including those from different disciplines, and to the general public.

"Open Innovation" resonated less with the interviewees. When asked about practices possibly related to the concept, private-sector employers mentioned various forms of research collaboration, but mainly with academia (IE_EMP_06), where Open Innovation might resemble commercialization (IE_ED_02). For other entities, collaboration on innovations lies in outsourcing activities that are outside the core business of the company (e.g. CZ_EMP_05, CZ_PHD_04). Important know-how is usually protected during collaboration with other companies or universities[2], and a challenge to this approach in the interest of gaining benefits from thoroughly collaborative R&D did not emerge strongly from the interviews. On the contrary, scepticism was expressed regarding the possibility to reconcile truly Open Innovation with generating profit (IE_EMP_01, IE_PHD_03). That was confirmed by employers' ideas that PhD students should be taught more about patent procedures (CZ_EMP_01), specifically that they should not publish their commercially valuable results before patenting them (CZ_EMP_05). An exception might be the use of increasingly available open-source codes in IT, created by crowdsourcing, by spontaneous activities of enthusiasts or by large companies, and afterwards usable by others (CZ_EMP_04, CZ_PHD_02, IE_ED_03). Some Open Science educators see Open Innovation as a separate concept they are not familiar with (IE_ED_01, CZ_ED_01) and vice versa for an Open Innovation educator (IE_ED_02).

The usefulness of a PhD for non-academic work

While the link between PhD education and potential subsequent academic employment is obvious, in the case of other careers, the perception of

1 DK_PHD_01, IE_ED_02, IE_EMP_02, IE_EMP_05, IE_EMP_07, IE_EMP_08, IE_PHD_02, IE_PHD_03, IE_PHD_04.

2 CZ_EMP_03, CZ_EMP_04, CZ_PHD_01, CZ_PHD_02, CZ_PHD_03, CZ_PHD_05, IE_PHD_01.

the applicability of the skills obtained during a PhD in non-academic settings varies more. The PhD graduates and students we spoke to had chosen their non-academic jobs usually on purpose, often with the intention to do practical work with a clear impact in the "real world". Nevertheless, they mentioned many benefits of their PhD experience for their work even if they believed they would be hired without a PhD. Methodological rigour and awareness about the limits of methods are one of these because they are hard to develop outside academic research (IE_PHD_03). Relatedly but more broadly, critical thinking is what a PhD medicine graduate feels distinguishes him in the treatment of patients and processing of information from drug distributors (CZ_PHD_05). Scientific knowledge is useful to better understand the background of practical solutions and increases the ability to explain them to clients (CZ_PHD_01). Resilience and independence naturally needed to finish a long-term PhD project are useful for any demanding job (IE_PHD_02). Besides the scientific core of the PhD education, teaching experience, conference, and international activities have been important for improving confidence and gaining valuable contacts (IE_PHD_01), even in the case of graduates who look at their PhD as a closed chapter (CZ_PHD_03, CZ_PHD_04).

These opinions of PhD graduates are mostly in line with those of employers. Independence of PhD graduates is highly appreciated, as much as their ability to see things in a broader context and to look for new knowledge in individual learning, where the capacity to read scientific articles might be an added value (CZ_EMP_04, CZ_EMP_05, DK_EMP_03). Employers also appreciate the PhD graduates' willingness to look for answers to complicated problems (CZ_EMP_05). That can be also seen as the courage to start solving a problem that nobody else has solved, thus facing considerable uncertainty and risk, as every PhD student experiences on their journey (DK_EMP_01). On the other hand, employers also highlighted disparities between business work and the PhD experience, especially a very different ratio between a focus on a method and on output, problems with deadlines, detachment from practical problems and little knowledge of the market (CZ_EMP_02, CZ_EMP_04).

Skill profiles of PhD graduates related to Open Science and Open Innovation

The main aim of the skills analysis was to identify key skills of PhD-level employees and job candidates related to Open Science or Open Innovation

concepts. Based on the interviews and job postings, the skills can be grouped into five skill profiles, presented below.

Collaborative and interdisciplinary research

The core of traditional PhD studies is often an individual research project that lasts several years. This model, however, is not mirrored in the reality of research jobs where work in teams and collaboration with experts from different disciplines is often and probably increasingly necessary (CZ_PHD_01, IE_PHD_01). In an individual PhD project, an early career researcher is often not exposed and/or not incentivised to engage in collaborative work which could be beneficial to the quality of research outputs. The PhD researcher can become more open to generating new ideas on an individual level by working collaboratively. PhD education is often, thus, carried out in a manner that very much differs from what the graduates face at their jobs. An isolated, highly focused PhD journey may not help early career researchers in developing the full potential of their research ideas nor in developing a network of contacts useful for their subsequent careers. At the same time, it should be kept in mind that some disciplines, e.g. history and music, have a strong tradition of individual work, and collaborative research can be more difficult to design (DK_EMP_05, IE_EMP_04).

In the view of employers and PhD graduates, it is highly desirable that teamwork and interdisciplinary skills are developed more during PhD studies. A pre-condition for that is the ability to see one's own specialisation in a broader context. The PhD students should regularly dive out from their deep work on a narrow topic in order to see, as one interviewed educator put it, that the airplane for which you design the metal for the propellor has to fly in the sky (IE_ED_02). It is a more system-thinking approach that is also in line with the movement of business models away from a focus on single elements to creating whole complex solutions. PhDs should be able to think about how their research relates to other topics or fields, what is the place of their research in the bigger picture, what expertise other than their own they need and, vice-versa, how they can contribute to other topics and fields. On the part of employers, this is reflected in a common requirement for readiness to work as a member of interdisciplinary teams rather than being thoroughly interdisciplinary as a person (Job postings CZ, Job postings IE, CZ_EMP_01). Such teams may also include various types of stakeholders

and professionals, sometimes called "cross-functional teams" (Job postings DK, Job postings IE). When different types of stakeholders are involved, it is necessary to bear in mind that expectations vary because, for example, value does not mean the same thing for academics and businesses (IE_EMP_01, CZ_PHD_02).

Based on such considerations, PhD students should be actively looking for opportunities to cooperate with other researchers. Participation in conferences, internships at other institutions and reaching out to potential colleagues with sensible suggestions for cooperation are all methods for connecting a narrow specialization to the outside world. Once individual researchers start creating a network around themselves, a cycle of success is started, because contacts bring about more ideas and more opportunities for future projects and possibly also for funding and employment (IE_EMP_02). Creating cooperative networks is very much facilitated by an ability to adapt one's own language style to audiences from various fields so a real mutual understanding can be reached (IE_PHD_01). On a higher level, the ability to work in interdisciplinary collective environments can be complemented by the skill to lead such diverse teams where even more perceptiveness to other colleagues' thinking and passions is necessary (IE_EMP_01). Academic employers see established professional networks as a value that job candidates bring with them into the organisation (Job postings CZ, Job postings IE, DK_EMP_02).

In this context, interpersonal skills play an important role. Unlike most other roles in a non-academic setting, a PhD student does not have to think much about colleagues' feelings and attitudes and develop compassion and empathy that is otherwise crucial for maintaining good cooperation (IE_PHD_03). A step to change that is learning how to give feedback on others' work and also how to accept feedback from peers and not take it personally if it is not positive (CZ_PHD_ED, IE_ED_03, IE_PHD_03). Researchers should learn how to show respect for each other's work so the interdisciplinary teams flourish (IE_ED_01) and also for the work of non-experts in their teams (IE_ED_02). Regulation of one's own ego that is often over-blown in experts' minds would ensure that researchers do not start needless conflicts with colleagues (CZ_EMP_03, CZ_EMP_04), a phenomenon that is summed up by the phrase "collegial approach" from academic employers (Job postings IE). Beyond the cooperation itself, a subsequent reflection of one's own and others' experience of the joint work further enhances self-awareness and the ability

to engage in other collaborations (IE_EMP_05). In this way, humility and acknowledgement of one's own limitations can replace the "tunnel vision" that is typically associated with an individual, long-term project (IE_PHD_03).

The practical applicability of research results

One of the components of our notion of Open Science and Open Innovation is opening more possibilities for PhD graduates to find jobs outside of academia. For that, the graduates need to be used to thinking about who and how may use the results of their research. There are good reasons for the abundance of recommendations to support that. Firstly, a tension between work habits and the mindset produced through university research versus the way of working in research and innovations in companies and other non-academic environments is strongly felt by both employers and PhD graduates. Academic research, including during a PhD, is typically driven by self-interest in a specific question, not necessarily linked to a need or desire of someone else to have the answer, while in non-academic settings, the client/customer needs to play a much more prominent role. A different meaning of time was also evident in our data between academic and non-academic settings, as there are usually less strict requirements for the delivery of academic research outputs and a PhD project has a very long duration in itself. Many PhD students would like to find a job outside the university, and many interviewed employers were quite clear that they can make use of the skills obtained during a PhD project, which is why it is not unrealistic to assume that more PhDs in non-academic high-skill jobs would benefit customers and society in general. It is also noteworthy that in some locations in some fields, there are not enough post-doc jobs at universities to absorb all the interested graduates and that such jobs are often short-term and insecure (CZ_ED_02, DK_EMP_04, IE_EMP_04, Job postings CZ).

In order to enhance the practical applicability of research outputs, at the start of a PhD, students may ask themselves questions like who the research outputs will help, who can potentially use them and in what way, and what difference will their project make -- in other words, the "so what" question (IE_EMP_01, IE_EMP_08, IE_PHD_03, CZ_PHD_01, CZ_PHD_05). In case the answers to these questions are not satisfactory, the project may be re-designed with the needs of potential users in mind (CZ_PHD_02). That means shifting from, in a way, an egocentric perspective of what is interesting only for oneself to what can bring

value also to someone else (IE_EMP_03) and so may require Open Science skill sets, especially empathy and expectation management needed for valuable collaboration. Another component of such an approach is the ability to build relationships with industry and other partners and to offer them value (DK_EMP_02, Job postings DK, Job postings IE), even in the role of an academic researcher who would commonly need data or other help from business entities (IE_EMP_03). Awareness of the differences between work organisation in academia and in business may help one's employability in the latter and reduce culture shock. If the requirements of the research project allow it, regulation of one's own methodological perfectionism in favour of realising the need to meet goals in a certain time period could be useful, not only for a future career but also in order to avoid a commonly occurring protraction of the PhD studies, leading to frustration and risk of dropping out (CZ_EMP_05). A related requirement for industry research jobs is innovative thinking or an entrepreneurial mindset (Job postings DK).

In order to improve the above thinking and skills, it is advised for PhD students to reach outside of the academic world during their PhD studies. The importance of taking opportunities for connecting the PhD project with a non-academic institution, looking for practical internships in industry or at least talking to practitioners (DK_EMP_02) was stressed throughout our interviews. Such experiences may serve as a "reality check" of one's own research agenda and stimulate thinking on how the research results can be used (IE_EMP_01). Actually, in some fields, practical experience may be required or appreciated even from academics, as is the case of medicine, pedagogy, social work, engineering and economic fields (Job postings CZ). But even if not, the contact with the world of practice helps academics to broaden their perspective on the issues of their interest (DK_PHD_01).

Involving the wider public in research

A large part of science circulation takes place within small groups of experts on a specific topic who may account for the entire audience. In an extreme case, it can happen that a researcher *"sit[s] on the results for 35 years and then (...) will die, and no one will get any wiser"* (DK_EMP_04) or, perhaps more typically, that *"hopefully 50 or 60 people have a skim read"* of a research paper (IE_EMP_05). Wider participation of the public in science is in the interest of many of those scientists who would like to see a broader impact of their

work, and definitely in the interest of the society that, ultimately, pays for the academic research, including that of PhD students. An important aspect of moving science out of an "ivory tower" or "siloes" is, therefore, involving broader audiences in communication about research results.

On a general level, PhD students should assess in what ways their research can have value for society and who could appreciate getting acquainted with it. The researchers should then be able to attract the attention of non-experts while explaining the motivation and the results which, besides awareness of what the audience needs and appreciates, requires also adapting the language style (Job postings DK, Job postings CZ). That might not be easy because researchers often don't know how to talk about their research and how to engage the public in it, which gives rise to specialised jobs focused on research promotion. Most universities expect their academics to have a certain amount of public engagement or dissemination activities (IE_PHD_04, DK_EMP_02). That obviously places some more burden on the researchers as they then must regularly redirect their attention between different activities in order to navigate between public and research interests (DK_EMP_05). Positive experiences that were shared with us in the interviews included writing blog posts that after some time may bring opportunities coming from people who read them by chance (DK_EMP_01), running science programmes on TV (IE_EMP_04, IE_PHD_04), participation in school education (IE_PHD_04) or in public debates (IE_EMP_04).

A component of this strand is the ability to defend the need to support certain research in front of the public or other funding authorities. The pressure on academics to do that regularly is obvious as many jobs, especially post-doc jobs at universities, are tied to grant projects, and the possibility to sustain the job depends on the researcher's ability to contribute to a new funding opportunity. In academic job postings, experience from grant projects and readiness to seek new funding are widespread regardless of discipline (Job postings CZ, Job postings IE). For that, knowledge of funding opportunities and proficiency in writing grant applications is necessary. Some employers require candidates who can lead big projects, demanding team leadership and project management skills (DK_EMP_05, Job postings DK) but also financial management (DK_PHD_04).

Engagement of the public in science is, however, not one-way. Some of the interviewees mentioned the need for the affected public to have a say, give feedback and be involved in the data collection. A longer-term trend of

adapting the designed solutions to the opinions of the affected residents has been reported from architecture (CZ_PHD_01), another interviewee is familiar with a project on indoor air quality that includes community workshops and identifies with the concept of citizen science (IE_PHD_04) while the need was mentioned for the medical researchers to represent more segments of the population or at least to be aware of their needs (IE_EMP_08). This idea was also seen in the democratisation of technology in the world of wearable devices in sports (IE_EMP_05). All these approaches require the researchers to be willing to come out of their expert environment and modify the procedures and goals according to what they hear from non-experts.

Use of Open Science tools

A variety of tools that help researchers implement Open Science practices are already available. They were also mentioned in our interviews, either by educators who focus on them or by employers and PhD graduates for whom sometimes open access or open data were the initial associations with Open Science. Open Science tools have got a growing prominence especially since the onset of the corresponding EU initiatives in 2016 which was followed by the implementation of open access policies into EU-funded programmes by creating the digital infrastructure for open data and by setting up units or positions whose jobs relate to Open Science promotion and education, including those of some of our interviewees (CZ_ED_01, CZ_ED_02).

Regarding open-access publishing of research outputs, the main factors are awareness of the advantages and motivation to choose such journals over others. A clear advantage for both the researchers and their institutions is better visibility of their work which can help them to get more opportunities in the future (CZ_ED_02, CZ_EMP_01, DK_EMP_04). At the same time, it is necessary to pay more attention to identifying predatory journals as they may be misusing the growing demand to publish open access (CZ_ED_01). A serious barrier to faster development of open-access publishing is the lack of incentives for going this way, as universities require the researchers to publish in high impacted journals that commonly belong to large publishing houses with a closed access policy (CZ_ED_01). It was also noted that the potential of discovery to get patented or commercialised prevents its (open) publication (CZ_EMP_05) while in the humanities, on the other hand, *"what can happen? We will never make a million dollars out of anything we do*

here which someone else can steal" (DK_EMP_04). Similar considerations can be made in relation to publishing research data (open data). Here, in case of the absence of a requirement by an employer, funder, or publisher to do so, the motivation to publish data is often small. Nevertheless, some researchers regard publishing their data as a doorway for further collaboration and network building. The availability of open datasets is growing, and researchers need to be aware of them and have the corresponding technical skills to exploit their potential.

Technical skills are indeed central in handling open-source codes. Reusing available resources of this kind is common in the business world, though often a company will not have its own capacity to create them (CZ_EMP_04). Open-source code creates a fruitful environment for creating communities that could encompass people remotely and with an interdisciplinary background. There are also persuasive sales arguments to get involved in open source as it creates useful ties with members of these communities (IE_EMP_07). For individual researchers, open source can facilitate easy orientation in the growing volume of scientific outputs, where attempts to find and use everything relevant that has been generated on their topic previously are becoming increasingly difficult (IE_EMP_07). Open source communities are very much spanning over the boundaries of the academic and other sectors (IE_EMP_07), while competences in programming and machine learning have been found prominent in both academic and non-academic job postings (Job postings CZ, Job postings IE, Job postings DK). Moreover, there may be some opportunity to employ a more advanced understanding of programming in practical, non-academic jobs, to be able to provide the knowledge underpinning the tools in data analysis and machine learning that are nowadays easy-to-use by non-experts, in sometimes a rather mechanistic way (CZ_PHD_04). Among other tools related to Open Science, some interviewees mentioned the use and creation of open educational resources (IE_ED_03, CZ_ED_01, CZ_ED_02).

Career planning

PhD studies are concentrated on an individual project that is supposed to initiate a subsequent research career. The work on a PhD project is very specialised, and academic in its nature, and the most obvious first career option for the graduates is applying for a university post-doc position

where they could work on the same or related topic. However, such an approach may be too restrictive as it may in advance exclude many other suitable options that could open the way for the skills learnt during a PhD education to be used in other types of professional settings. Additionally, if PhD researchers open their minds to more future career possibilities, this may lessen the precarious feelings experienced as PhD researchers begin their efforts to secure a suitable post-doc relevant to their research trajectory (IE_PHD_01). As a career counsellor puts it, when PhD graduates *"approach the end of their PhD, they start worrying and think, well, 'if all I know is (...) church history between 850 and 900, you know, how is that applicable in a broader context'"* (DK_ED_02). In a similar vein, an employer in humanities believes *"we are educating PhD's to follow (...) university tracking, but there's not that space for them and I can see their sorrowful faces when they're like in the sixth year post PhD and they haven't got their positions and they haven't got the things they wanted to."*

An important, though not always easy, the task is to look at one's own PhD experience in a broader context than the research topic itself. That means asking questions such as what have I learnt during the PhD apart from what is in my thesis; how can I contribute to organisations that do not overlap with my PhD project; what skills helped me to complete my PhD? As well as the identification of one's own skills, they need to be communicated in an appropriate format and style so they are accessible and understandable by potential employers. Awareness about opportunities in the labour market needs improvement – graduates should think about non-academic careers and follow the trends in suitable vacancies outside the university (CZ_ED_02). Such considerations should start early enough so the PhD students can adapt their activities during the work on their project, including, possibly, getting in touch with potential employers (DK_ED_02).

This way of career planning can be based on the PhD graduates' competences that are useful in a wide range of jobs. The scientific approach in practice has been reported to enrich work with clients as it offers a deeper understanding of the practice (DK_EMP_03), a better ability to explain the reasons why something needs to be done in a certain way, to critically evaluate one's methods of work and their limitations (CZ_PHD_01, CZ_PHD_05, IE_PHD_03). Undertaking a PhD project requires the person to design a novel endeavour without the possibility of knowing how exactly it will be carried out, and possessing resilience in the face of unpredictable

problems (DK_EMP_01, IE_EMP_05), curiosity to ask complex questions and the courage to look for answers are also valued by employers (CZ_EMP_05, IE_EMP_08), as well as the willingness to learn new things and move knowledge forward (CZ_EMP_03, CZ_EMP_04). Thanks to the opportunities for various collaborations, participation in projects, foreign stays and teaching during a PhD, the graduates may be also very skilled in teamwork, project management, leadership, presentations and other activities (DK_ED_02) and, in addition, may become more aware of what kind of jobs they want to look for afterwards (IE_EMP_01). Working on interpersonal skills during a PhD is especially important because employers outside academia put more stress on these and clearly state them in a more detailed manner than universities – for example, such demands in business include knowledge transfer and sharing, the ability to train and mentor junior colleagues and to guide or assist customers or partners (Job postings CZ, Job postings DK, Job postings IE).

4. DISCUSSION

Our findings are limited by the geographical scope of the project, qualitative methodology and specific conceptual background. The project was restricted to three EU countries that furthermore rank among the smaller ones. That has two consequences: on one hand, the survey sample was heterogeneous as it was recruited in three separate labour markets, while, on the other hand, it doesn't necessarily represent the situation in the whole EU area. The findings would therefore deserve validation in either a broader or, by contrast, on a more homogeneous territory. Secondly, the identified skill sets that are based mainly on semi-structured interviews would need quantitative verification to show the extent of the demand for the skill sets and their applicability across the high-skilled segment of the labour market. Thirdly, the conceptualisation of the topic was specific in several respects. We were searching for common patterns across disciplines, sectors and industries. The findings can, therefore, provide only a basic framework that needs to be further elaborated to fit individual specialisations of PhD graduates. Besides, the practices of Open Science and Open Innovation are surely not universal among employers of PhD graduates, even if we significantly broadened these concepts compared to their usual understanding. That is especially the case of how open the innovation process in business is. Namely, part of the explored preferences of employers aims at the protection of ideas for the sake of their

commercial use rather than at sharing them. The concept of Open Innovation in its pure form (Chesbrough, 2003) thus appears to have a limited presence in the labour market. Even if we understood the concepts of Open Innovation and Open Science more broadly, our findings still reflect only one specific way of looking at the outcomes of PhD education.

We have identified several skill sets useful for PhD graduates for working in environments that exhibit the features of broadly understood Open Science and Open Innovation. The gap that exists between the way research and innovation work is presently carried out in both academia and business, and the way PhD projects are usually organised, is striking. A clear implication of our findings is the need to focus on teamwork and collaborative skills in PhD education. That includes the capacity to get involved in interdisciplinary interactions, where individual contributions from various fields complement each other. A clear-cut pre-requisite for succeeding in a non-academic research job is the openness to think about whether research results would be practically applicable. For this, a user-centred perspective or, as one of the interviewed employers put it, departing from an egocentric standpoint of what is interesting for oneself, is necessary. Moreover, the "translation" of research into a language comprehensible to wider, non-expert audiences mitigates the risk of science being closed up in an ivory tower. It also enables the researchers to procure resources for their work. The use of Open Science tools, including open-access publishing of data and outputs, is an important way to communicate research outside a narrow circle of experts. While strong incentives to avoid these channels persist, benefits are often overlooked, including possible positive effects of open publishing for profitability, at least in an indirect way. Finally, career planning emerges as an important yet inadequately pursued skill during a PhD. A stronger and earlier focus on it could help young researchers to open their minds to a broader range of career pathways than the anticipated academic one. These skill sets, especially if combined, have the potential to improve the valuable utilisation of research skills of PhD graduates in various career paths, which they increasingly need to consider (Boman *et al.*, 2021, Hnátková *et al.*, 2022).

The presented opinions of PhD graduates and employers may be also translated into ideas on organisational change in the PhD education systems. PhD studies could be organised in less individual and more collaborative ways, as a generalised model. The traditional individual PhD project embedded into a relationship between a student and a supervisor could be

given more elements of teamwork with other colleagues, including those from different disciplines. In such a way, PhD studies would move closer to the organisation of work at many potential workplaces. Visits to other institutions including practical internships may be given a more prominent place in the requirements of PhD programmes. Internships have been assessed by interviewees as a key method by which PhDs get collaborative experience, new ideas and contact with practice. More opportunities can be given to practically oriented PhD topics. Furthermore, in cases of programmes in which it often takes students significantly more time to finish, it would be advantageous to all to encourage faster progress through appropriate policies and structures, so PhD studies do not differ from other projects or jobs in this respect. However, systemic barriers to timely completion, including insufficient funding for PhD students, should be dealt with before any other intervention. A specific topic mentioned by some employers is business skills and patent procedures. If Open Science and Open Innovation are understood also as the transfer of knowledge from university to business and more permeability between the two worlds, more room for teaching business skills, including patent procedures where applicable, can be considered. If further developed and validated, these recommendations can be used to support the ongoing trend of diversification of models of PhD studies (Kosová *et al.*, 2019, Mountford *et al.*, 2020).

CONCLUSION

Our findings confirm that changes in the world of work provide useful incentives for PhD education to evolve. The growth in the number of PhD graduates is an integral contributor to the highly educated society we live in today. That has led to knowledge intensification in the professional sector, especially in the already high-skilled segment of employment. New opportunities to carry out research and innovation emerge especially in the private sector, while academia cannot absorb the rising numbers of PhD graduates. These trends, along with the changes within academic work itself, make it necessary to rethink traditional approaches to the organisation and content of PhD education. Graduates can leverage these new opportunities in open innovation, and society can benefit more fully from PhD graduates' expertise. Our interviewees presented diverse ways of how research and innovation activities are organised at

workplaces and how the skills of PhD graduates can be used. At the same time, however, a dissonance between an individual's long-term focus on a narrow topic during a PhD and the real-life needs of employers is evident. That does not imply that a mechanical projection of the employers' demands into radical changes in PhD education should be assumed – PhD education needs to maintain its specificity, autonomy and an emphasis on rigorous, deeply thoughtful research. We suggest that adaptations in PhD education to changes in the "outside world" should be evidence-based and participatory, as we have endeavoured to demonstrate here. PhD researchers need to be supported in a multitude of ways to find their place in their world, to understand what and where their contribution can be, and how this translates to their career prospects and choices.

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APPENDIX: LIST OF INTERVIEWS

Interview ID	Type of respondent	Sector (business, NGO, state, academic)	Discipline / industry (where applicable)
CZ_EMP_01	Employer	Academic	Biochemistry
CZ_EMP_02	Employer	Business	Applied natural science research
CZ_EMP_03	Employer	Business	Biotechnology
CZ_EMP_04	Employer	Business	ICT
CZ_EMP_05	Employer	Business	ICT / Big Data analytics
IE_EMP_01	Employer	Academic	Data analytics
IE_EMP_02	Employer	Academic	Public health
IE_EMP_03	Employer	Academic	Business studies
IE_EMP_04	Employer	Academic	Music
IE_EMP_05	Employer	Business	ICT and electronics
IE_EMP_06	Employer	Business	Digital health
IE_EMP_07	Employer	Business	Open Science
IE_EMP_08	Employer	NGO	Digital medicine
DK_EMP_01	Employer	Business	ICT (Educational technology)
DK_EMP_02	Employer	Academic	
DK_EMP_03	Employer	Business	Publishing
DK_EMP_04	Employer	State	Culture
DK_EMP_05	Employer	State	Culture
CZ_PHD_01	PhD student / graduate	Business	Architecture
CZ_PHD_02	PhD student / graduate	Business	ICT (SW and HW)
CZ_PHD_03	PhD student / graduate	Business	ICT (SW and graphics)
CZ_PHD_04	PhD student / graduate	Business	Mathematics

CZ_PHD_05	PhD student / graduate	State	Medicine
IE_PHD_01	PhD student / graduate	Business	Digital Health
IE_PHD_02	PhD student / graduate	Business/State	Healthcare Delivery
IE_PHD_03	PhD student / graduate	Business	Sports Technology
IE_PHD_04	PhD student / graduate	State	Physics
DK_PHD_01	PhD student / graduate	Academic	Political Science
CZ_ED_01	Educator	Academic	
CZ_ED_02	Educator	Academic	
IE_ED_01	Educator	Academic	
IE_ED_02	Educator	Academic	
IE_ED_03	Educator	Academic	
DK_ED_01	Educator	Academic	
DK_ED_02	Educator	Academic	

The interviews were carried out in April and May 2021 by interviewers from the University College Dublin, Insight Centre for Data Analytics / Ireland (Denise McGrath, Ciara Duignan, Eleni Makri), National Training Fund / Czech Republic (Michal Janíčko, Věra Czesaná, Zdeňka Šímová, Zdeňka Matoušková), and Aarhus University/ Denmark.

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