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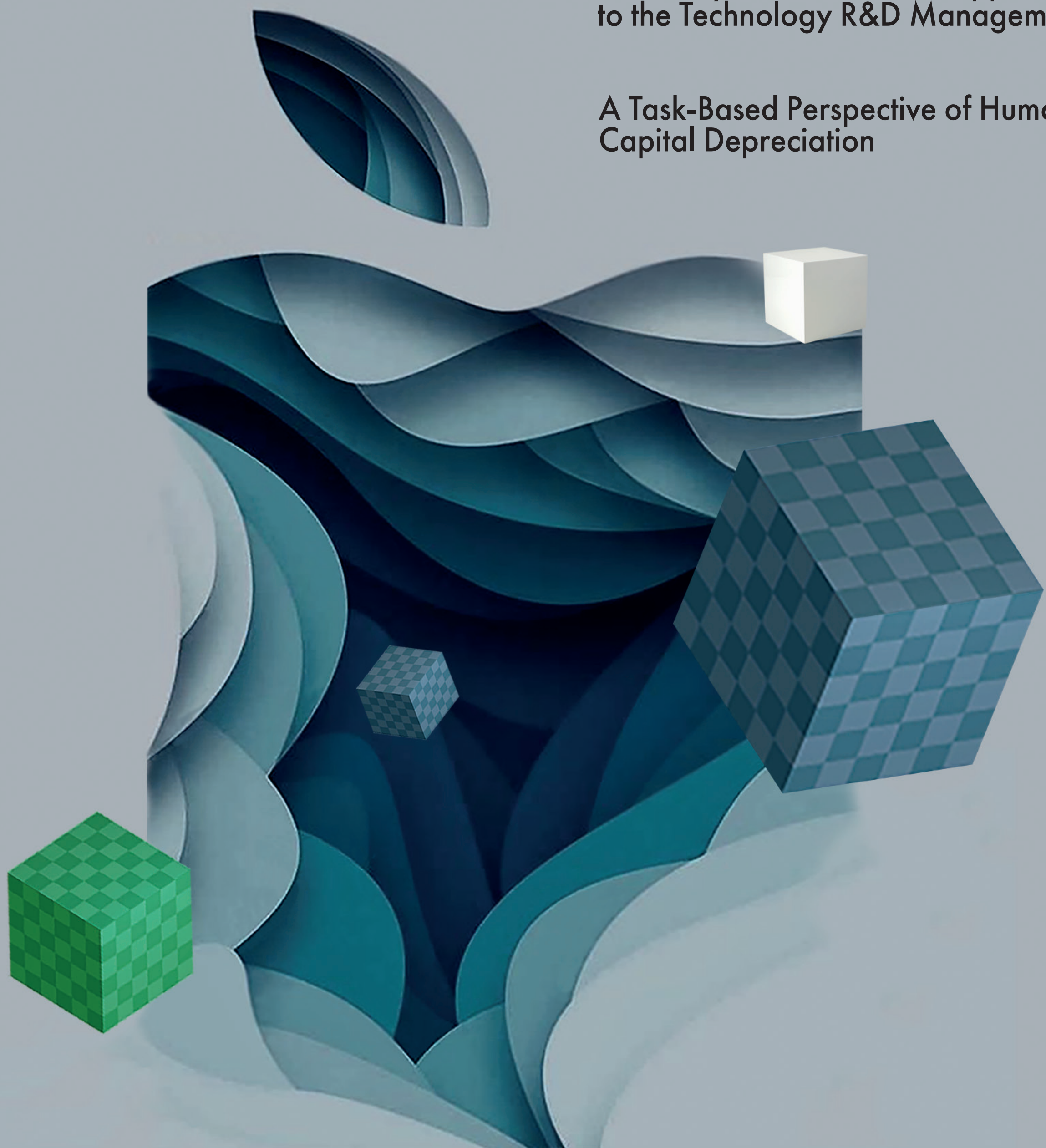

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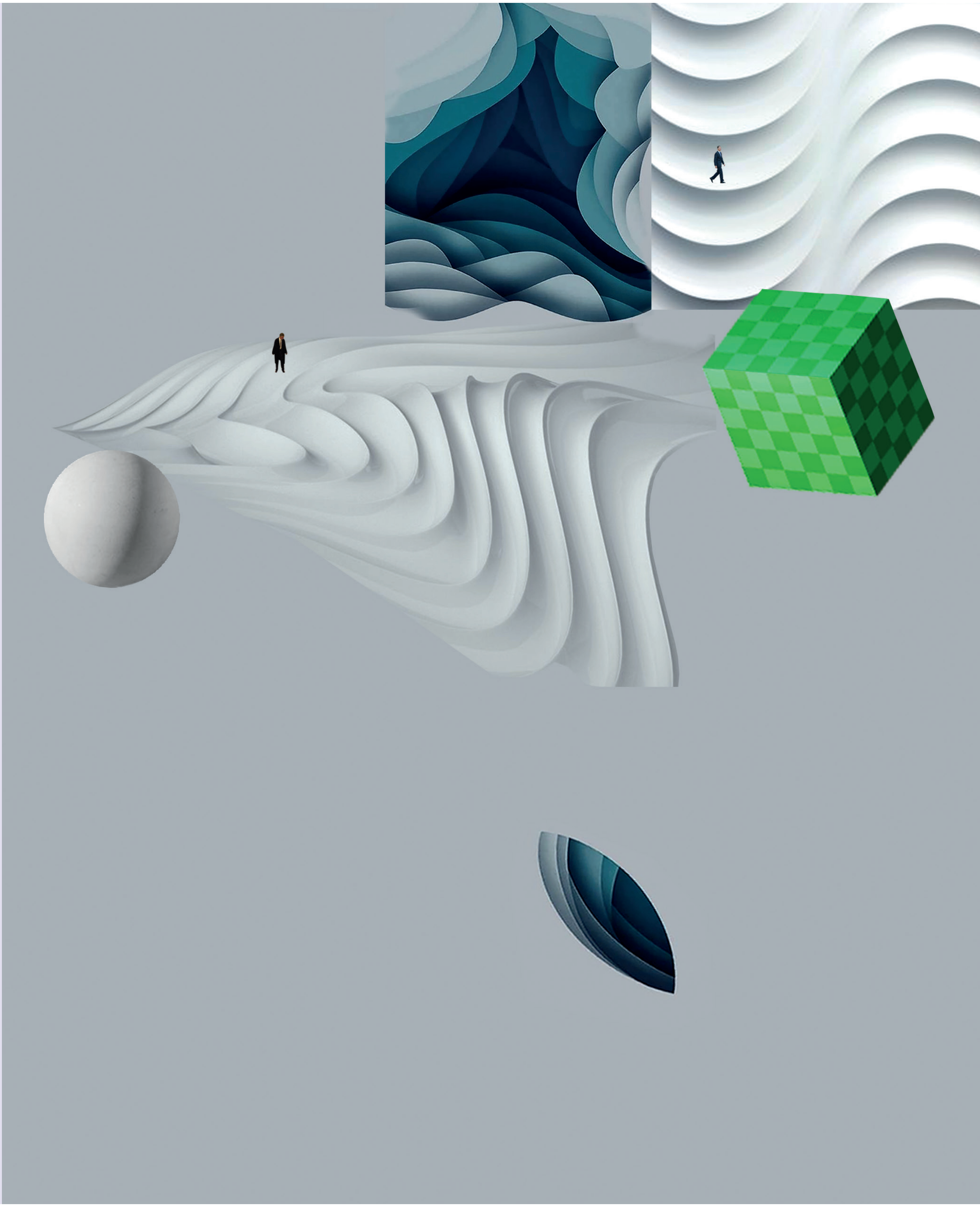

Academic, Commercialization and Societal Effects of Joint Research

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Abstract

This work investigates the effects that a specific science industry collaboration scheme, joint research, generates in three areas: the production of academic activities, scientific knowledge commercialization, and society at large. This is an in-depth work on joint research in a developing country that covers three different types of effects. The work highlights the specific industrial contributions that make it possible for such effects to be verified, with special attention to societal effects, an aspect rarely present in the literature. Based on some dimensions that recent literature has identified and where more empirical evidence is needed, a multiple case study has been carried out through the selection of three public-private collaborations in the Argentine biopharmaceutical sector responding to joint research characteristics.

Among the main findings, the identification of the different ways in which a relationship with industry allows science: to intensify its publication activity, by having more resources and identifying new thematic niches to publish; to improve teaching, using co-generated knowledge and shared equipment; to expand its research agenda both toward applied topics and toward more basic ones. Likewise, relationship with industry allows knowledge generation that, in addition to being central in the creation of start-ups and patents, also contributes to perform new services of a commercial nature. Finally, joint research generates effects that benefit society in general, through cheaper domestic diagnostics or therapeutic solutions improving public health.

Keywords: science; industry; knowledge; joint research; biopharmaceutical

Paper type: Research Article

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Introduction

Science and industry are considered two different worlds governed by different approaches and strategies (Bruneel et al., 2010). Collaboration between science and industry can be carried out through multiple modalities and some of them, such as joint research, contract research, and consulting, are characterized by their strongly relational imprint, as they are based on frequent personal interactions and generations of mutual trust between the parties (Perkmann, Walsh, 2009; Milesi et al., 2017; D'Este et al., 2019). The recent literature has found that the effects of such collaboration are verified mainly in three areas: academic activities such as research and teaching; the commercialization of the knowledge generated in the academic sector; and society at large (Perkmann et al., 2021). Existing literature has tried to identify correlations between collaboration with industry and scientific publications, teaching activity, and the expansion of research into more applied areas. An attempt has also been made to verify whether linking with industry favors the creation of start-ups and intellectual property rights. However, the area, which transcends the parties and refers to possible economic and social effects for the rest of society, constitutes a little addressed aspect. Most of the existing studies are quantitative in nature and allow for finding positive correlations between science industry collaboration and several of these dimensions.I In some cases, however, the evidence is contradictory, and in others there is still little of it. On the other hand, these studies do not capture relevant qualitative aspects, for example, what are the elements provided by industry that contribute to generating effects and how does the public sector translate what it absorbs from the relationship into effects of different kinds? It was also observed that most of these studies address the problem in the context of developed countries, with few studies providing a view from developing ones.

The objective of this work is to delve into different types of effects generated by science-industry cooperation. To this end, a multiple case study is carried out in a developing country, Argentina, and in a particular sector, biopharmaceutical, which due to its characteristics allows the economic and social effects to be observed in more detail. Within science industry cooperation, a specific scheme is considered, joint research, where industry participates actively and bidirectional flows of knowledge and learning opportunities are more widespread than in other schemes.

Conceptual Framework

The evolutionary and neo-Schumpeterian approaches have contributed to the affirmation of an interactive vision of the innovation process, where the latter is conceived of as a phenomenon that, far from occurring exclusively within the firm, has a markedly systemic nature (Nelson, 1993; Lundvall, 1997; Freeman, 2004). In this way, growing interest in innovation has gone hand in hand with a growing interest in collaboration between industry and the academic and scientific-technological sector given the positive role such cooperation can play in the production system (Meyer-Krahmer, Schmoch, 1998; Lee, 2000; Schartinger et al., 2002). Science-industry cooperation can take many forms and takes place through multiple channels (Meyer-Krahmer, Schmoch, 1998; Lee, 2000; Schartinger et al., 2002; D'Este, Patel, 2007). Various works (Perkmann, Walsh, 2009; Arza, Carattoli, 2017; Milesi et al., 2017; D'Este et al., 2019) indicate that some forms of cooperation are based on frequent personal relationships, the exchange of tacit knowledge and the creation of trust. In joint research, for example, both science and industry play an active role in terms of R&D and knowledge flows between the parties assume a two-way dynamic, which generates greater opportunities for interactive learning. This work focuses on the effects, which can occur in three main areas: academic activities, commercialization of knowledge generated by the public sphere, and society in general (Perkmann et al., 2021).

Within academic activities, research and teaching stand out. Regarding research, there is a consensus regarding the positive effect of cooperation with industry on publications produced by the scientific sector (Hottenrott, Lawson, 2017; Banal-Estañol et al., 2015; Bikard et al., 2019; Garcia et al., 2020). There is some evidence that cooperation with industry can guide public researchers toward more applied areas of research (Van Looy et al., 2006). However, it is necessary to verify whether this is associated with a reduction or an expansion of the public research agenda and, eventually, if there may be an effect in the opposite direction, that is, toward more exploratory and basic research (Perkmann et al., 2021; Verre et al., 2021).

Regarding teaching, the evidence is contradictory since, on the one hand, there is a negative effect of cooperation (in the form of consulting and in the engineering sector) on the quality of teaching (Bianchini et al., 2016), on the other hand, positive effects exist in different disciplines in terms of an improvement in the presentation of teaching material. In this case, it is necessary to delve into which elements of the relationship with industry can help enrich teaching (Hughes et al., 2016; Verre et al., 2021).

Another area where science-industry cooperation generates effects is commercialization. This field is usually approached by literature mainly from two perspectives: the generation of intellectual property rights and the creation of academic start-ups. In the first case, there are quantitative studies (Beaudry, Kananian, 2013; Libaers, 2017) that find a positive correlation between collaboration with industry and the generation of patents in the academic sector. It is worth considering whether this indicator is the most appropriate in developing countries, where there may be other effects of a commercial nature, for example the realization of new services, which emerge from the link with industry and are highly relevant for the academic sector. Regarding entrepreneurship, there is a positive relationship between having collaborated with industry and the predisposition to create a company (Fritsch, Krabel, 2012), while the probability of founding a company declines if the researcher is a scientific advisor at a firm (Ding, Choi, 2011). In the case of long-term alliances between public institutions and firms, it is appropriate to consider which elements are absorbed and then used in the creation of a start-up and how this challenges (or not) the previous relationship with firms.

Finally, the effects on society in general are a less studied topic (Perkmann et al., 2021). From a perspective focused on the public sector, Iorio et al. (2017) consider the social motivations that underlie the decision to cooperate, while Hughes and Kitson (2012) address the socially oriented channels of universities to cooperate with external organizations. Further, Ankrah and Al-Tabbaa (2015) identify effects deriving from science-industry collaboration that transcend the parties in the economic and social field. This third type of effect needs more qualitative empirical evidence to identify, on the one hand, which elements compose it and, on the other, what the link is with science-industry cooperation.

Most of the cited works refer to North America and Europe and there are not many studies on other contexts, for example, Latin America (Arza, Carattoli, 2017; Milesi et al., 2017; Garcia et al., 2020; Verre et al., 2021). This work, then, aims to analyze the effects in the three aforementioned areas of a specific collaboration scheme as joint research through a case study within the Argentine biopharmaceutical sector. Due to its relational characteristics, joint research allows for gathering evidence that is relevant, both in terms of the chosen context and the dimensions previously indicated as vacancy areas.

Methodology

The empirical object of this work is constituted by knowledge flows between firms and public R&D institutions, within joint research collaboration. To carry out the study, the Argentine biopharmaceutical sector was chosen, its characteristics make it suitable to observe the empirical object, being intensive in science and science-industry cooperation and being focused on human health, which allows for a better observation of social and economic . Within the sector, collaborations were identified in which both parties have high R&D capabilities and are involved in long-term, highly complex and uncertain projects, which makes the presence of relevant knowledge flows between the parties, such as the generation of multiple effects in different areas, more likely. Three cases were then chosen, which coincide with those public-private collaborations involving the largest firms and some of the most prestigious institutions at a national level in that scientific-technological area. The three selected cases are presented below, with their main members and the projects they cover (Table 1).

In this multiple case study, the main unit of analysis is the perspective of researchers belonging to public R&D institutions who collaborated with firms. However, to ensure the reliability of the collected information, two other perspectives are considered, first, the vision of firms' R&D personnel that interacted directly with public researchers and, second, the people belonging to the public institution's hierarchy that provide a comprehensive view of the projects and relationship with industry. The intention to use three such perspectives is not to make a comparison between them, but to complement and contextualize the information collected in the main unit of analysis. Likewise, the main objective is not to compare the three cases among them, but on the contrary to combine them, to provide the greatest possible empirical evidence regarding the effects resulting from the specific scheme of joint research. Regarding data collection, 34 in-depth interviews were carried out. A documentary analysis was also carried out on some secondary sources that were accessed (project forms, technical reports, and other documentary material provided by firms and public institutions).

The Three Selected Cases

In all three cases, science-industry cooperation assumes some common characteristics that correspond to the scheme of joint research. The parties are in a complementary relationship, that is, industry participation is an essential condition to generate knowledge, since capacities are needed that the public party lacks. The projects are long-term and highly uncertain, and this complementarity translates into constant interactions between the parties, who share partial results and discuss them collectively, generating feedback, all within the framework of strong interpersonal trust. This context induces bidirectional flows of knowledge between the parties and is a very different form of collaboration with respect to the transfer vision, in which an active party (public) generates and transfers knowledge to the passive one (private). Beyond the existence of peculiarities in each case, this common denominator is a rare way cooperating in a country like Argentina, where the transfer vision prevails. Even in the biopharmaceutical sector, where cooperation assumes complex and interactive characteristics, not all relationships go in the direction of joint research (partly because not all firms have sufficient R&D capabilities to generate feedback for the public partner). The three cases are analyzed below, specifying the characteristics of the actors, the relationship's historical trajectory, the projects covered, and the object of the collaboration.

Case 1. Joint Research between the LOM-UNQ and the Insud Group

The first case covers a broad set of actors. This consortium has been forming and expanding over more than 20 years and is made up, on the one hand, by the Insud Group, one of the main Argentine pharmaceutical groups that controls several firms; on the other, a series of public actors, among which the Molecular and Translational Oncology Center (LOM-UNQ) stands out as a central partner of the Insud Group, in addition to some hospitals, such as Garrahan (the most relevant pediatric hospital in Latin America). Within this collaboration two large macro-projects can be identified: immunotherapy and desmopressin. The immunotherapy project stems from Insud's relationship with Cuban biotechnological centers and covers several products: Racotumomab (a monoclonal antibody used in lung cancer), two glycoproteins with antitumor action (N-glycolyl GM3/VSSP, for breast cancer and N-acetyl GM3/VSSP, for cancer and HIV), and two biosimilar monoclonal antibodies such as Rituximab (used in non-Hodkin's lymphoma, chronic lymphatic leukemia and rheumatoid arthritis) and Bevacizumab (colon cancer). The other macro-project has to do with Desmopressin, a synthetic organic peptide used for antimetastatic functions (to prevent the spread of cancer cells after surgery), which also has a protective effect by promoting coagulation. The immunotherapy project was launched between 1994 and 1996, from the collaboration established between Insud and two Cuban biotechnology centers. The LOM-UNQ was initially incorporated into the project through pre-clinical services, tests on laboratory animals in cancer models, but over time it became increasingly involved in the development and clinical phases of each product, interacting closely both with hospitals and Insud's firms. While Racotumomab has been on the market since 2013, the other products are in different stages of development. The Desmopressin project presents the opposite route, it was developed entirely within the LOM-UNQ and, later, the entry of Insud allowed for carrying out co-development in two fields, veterinary and human. Currently, the product for veterinary use is on the market, while clinical trials for its use in humans are nearing completion.

Case 2. Joint Research between the LCC-UNL and the Amega Biotech Group

In this second case, unlike the previous one, there are only two cooperating actors: Amega Biotech Group and the UNL. Amega Group includes three companies and one of them, Zelltek, was founded as an incubated start up within the UNL. The LCC-UNL stands out as the main knowledge generation actor upon which Amega relies and also shares the same physical space as Zelltek within the UNL. The cooperation between Zelltek and the LCC-UNL covered countless projects over more than 20 years, among which the development of erythropoietin (EPO), which motivated the emergence of the incubated firm, stands out. Within this consortium, two specific projects are considered, which coincide with the development of two highly complex proteins: Etanercept (for the treatment of rheumatoid arthritis, childhood rheumatoid arthritis and psoriatic arthritis) and truncated coagulation Factor VIII (an essential element in the blood coagulation process and used to reverse hemophilia A). Within the same physical space, there is coexistence between LCC-UNL researchers and the firm's R&D personnel in such a way that in the daily dynamics of the laboratory, lines between what is private and what is public, between academic and business, are blurred. On the one hand, this coexistence means that public researchers located there are familiar with the problems that other R&D groups, without links to industry, perceive as distant or completely foreign. On the other hand, this aspect allows the firm to take advantage of the continuous flow of human resources and knowledge existing in the laboratory. This peculiarity has enhanced R&D collaboration opportunities, which is reflected in the richness of the co-development agenda between parties,

Table 1. **The Selected Cases**

Case	Firms	Public partners	Projects
1	Insud Group	Laboratorio de Oncología Molecular de la Universidad Nacional de Quilmes (LOM-UNQ) and other institutions	- Desmopressin: for veterinary and human use - Immunotherapy: monoclonal antibodies and other products
2	Amega Biotech Group	Laboratorio de Cultivos Celulares de la Universidad Nacional del Litoral (LCC-UNL)	-Recombinant proteins: Etanercept and Factor VIII
3	BioSidus	Instituto de Biotecnología y Medicina Experimental (IByME), Instituto de Virología del Instituto Nacional de Tecnología Agropecuaria (IV-INTA)	-Transgenic animals: human growth hormone, insulin, etanercept and VHH nano-antibodies
Source: authors.			

within which the two aforementioned proteins stand out. Currently, the development of these products has already concluded and the Group is undertaking the necessary clinical trials for their regulatory approval.

Case 3. Joint Research between IByME, IV-INTA, and Biosidus

The third case involves the company Biosidus and two public institutions, the Biology and Experimental Medicine Institute (IByME) and National Institute of Agricultural Technology (INTA). The collaboration between Biosidus and the IByME has a history of 20 years and is at the base of the generation and consolidation of the platform for transgenic animals, surely one of the greatest achievements of Biosidus, while firm's collaboration with the IV-INTA began later, having started in 2010. Both collaborations have the use of a transgenic animal platform in common, which is employed to generate a series of products to be used in human health, such as human growth hormone, insulin, etanercept, and VHH nanoantibodies. Biosidus was pioneer in Latin America in the development of a transgenic animal platform, which consists of using cows as production systems, inserting the gene that produces a protein or molecule of interest into an animal (that is, genetically modifying the animal) to then obtain that protein or molecule in its milk. From the beginning, the IByME has collaborated with Biosidus in the development of this platform, being the main external source of knowledge of the firm in transgenesis and cloning. The Physiology of the Mammary Gland Laboratory assumed a key role from 2003 in producing most of this project's knowledge and providing the firm with critical human resources. The IByME has accompanied Biosidus in the development of a technological platform and has collaborated on each of the proteins the firm decided to produce, for example, human growth hormone (for the treatment of delayed growth in children and Turner syndrome), insulin (to treat diabetes and hyperglycaemia), and etanercept (for rheumatoid arthritis). The objective of the collaboration with IV-INTA is to use this platform to produce another molecule, the VHH nanoantibody, which is a monoclonal antibody derived from camelids that neutralize the Rotavirus infection, the main agent that causes diarrhea in children worldwide. Until now, the production of all molecules has been achieved in transgenic cows, with different levels of productivity, however, the transgenic cow platform faces critical uncertainties from a regulatory point of view and there are still no products on the market.

Joint Research Effects in The Cases

Academic Activities

In relation to the publications, in Case 1 it is observed that the practices developed during the interactions between industry and hospitals is an important source of time savings, since it allows for a more accurate choice of both the preclinical models to be used, such as the specific subgroup of the pathology toward which to direct the study, for example, where patients have fewer therapeutic alternatives. This is important for LOM-UNQ researchers, who try to publish in journals with a preclinical and clinical perspective, where reviewers are very familiar with what happens in the preclinical phase or in new drugs development. Likewise, LOM-UNQ researchers highlight that some publications arise as a result of research questions that originate in industry during the collaboration. Garrahan Hospital researchers underline how collaboration with industry and the LOM-UNQ has allowed them to publish articles on retinoblastoma and Racotumomab in the journal of the International Society of Pediatric Oncology and in an English ophthalmology journal, both with high-impact factors. In Case 2, LCC-UNL researchers highlight that research activity in their discipline is very expensive and collaboration with industry helps to improve the opportunities for publishing since, by having public facilities in terms of access to supplies, equipment, and financial resources provided by the firm, this translates into greater speed in obtaining results and publishing them. Finally, in Case 3 collaboration with industry determined a leap in quality in publication activity, for example, several IByME publications could be carried out thanks to the infrastructure and capabilities that Biosidus provided for carrying out innumerable experiments with transgenic animals. More recently, IV-INTA highlights the publication of two articles in high-impact journals (PlosOne and Plos Pathogen).

About the direction of research, in the studied cases it emerges that the link with industry exposes the public actors to problems that, otherwise, would not be under consideration. In both Cases 1 and 2, joint research has allowed the public sector to multiply existing research lines and enrich the research agenda. This is due, firstly, to the public sector's greater economic resources (as a result of collaboration with industry) to finance and support new lines of research, which in several cases are not firm linked. Secondly, the public sector is introduced to unfamiliar, new topics as a result of the broadening of horizons through interactions with industry by addressing applied problems closer to the productive phase. Third, some issues are not of direct interest to the firm but may be in the future, and the public's decision to address them, in addition to intellectual curiosity, is further stimulated by the presence of a potential adopter with which there is already a lasting and trusting relationship. The public sector's research agenda, then, is not reduced but rather broadened and diversified. Furthermore, it can also be extended in the direction of basic science. For example, in Case 1, LOM-UNQ researchers point out that from the initial collaboration with Insud in immunotherapy, a new line of research was started in which new antigens linked to Racotumomab were identified and characterized, which it represents feedback from applied research to basic research that was determined by the interaction with industry. On the other hand, in Case 2, the LCC-UNL, as a result of the collaboration with industry, has over time moved from an initial very applied and production-oriented activity toward an expansion of its basic research, for example, on issues such as vaccines and stem cells (unrelated to the firm) or on a frontier issues that few research groups in the world address, such as immunogenicity. The LCC-UNL linked up with the University of Rhode Island, where advanced research is being carried out on the subject of immunogenicity with transgenic animals, and sent some of its researchers to the US to receive training in these techniques. The LCC-UNL autonomously decided to address this new topic, not only due to its being a possible interesting new line of research, but because it predicted that Argentine health authorities would eventually require this type of control for medicines' approval, which may be of interest to Zelltek. The existence of such an intense and longstanding collaboration with industry has been a stimulus for public researchers to broaden their agenda toward a more exploratory area and Zelltek has already requested permission from the LCC-UNL for Factor VIII and Etanercept, two central products of the joint research agenda.

Regarding teaching, science-industry collaboration can strengthen it in three different directions. First, co-generated knowledge in joint research flows through researchers and teachers to the students.[1] Secondly, the public sector can use firms' equipment to carry out the practical and laboratory part of teaching, facilitating and enriching the teaching task. This is particularly visible in Case 2, where students use the equipment installed at the LCC-UNL, more than half of which belongs to Zelltek. The possibility of using firm's equipment allows students to have a deeper understanding of R&D activities, allowing them to see and use equipment that is not readily available in the academic field. It also serves as a means of obtaining data for students who are writing their thesis. Finally, researchers use the experience of joint research itself in teaching, for example, in subjects such as formulation and project management, and as a paradigmatic model of scientific-technological management to convey the difficulties and potential of such collaborations and foster a culture of commitment to the application of knowledge (Cases 1 and 3).

Commercialization

Within the LOM-UNQ (Case 1) some researchers created their own enterprise, which is focused on Functional Foods and the Nutraceutical approach. It is about vitamin-mineral formula development including functional extracts, basically from vegetables, characterized and enriched with functional principles. Although they are not pharmaceutical products, they follow some development stages similar to drug formulas. Researchers acknowledge such developments derive from applying critical knowledge gained through collaboration with industry over the course of 15 years. On the other hand, Case 2 is even more interesting because originally a start-up arose, which was later bought by the Amega Group. Then intense and growing joint research activity was established between the LCC-UNL and Zelltek, with a multiplication of lines of research. From this alliance an incubated firm was created, Empretech, dedicated to veterinary vaccine production. The firm is oriented toward animal health, but it benefits from knowledge acquired by the LCC-UNL throughout these years of close collaboration with Zelltek. Researchers point out that veterinary medicine is currently getting closer to pharmaceuticals in work methodology and many aspects and criteria. With the knowledge jointly developed by Amega and the LCC-UNL, new discoveries may be used and incorporated by this new firm. Likewise, in 2020 another firm was created, Biosynaptica, which although it is in the pharmaceutical field, does not compete with Amega's interests and is nourished by the knowledge generated by researchers in collaboration with industry. In addition to entrepreneurship, commercialization effects are also manifested in two other aspects: the creation of new intellectual property and the generation of new services. In all three cases there is evidence of the creation of new intellectual property as a result of collaboration with industry. In the Desmopressin project (Case 1) there was a previous LOM-UNQ patent that was later licensed to the Insud Group and later more patents were generated on a panel of derivatized peptide products and a new family of Rac compounds, which are jointly owned with industry. In the Immunotherapy project, on the contrary, there were already patents held by industry prior to collaboration, which has maintained control of intellectual property in this area. In Case 2, although collaboration with industry is mainly focused on biosimilar products, where patents are an obstacle, LCC-UNL has generated several patents directly related to the Amega Group, for example on vero cells, which can be used for human vaccines and, more recently, a molecule for therapeutic use in neurodegenerative diseases obtained by genetic modification of EPO. In Case 3, Biosidus and the IByME have a long history of jointly generating patents related to the transgenic animal platform and, with respect to IV-INTA, in 2018 the transgenic bovine platform producing VHH was jointly patented. In all cases, the creation of new patents is strongly related to collaboration with industry, although its commercial exploitation is still far away for many of them. However, joint research also generates effects in other commercial aspects, which can be very relevant for the public sector. In Case 1, within the Immunotherapy project, LOM-

[1] In Case 1 this occurs particularly in postgraduate courses, while in Case 2, in addition to it, for example in the Doctorate in Biological Sciences, developed knowledge is also used in undergraduate courses, such as Cell Cultures, Molecular Biology for cell culture in animal cells and Downstream Processing, within the degrees in Biotechnology and Biochemistry..

UNQ collaborated with Insud to develop two sophisticated analytical techniques to evaluate Rituximab. All the knowledge received from the Insud Group has allowed LOM-UNQ to currently have a platform for the evaluation of preclinical efficacy of any type of biosimilar substance. In Case 2, the firm's know how was essential to developing quality control techniques necessary for the evaluation of products. When Zelltek was absorbed by Amega, all these techniques remained as an inheritance in the LCC-UNL, which today provides quality control services for approximately twelve pharmaceutical firms, both national and foreign. In Case 3, IByME researchers applied part of the knowledge developed together with Biosidus in the provision of services within the framework of another collaboration, with a startup created by a public university.

Socioeconomic Effects

Science-industry collaboration also generates effects on society at large. The public sector's commitment to the application of knowledge and to reaching out to society translates into patients whose quality of life improves thanks to the drugs developed. In Case 1, LOM-UNQ researchers emphasize that society begins to benefit from cancer drugs' effects already during clinical trials, because they offer an alternative treatment before the product is approved. In addition, once the product is approved, to the extent its beneficial effects are demonstrated for subsequent pathologies, the impact on society grows. In Case 2, LCC-UNL researchers emphasize that joint research allowed for the development of two biosimilars that, once approved, could reach Argentine patients at a significantly lower cost compared to the original products, which are currently imported. This doubly favors the Argentine health system, on the one hand, due to lower costs, for example, on the Argentine market there is currently no original EPO, since it costs 10 times more than the local biosimilar version; on the other, import substitution represents a saving of foreign exchange needed to acquire them, an important point for a country with chronic problems of foreign exchange availability. To this must be added the advantage of being able to gradually strengthen an industrial sector, in this case biopharmaceuticals, which, being intensive in knowledge, is essential for the country's development. In Case 2 another consequence was also observed deriving from the Amega Group and LCC-UNL collaboration. These two entities agreed with the Pharmaceutical Industrial Laboratory (LIF), the public drug production firm of Santa Fe Province, so that the latter can manufacture some of the drugs produced by Zelltek, used to treat diseases such as cancer, multiple sclerosis, HIV, and chronic kidney failure. The agreement implies that LIF can manufacture and sell these medicines at cost price since both Amega and the UNL waive corresponding royalties, generating a price drop and a positive impact on provincial health spending. On the other hand, the objective of reaching society can be achieved through other ways, for example, regardless of concrete results from collaboration projects, there are possibilities for lateral applications of knowledge that are exploited above all by the public sector, as is the case of diagnostic kits developed for Garrahan Hospital and Malbrán Institute. In Case 1, when the immunotherapy project was started, the idea of developing a quantitative PCR-based tumor diagnosis kit arose. However, the kit was not feasible from a practical point of view and it was decided to transfer its know-how to Hospital Garrahan. This hospital currently has a molecular diagnosis service for residual pediatric cancer cells, especially retinoblastoma and neuroblastoma, which it offers to the community. The knowledge underlying this development was jointly generated by LOM-UNQ and Insud. In Case 3, IV-INTA underlined that VHH not only serves to create a therapeutic product protecting against a certain pathogen but also to diagnose the presence of that pathogen. As a result of what the IV-INTA was developing together with industry, the Malbrán Institute (the national reference institution for the prevention, control, and research of all pathologies, including neonatal diarrhea), asked the IV-INTA to develop an Elisa kit for Rotavirus. In this way, IV-INTA researchers obtained the kit prototype in five months and Malbrán Institute no longer has to import it. Based on this, the Malbrán Institute orders diagnostic kits for other pathologies such as human influenza and another public institution, the Leloir Institute, asked that IV-INTA develop kits for breast and colon cancer. The social impact, in these lateral applications of knowledge, is verified through import substitution and national health system diagnostic capacity improvement.

The summary of joint research effects on academic activities, commercialization, and society is described in Table 2.

Conclusions

This work has analyzed the effects that joint research generates in different areas. For this, a case study has been carried out in the Argentine biopharmaceutical sector through the selection of three science-industry collaborations where both firms and public institutions are active in knowledge generation and maintain long-term links in the framework of highly uncertain projects. The analysis of the cases has allowed for gathering empirical evidence that allows one to deepen different dimensions that make up the effects.

Joint research positively affects the quantity and quality of scientific publications, through material resources and new questions coming from industry and through the dialogue between preclinical and clinical actors that it promotes. The public research agenda is expanding, not only due to the greater availability of resources, but also due to the presence of a private partner as a stimulus for approaching new research topics. These

Table 2. **Joint Research Effects on Academic Activities, Commercialization and Society**

Types of Effects	Evidence of the cases in the different dimensions
	Academic activities
Publications	- Increased productivity motivated by new questions that originated at the firm - Increased impact index due to the better ability to choose preclinical models and pathological niches (thanks to the dialogue between preclinical and clinical actors promoted by industry) - Greater speed in obtaining results and publishing them thanks to firm's resources
Research direction	- Multiplication of research lines thanks to resources derived from collaboration with industry - New applied research topics that are or could be of interest to the industry - New research topics that are more exploratory and basic due to intellectual curiosity and due to the greater resources derived from collaboration with industry and the encouragement of having an adopter with whom there is a long-term alliance
Teaching	- Transmission of scientific-technological content developed together with industry to undergraduate and postgraduate students - Use of firm's equipment for practical teaching activities - Use of joint research experience as a management model, to encourage commitment to the application of knowledge
	Commercialization
Start ups	Creation of firms by researchers thanks to the knowledge absorbed during joint research, but in commercial areas not competing with the private partner
Patents and new services	- Creation of new intellectual property related to the collaboration with industry as well as licenses - Reuse of knowledge absorbed from industry (analytical control techniques) in services for other firms and institutions, with increased resources for research
	Society in general
Healthcare effects	- Medicines curing patients, from the clinical phase until market introduction, when regulatory authorities may extend their use to further indications - Cheaper medicines and lower expenses for the health system and patients (the articulation with public medicine production deepens price drops)
Imports substitution	Foreign exchange savings and strengthening of a local high-tech industry
Lateral applications of knowledge	Knowledge generated in treatment products is used for other developments contributing to a diagnostic capacity increase of different pathologies

Source: authors.

new topics belong both to the applied area, where industry has greater knowledge, and to more basic and exploratory lines. Joint research may be helpful as well for teaching, through the transmission to students of both co-generated scientific-technological knowledge and the associated experience itself as a management model and through the use of a firm's equipment in the practical part of teaching.

This type of collaboration also has a positive effect on the commercialization of academic knowledge. In the cases, public participation not only generates patents linked to its work agenda with industry, but these actors also absorb industrial knowledge to generate new services that, in turn, increase resource availability for new research lines. On the other hand, researchers find an incentive to create startups, exploiting knowledge acquired during interactions with industry and focusing on sectors and products not competing with a partner's business.

Regarding the effects for society in general, the cases make it possible to identify some dimensions: an improvement in quality of life and public health through innovative medicines; lower public and private spending on health for lower-cost medicines; greater foreign exchange savings due to import substitution; strengthening of a knowledge-intensive local industrial sector; and lateral applications of collaboration-generated knowledge to respond to other health and social needs.

A limitation of this work is that it analyzes a single sector and similar dynamics take place in other high-tech sectors. The selected cases are exceptional in the Argentine context, which allows for seeing only indirectly the (cultural, business, and technological) obstacles preventing the generation of virtuous effects in the three considered areas. As a future agenda, it is necessary to consider other associative schemes, such as contract research and consulting, to analyze how the dimensions considered here behave. Particular attention deserves to be paid to the analysis of industry feedback's impact on public R&D in terms of learning and research direction. Relating to public policy recommendations, it would be desirable to encourage associative and sectoral financing instruments that encourage joint research and deliberately promote the achievement of effects in the three mentioned areas, so that these are not merely emerging from virtuous cases or depend exclusively on the commitment and will of certain actors. In this sense, the socioeconomic sphere is the most sensitive since it transcends the collaborating partners.

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University 3.0: A Portfolio Approach to the Technology R&D Management

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Abstract

Modern universities play increasingly important role in contemporary society, advancing frontiers of science and transforming regional economies. As funding models of modern universities change, they adopt some features of a business organization. While their ability to attract funding becomes vitally important for universities, especially from private sources (industry), a balance between fundamental and applied research becomes vital. The current research investigates five years of activities of the Skolkovo Institute of Science and Technology (Skoltech) and particularly its research portfolio. It is based on the theory and practice of the Research Domain Portfolio Matrix (RDPM) approach, which considers a university a portfolio of R&D technologies in diverse scientific areas and at various stages of technological maturity. It is of utmost importance for universities to find a balance between basic and applied research while making decisions on launching new projects/programs or modifying the existing projects/programs. The proposed RDPM approach helps to leverage limited resources, establish priorities, monitor risks, and influence outcomes in the short and long term.

Keywords: basic and applied research; R&D technology portfolio; technology management; industrial funding; research domain portfolio matrix

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Changing Roles of Universities in Society

Most universities engage in a combination of basic and applied research. According to the definition of basic research, this is “experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable tasks, without any particular application or use in view” (OECD, 2002). Essentially, basic research is research undertaken with the primary purpose of the advancement of knowledge (Bentley et al, 2015). The main difference in the definition of applied research is that it addresses primarily a specific practical aim or objective, usually focusing on solving a particular problem.

There is almost thirty years of debate about the role of universities as the primary source of research. In the late 1990s and early 2000s, the concept of university research turned increasingly toward industrial problem-solving and practical applications emerged. Gibbons et al. (1994) suggested that disinterested and research focused on basic principles by universities could not be considered a primary source of knowledge production (stated as Mode 1 of knowledge production). Increased direct interactions between universities and industry, so-called “Mode 2 knowledge production system,” is described by Gibbons et al. (1994) as a new type of social contract. Further, it is said deeper involvement of universities in solving applied problems (Slaughter, Leslie, 1997) is needed. According to the Mode 2 model, universities will not be the only source of knowledge as others, i.e., research institutes, hospitals, think tanks, and so on will contribute as well (Tijssen, Winnink, 2016). Etzkowitz and Leydesdorff suggest a triple helix model of university-industry-state relationships that shape national innovation systems (Etzkowitz, Leydesdorff, 2000). According to this model, university systems are able to play an enhanced role in innovation development contributing to national economic growth. As authors state, this concept was different from earlier approaches of national systems of innovation (Lundvall, 1988; Nelson,1993) under which the industrial company, or the firm, is leading innovation. They stipulate that dynamic relationships between the three elements of the helix indicate the unique role of the universities as core knowledge institutions. Comparing three possible models of the triple helix interaction (state-dominated – Triple Helix I, “laissez-faire” relationship – Triple Helix II), they proclaim it is the third model, that is supposedly the best fit for knowledge-based economics (Triple Helix III). The common objective is to realize an innovative environment consisting of university spin-off firms, trilateral initiatives for knowledge-based economic development, and strategic alliances among firms (large and small, operating in different areas, and with different levels of technology), government laboratories, and academic research groups. These arrangements are often encouraged, but not controlled, by government, whether through new “rules of the game,” direct or indirect financial assistance (Etzkowitz, Leydesdorff, 2000).

Responding to the change in roles of universities as “innovation machines” (Xu et al. 2018; Rücker Schaeffer et al., 2018), universities globally underwent a transformation from pure teaching into organizations that combine teaching and research including a strong component of solution-driven research.

Crawley et al. (2020) distinguish between “the curiosity-driven research when scholars are motivated by interesting problems at the frontiers of knowledge, which may or may not be immediately relevant to existing societal or industry issues” (Type 1 research), the “use-inspired research” motivated by the problems of industry or society (Type 2 research), and the research which aims for “directly implementable solutions to larger scale problems of industry, enterprise, government, and society” (Type 3). Curiosity-driven research and use-inspired research are more fundamental by nature, while the solutions-oriented research is usually conducted in the interests of university partners (industry, government).

Considering these trends, academia is increasingly finding itself engaged in solutions-oriented research also known as practical application, industry-funded research (Tijssen, Winnink, 2016), which corresponds to the Triple Helix III model (Etzkowitz, Leydesdorff, 2000). Thus, it is important to find the right balance between basic and applied research in academia.

Bentley et al. (2015) conducted a comprehensive analysis of individuals (more than 10,000 surveyed) from 15 countries mapping differences in focus on basic (fundamental) and applied (practical) research. There were noteworthy country differences in the balance between basic and applied research, i.e., Australian, US and Hong Kong researchers were more likely to specialize in applied research, while Scandinavian (Finnish, Norwegian) and Dutch researchers lean toward basic. The authors note that such differences might be attributed “to specifics of academic governance systems with a stronger academic oligarchy protecting the place of basic research compared to market-driven systems” however noting, that “this was not consistent with results in all countries” (Bentley et al., 2015, p. 704). Another reason for country differences are “institutional norms emphasizing research commercialization” which are, for instance, traditionally weaker for Latin American universities. However, Bentley et al. cautiously note that cross-country results are difficult to explain and “should be treated with caution due to the limitations of the data.”

China and Malaysia were identified as unique cases since their research traditions were rapidly evolving. Chinese universities prior to the 1980s were predominantly focused on teaching and later the government encouraged basic research capabilities; at the same time, Chinese researchers are traditionally eager to respond to applied research demands given professional obligation norms to solve society's problems (Mohrman, Baker, 2008). They concluded that "engagement in basic and applied research clearly has strong country-level features" (Bentley et al., 2015). Interestingly, it revealed that most researchers tend to engage in a combination of basic and applied research while researchers specializing in basic research tend to receive *less* external funding. Obviously, the balance between basic and applied research varies from discipline to discipline.

Increasingly universities are not viewed as only centers for teaching and research but also as entities responsible for the economic development of the society (Grover, 2019; Crawley et al., 2020) which has recently sparked their entrepreneurial activity (Schubert, Kroll, 2016). Governments envisage a broader view of the universities playing a key role in modern economies, i.e., contributing to social progress and the common good, enhancing social mobility, and producing talented graduates, discoveries, and creations:

> Government officials… seek stronger engagement of universities with society. They want universities to pay closer attention to society's needs, to become more involved, and better contribute to solutions. They believe that if universities engage with the users of knowledge, the outcomes will be more valuable goods, services, and systems, as well as stable and rewarding jobs (Crawley et al., 2020).

Research shows that the impact of leading universities on the economy can be tremendous. Goldstein and Renault (2004) provided a methodology describing how universities contribute to regional development. Typically, the contribution of a university to a regional economy is provided in a number of ways: i.e., research, technology development and knowledge transfers, and job creation through startups and spin-offs. However, it is still a challenge to quantify the magnitude of such contributions. We can roughly estimate it by calculating the core impacts (direct spending of university itself and its staff) and commercialization effects (startups created, the value of technology transferred to industry through direct contracts and/or technology licensing). For instance, Roberts et al. (2019) conducted a study of MIT's entrepreneurship and innovation impact on the US economy. They estimated that over the period of study (1950-2014), MIT alumni have launched more than 30,000 active companies, employing roughly 4.6 million people, and generating roughly $1.9 trillion in annual revenues, the equivalent of the 10th largest global economy by GDP in 2015.

Thus, "leading universities have an outsized economic impact on their city or region: through spun-off research; as a magnet to attract both students and an educated workforce; and as a direct employer" (EIU, 2020). Long-term contributions of universities to economic development strongly depend on the level of knowledge exchange between the partners, including industry and government (Crawley et al., 2020).

University Funding: A Change in the Funding Paradigm

However, the transition of universities' role and mission from teaching and research toward a more developmental role in society presupposes an inevitable shift in funding paradigms. Although public funding is still the predominant source of funding for university research, some recent studies suggest that public funding of universities is declining while industrial funding and other forms of public-private funding are growing. According to a Council on Foreign Relations report (USA), "despite its importance to the nation's innovation base, federal spending on research and development as a percentage of the overall economy has declined since the mid-1980s, from 1.2 percent of GDP in 1985 to 0.66 percent in 2016" (Manyika et al., 2019). In 2015, for the first time in US history, private sector R&D spending prevailed over the public funding (Mervis, 2017). In Russia, by contrast, government spending on scientific research has been modestly growing in absolute funding in 2015-2019 reaching 1,134 trillion rubles. However, R&D spending in terms of it as a percentage of GDP has not been able to exceed 1.11% over the last ten years, and even slightly declined in 2018-2019 ranging between 0.98% and1.03%. Contrary to the US and Western European countries which boast the dominance of private funding in R&D, in Russia the government's share of R&D funding is estimated in the range of 60% to 70%. Continuous tightening of funding conditions put pressure on the universities to engage more in international collaborations to become more cost-effective as well as to seek more non-governmental sources of funding.

Funding models for universities are typically classified by source of funding into internal (government core funding) and external (public or private funding not part of the core funds – i.e., project-based funding or grants by public funding agencies) (Irvine et al, 1990). It is recognized that core funding may increase stability in the university system by covering the salaries of permanent faculty members for research and teaching and basic infrastructure. University systems relying more on external funding are typically prone to more volatility compared with systems based on core funding. However, externally funded universities have more flexibility for new initiatives while universities with predominantly government core funding are potentially less dynamic (Geuna, Martin, 2003).

There is still no clear evidence whether a mixed funding model for a university accounts for more productivity within the university system. For instance, Auranen and Nieminen (2010) studied whether there is a connection between funding models and established financial incentives on the one hand and the efficiency of university systems on the other. They compared funding systems in seven European countries (Denmark, Finland, Germany, the Netherlands, Norway, Sweden, and the UK) and Australia concluding that although there are significant differences in the competitiveness of funding systems in these countries, there is no straightforward connection between financial incentives and a boost in publication productivity. However, Gulbrandsen and Smeby (2005) claimed that there is a significant relationship between industry funding and research performance. By questioning all tenured faculty in Norway, they found that faculty with industrial funding are involved in applied projects to a greater extent, tend to be more collaborative ("a highly collaborative mode of research") with other research institutions and international partners, produce more scientific publications, and, interestingly, generate more entrepreneurial output (consulting work, creation of spin-off companies, patent production, etc.) (Gulbrandsen, Smeby, 2005).

Over time, expenses in operating budgets have increased at a more rapid rate than sources of funding at many colleges and universities all over the world and these institutions are finding themselves in a difficult financial situation (Drucker, 1997; Selingo, 2013; Lyken-Segosebe, Shepherd, 2013). As a response to these financial issues, colleges and universities are investing significantly in market-driven academic programs (Seers, 2007; Altbach, Knight, 2007; McDonald, 2007; Hemsley-Brown, Oplatka, 2010). These programs leverage academic research in a variety of disciplines as well as leading practices from industry to prepare students to address opportunities and challenges that exist in these areas of focus. Market-driven academic programs that address market gaps and needs for employee development of specialized skills, knowledge, and capabilities have the potential to not only impact society in a positive way, they can also play a key role in addressing the financial challenges of the colleges and universities who effectively address these market needs.

Hypothesis: Universities with a Balanced Portfolio of Research Projects are Able to Leverage Funding

University funding is typically a scarce resource and the question of the allocation of resources is a vital one. The question of scarce resource allocation between various research domains becomes particularly important.

There have been numerous studies in resource allocation in the academic environment (Kotler, Fox, 1985; Dolence, Norris, 1994; Wells, Wells, 2011). Some research projects tried to assess academic educational programs via a business toolkit using product portfolio models. The most recognized product portfolio models are probably the General Electric (GE) McKinsey model and the Growth Share Matrix by the Boston Consulting Group, BCG. Although product portfolio models have been successfully used as tools for strategic analysis for many decades already, their application is not quite widespread in the academic context.

One of such applications is an approach by Wells and Wells (2011) who proposed an Academic Program Portfolio model (APPM) essentially based on a customized GE McKinsey Product Portfolio model. The application of this model is widely used by industrial consultants and extensively described, for instance, in (Yip, 1981). The APPM approach has a number of advantages since it has only two dimensions (educational program attractiveness, institution competitive capabilities) which is easy to understand and measure. The researchers suggest that academic administrators should integrate APPM into the university strategic analysis and planning mechanism. As the authors claim, a potentially fruitful idea might be to build a university product portfolio based on APPM.

In a recent study Burgher and Hamers (Burgher, Hamers, 2020) proposed a quantitative model that can be used for decision support for planning and optimizing the composition of academic program portfolios in higher education. The model provides five-year horizon planning and was tested on the data of a leading US private university (not disclosed). A portfolio of six master programs was evaluated over the period of 2011-2015 with some 800 students involved. The objective of the model was to maximize cumulative financial surplus for the planning period. The application of the model suggested modifying three original programs, canceling one program, and adding three programs each consecutive year over the next three years of the planning cycle. The authors concluded that a portfolio approach might be useful for achieving enhanced financial returns on academic products (in particular, market-oriented educational programs). Overall, this research is useful in providing not only a qualitative but also a quantitative approach to decision-making for the management of a university striving to create additional capacity and impact.

The research conducted by Arman (2019) introduced a case study of the Kuwait Institute of Scientific Research (KISR), describing the concept of the Portfolio Evaluation Matrix (PEM) to allocate limited resources across a set of strategic research initiatives of KISR. The PEM represents a bubble chart with "a two-dimensional matrix consisting of two criteria: a potential impact that the solution may have in the next five years and the ability of the current program team to deliver what is being promised" (Arman 2019, p.154). The axes on a scale from 1 to 10 reflect an internal assessment of each project by the staff of KISR. The size of bubbles represents the anticipated revenue stream from the R&D projects. He argues that introduction of this tool has helped the research center at KISR become more focused on aligning its R&D portfolio with long-term goals. However, this model is mainly a forward-looking approach based on a subjective evaluation of R&D outcomes.

We find the idea of viewing a university through the lens of a **portfolio** theory a worthy approach to explore. Crawley et al. (2020) insist that "research groups and universities would do well to have a balanced portfolio of these approaches. This balance will create knowledge outcomes that will influence economic development in the near-, mid-, and long term." This is an important implication for viewing a university from an R&D portfolio perspective.

The practice of R&D portfolio management has been extensively practiced by leading technology businesses over the last 30 years already. As Cooper states, "portfolio management is a critical topic because it integrates a number of key decision areas, all of which are problematic: project selection and prioritization, resource allocation across projects, and implementation of the … strategy" (Cooper et al., 1998). We hypothesize that *a university can be viewed from the perspective of a portfolio of R&D projects ofvarying maturity and timelines*. The management of a university has to make decisions for allocating scarce funding to a limited number of R&D programs in various technology areas and with varying levels of maturity. The goal of our research is to test this hypothesis using the Skolkovo Institute of Science and Technology (Skoltech) as a case study.

We draw from the modern investment portfolio theory founded by American economist Harry Markovitz. Markovitz laid the groundwork of investment portfolio selection theory. Markovitz was awarded a Nobel Prize for his contribution to economic sciences in 1990. His valuable addition to the investment field was the introduction of the portfolio diversification concept, which allows for the lowering of overall investment portfolio risk when properly selecting non-correlating individual investment assets (Mangram, 2013).

We suggest applying a similar approach to the research management of a university, assuming that it can viewed as a portfolio of R&D technologies in diverse scientific areas and at various stages of technological maturity. Therefore, the *goal* of our research is to develop a simple and useful methodology to assess the R&D portfolio of a modern technology university to lower R&D risks while maximizing its potential.

In order to achieve this goal, we have to provide:

1) An assessment of the of R&D technology portfolio balance in terms of fundamental (basic) and applied research in diverse scientific areas and at various stages of technological maturity;

2) A performance assessment of each research area (Target Domain) by differentiating between the leading performers, average performers, and laggards (low performers);

3) Regular monitoring of progress in each research area over time in terms of both scientific impact (i.e., publications) and value generation (i.e., external funds attracted).

Thus, we claim that a modern university needs to:

1) diversify its research technology portfolio by having both *basic* (fundamental) and *applied* research;
2) diversify its technology portfolio across *various fields of science* that are not correlated with one another;
3) develop a balanced technology portfolio consisting of technological projects and competencies at *different stages of market maturity* (some of them might be benchmarked by a famous "technology hype curve" used by Gartner[1]);
4) find the right *balance along the R&D project horizon* (i.e., short and long-term projects);
5) carry out *regular audits of its technology portfolio* (at least once in 2-3 years) in order to reassess and optimize the R&D portfolio
6) balance its research portfolio with educational programs aiming to optimize its benefits for society.

We test our hypothesis by analyzing the case of the Skolkovo Institute of Science and Technology (Skoltech), a newly established technological university.

Skolkovo Institute of Science and Technology: A Brief Overview

It was decided to test the proposed hypothesis using the Skolkovo Institute of Science and Technology (Skoltech) and its five years of activity as a case study. The Skolkovo Institute of Science and Technology (Skoltech) was founded in 2011 by the Russian government in partnership with the Massachusetts Institute of Technology with the vision of creating a world-leading academic institute of science and technology. Skoltech is performing cutting-edge basic and applied research in priority areas, promoting innovation and entrepreneurial activity while educating future specialists in science, technology, and business. In 2019, Skoltech was included in the top-100 Nature Index Young Universities ranking[2].

The total grants and contracts portfolio for 2016–2020 exceeds RUB 5.72b or USD 7.74m (at the rate of the Central Bank on December 31, 2020) corresponding to approximately RUB 13m or USD 0.17m (at the rate

[1] https://www.gartner.com/en/research/methodologies/gartner-hype-cycle, accessed 19.05.2022.
[2] https://www.natureindex.com/supplements/nature-index-2019-young-universities, accessed 19.05.2022.

of the Central Bank on December 31, 2020) *per faculty member* in 2020. More than 116 startups have been founded by Skoltech faculty, students, and alumni between 2011 and 2021.

An interesting question remains about the potential effects of Skoltech on regional economic development. According to some internal assessments conducted recently, such contribution might be tow to three times the amount of state funding of Skoltech, reaching as much as RUR 15-18 billion in 2020.

Skoltech research is closely linked with its educational and innovation activities. The combination of these activities contribute to Skoltech's Target Domains, which are broad scientific areas in which research, education, and innovation activities are concentrated. For now, there are seven key Target Domains contributing to Skoltech's mission by implementing long-term programs on academic and technology excellence in priority areas of science and technology development:

- Data Science & Artificial intelligence
- Life Sciences & Health
- Cutting-edge Engineering & Advanced Materials
- Energy Efficiency
- Photonics & Quantum Technologies
- Oil & Gas
- Advanced Studies (theoretical mathematics & physics)

A Target Domain is a lever for academic and technology excellence. Target Domain Programs are subject to a regular international expert review to assess achieved results, their relevance to strategic goals, and elaborate recommendations on improving activities.

Each Domain represents a combination of basic and applied research. However, some of Domains are more focused on applied research and collaboration with industry, i.e., Data Science & Artificial intelligence, Oil & Gas, and Cutting-edge Engineering & Advanced Materials. Meanwhile Life Sciences & Health, Energy Efficiency, and Photonics & Quantum Technologies represent a combination of applied and basic research with fundamental research prevailing. Domain Advanced Studies (theoretical math & physics), perform purely basic research.

As per our estimations, Skoltech's "curiosity-driven research" (Type 1 research) accounts for 50%-55% of total research funding (internal and external) while the "use-inspired research" (Type 2 research) has a share of 12%-15%, and the rest (30%-40%) should be attributed to "directly implementable research" (Type 3 research).

Considering the university as a portfolio of Target Domains, there is an opportunity to update the research priorities in a flexible manner, to conduct cutting-age research as well as to move into new emerging research areas.

Methodology

In the study, we examine the distribution of research publication output and attracted external funding output across the Institute's Target Domains.

Both publications and funding can be classified as basic (fundamental) or applied, although in some cases such classification can be rather tricky. Therefore, in this study for simplicity reasons we assume that the applied research is

(1) *research which is either supported by an industrial company* or

(2) *the results of the research that are likely to be commercialized within the two to three years.*

If research does not match any of these criteria, it is considered fundamental (basic) research.

There are certain exceptions to this rule, i.e., companies with long-term research timelines that are eager to fund even basic research in some areas of high interest and priority to them (i.e., quantum technology, new math methods, etc.), however such cases represent exceptions of the rule. Thus, our study revealed less than ten projects with industrial partners out of more than 850 projects analyzed that can be classified as fundamental research (with results that are potentially applicable for industrial use on a horizon of more than five years).

Research publications include faculty publications affiliated with Skoltech. The analyzed publications are indexed in Web of Science (WoS) and Scopus and published in high impact factor journals (mostly Q1 and Q2). The indicator "Research Publications" is used as a measure of academic excellence in cutting-edge basic and applied research.

The indicator "External attracted funding" defines funds attracted from different external funding sources in the form of R&D funding from governmental, non-governmental and industrial sources, professional education, advisory services, services of shared facilities, and technology licensing. The indicator "External attracted funding" consists of two types of funding - basic and applied attracted funding. Basic attracted funding is funding supporting fundamental R&D activities. It is typically provided by either Skoltech's internal sources or national and international funding agencies and foundations (i.e., the Russian Science Foundation) to support curiosity-driven research and use-inspired research.

Applied research funding is based on directly implementable industry-oriented research funded by national and international industrial players (large corporates or midsized high-tech companies) as well as research and innovation agencies (i..e., Foundation for Assistance to Small Innovative Enterprises, FASIE in Russia), the Russian National Technology Initiative, the Ministry of Education, or the Ministry of Industry and Trade of Russia through specially designed mechanisms to support applied R&D.

The analyzed projects vary from short-term (1-2 years projects) to large-scale, long-terms projects (3-4 years) including joint laboratories with industrial partners for multi-year research programs.

The quantitative and qualitative methods as well as comparative analysis were used in the study to make the analytical process more profound and broader. Our analytical framework is based on data from 2016 through 2020 for the Skoltech's Target Domains. We assume that the information from this subset is fairly representative for an in-depth analysis.

In order to analyze the research publication output of each Target Domain, we grouped publication data for 2016-2020 by each Target Domain per year. We used the same approach for analyzing external funding output for each target Domain. To make the study more accurate, we analyzed the funding output for each type of funding separately, in particular, for basic and applied.

The qualitative analysis has been made to identify the progress and achievements in each Target Domain. The following data have been analyzed and classified:

1) More than 2,500 papers in WoS and Scopus in 2016–2020 cited more than 32,000 times. A substantial part of papers were written in partnership with international and national universities and centers. Top international collaborators include CNRS (163), MIT (140 papers), papers), Aalto University (88 papers), Harvard University (66 papers), RIKEN (55 papers), Chinese Academy of Sciences (53 papers), NWPU Xian (50 papers), Stony Brook (46 papers).

2) More than 850 projects with funding totaling RUB 5.7 billion (USD 88.5m dollars) for 2016-2020 were analyzed including projects supported by national and international funding agencies and foundations (Russian Foundation of Basic Research, Russian Science Foundation, Horizon2020), national research and innovation agencies (Ministry of Science and Higher Education of the Russian Federation, Russian Government Programs, e.g., the National Technology Initiative and the Digital Economy), and leading national and international companies (Sberbank, Huawei, Gazprom Neft, Philips, Lukoil, Bayer, Alibaba, etc).

In summary, we introduce sboth quantitative and qualitative models that should provide support in selecting the composition of project portfolios with a goal to achieve the planned financial and non-financial objectives of the institute or university.

Results

In this section we present the results of our approach. We analyzed the previous four years of Skoltech development (2016-2020) by comparing achievements of Skoltech's key Target Domains in terms of

1) publications in quality scientific journals (Q1-Q2);

2) attracted external funding (both grants and industrial funding);

We further decompose investments and results by top areas of Skoltech expertise: i.e., Data Science & Artificial Intelligence, Life Sciences & Health, Cutting-edge Engineering & Advanced Materials, Energy Efficiency, Photonics & Quantum Technologies, Oil & Gas, and Advanced Studies (theoretical math & physics). Mapping the results against investments in these areas provides a clear picture of the university portfolio structure (see *Figure 1*) and insights into optimal strategy for future development.

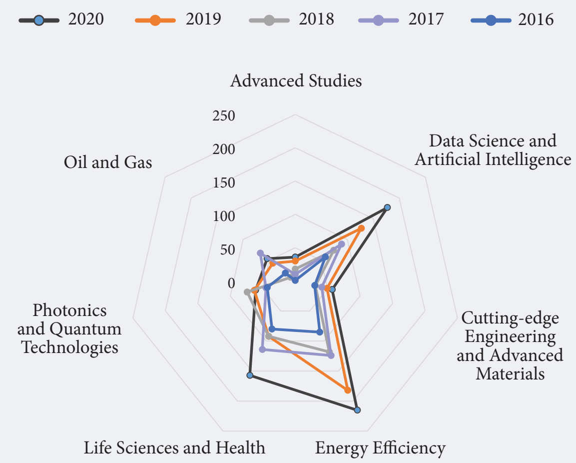
Skoltech's scientists have published mostly in the spheres of Data Science & Artificial Intelligence and Energy Efficiency, which prevail over other fields. The least amount of publications were noted in the Domain of Advanced Studies (theoretical math & physics) and amounted to 36, this field was established only recently (2017). Three Target Domains - Data Science & Artificial Intelligence, Energy Efficiency as well as Life Sciences account for most of the publications. Taking into consideration that Skoltech is a relatively young university starting its operations in 2011, this steady increase demonstrates the growing research activity of Skoltech faculty.

At Skoltech, applied research plays an important role in the university's everyday activities. Figure 2 shows that there has been a considerable increase in attracted applied research funding from 2016 to 2020. The most industry-oriented spheres in Skoltech are Data Science& Artificial Intelligence and Oil & Gas. The Domain of Advanced Studies (theoretical math & physics) has attracted zero industrial funding due to the nature of the Domain. Also, the least applied research funding was attracted by Life Sciences. The same phenomenon is detected in the sphere of Photonics and Quantum Material, where the most successful year from that point of view was 2019. In general, the diagram shows that each year there is steady increase in attracted external applied research funding almost in all spheres.

As shown in Figure 3, attracted basic research funding grows annually. Most grants in 2020 were received by Data Science & AI and Energy Efficiency. The Domain of Advanced Studies (theoretical math & physics) at Skoltech is exclusively grant-oriented, since it performs only basic research. The other Domains – i.e., Oil & Gas and Cutting edge Engineering – are predictably more focused on applied research and less on basic research.

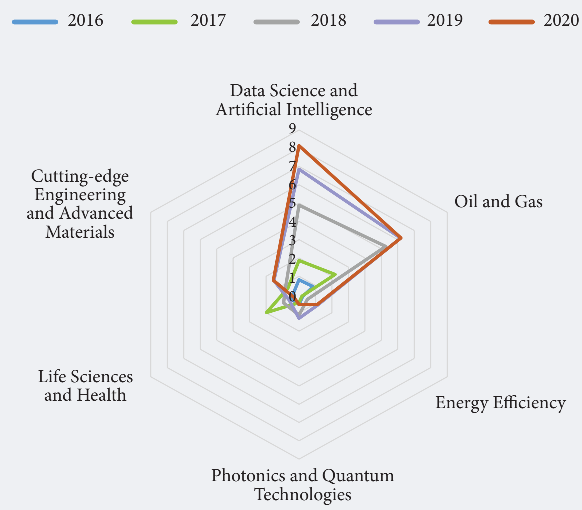
From the point of view of publications and attracted external funding, the most balanced sphere is Data Science & AI with a good quantity of publications and attracted external funding (Figures 4 and 5). The Oil & Gas Target Domain is definitely the most industry-oriented sphere, with rather few publications. Energy Efficiency has a considerable number of publications but less external funding. External funding for Data Science & AI as well as Oil & Gas has grown drastically over the period of 2016-2020.

Figure 1. Publications of Skoltech 2016-2020 according to Target Domains



Source: Composed by the authors on the basis of Skoltech Annual Reports. https://www.skoltech.ru/en/about/annual-reports/, accessed 14.11.2021.

Figure 2. Attracted Funding – Applied Research 2016-2020 as per Target Domains, USD mln



Source: Composed by the authors on the basis of Skoltech Annual Reports.

From 2016 to 2020, these two areas have become much more industry-oriented. The changes that took place from 2019-2020 are shown in the Figure 5. Energy Efficiency clearly grew in both directions – publications and external funding, becoming comparably more balanced. Oil & Gas increased its publications. Life Sciences and Photonics and Quantum Materials slightly decreased their publication activities but augmented attracted funding. Data Science &AI and Engineering & Advanced Materials show similar pattern dynamics, but on a much different scale.

Discussion

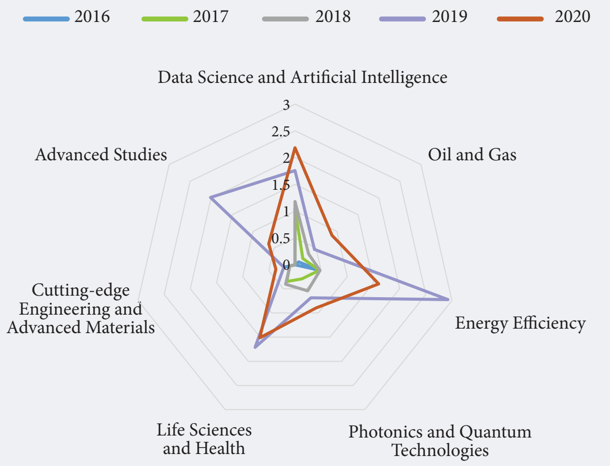
Some early research in the Academic Portfolio Model includes (Kotler, Fox, 1985) who proposed the Academic Portfolio Model for the strategic analysis of a university's academic programs. They mapped three dimensions for assessment of an academic portfolio strategy: (1) how central is the academic program to the university's mission; (2) academic quality of the program (program depth, rigor and faculty quality); (3) the market demand for the program.

Wells and Wells (2011) proposed the Academic Program Portfolio Model (APPM) for the strategic evaluation of university's academic programs adapted from the GE McKinsey Product Portfolio Model. The GE McKinsey Product Portfolio Model is based on the assessment of a company's products on two dimensions – industry attractiveness and competitive capabilities. The APPM approach proposes assessing university academic programs based on the following dimensions – Program Marketplace Attractiveness (industry attractiveness) and Program and Institution Capabilities (similar to competitive capabilities). The assessment criteria are selected and measured by a 1-5 score metric to be later mapped on the portfolio matrix. The analysis can be performed at the level of either interfaculty (comparison of faculty members of the university or its science domains) or within academic programs of a particular faculty (i.e., within Medical School programs). As Wells and Wells conclude, "the APPM, offers the opportunity to assess the strategic direction of specific academic programs relative to one another and relative to the institution… administrators simultaneously consider multiple academic programs relative to strategic direction, resource allocation, financial returns, and importance to the institution…" (2011, p. 11).

The research of (Wells, Wells, 2011) is mainly based on qualitative methods. However, a quantitative approach is of particular interest since it leads to a fact-based judgement when designing and promoting academic programs. (Labib et al, 2014) proposed a framework for the formulation of a higher education institutional (HEI) strategy based on an operational research (OR) methodology. Recently (Burgher, Hamers 2020) proposed a decision support tool based on a quantitative approach aimed at optimizing the composition of portfolios of market-driven academic programs.

Both the approach proposed in this paper and the approach introduced by (Burgher, Hamers, 2020) are focused on optimizing financial and non-financial dimensions of portfolios, i.e., the R&D Technology Portfolio and the Portfolio of Market-Driven Aca-

Figure 3. **Attracted Funding – Basic Research 2016-2020 as per Target Domains, USD mln**



Source: Composed by the authors on the basis of Skoltech Annual Reports.

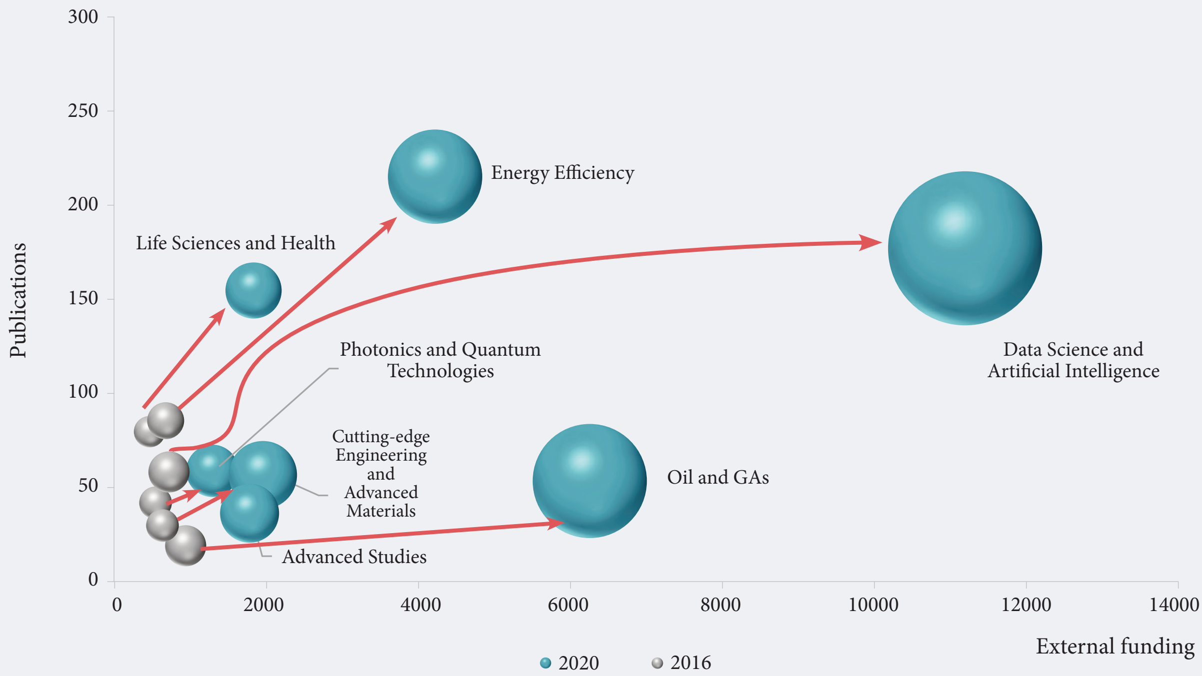
demic Programs. The main idea of both approaches is balancing financial and non-financial dimensions to achieve the desired impact of portfolios upon universities' strategic goals and their financial stability as well as market needs.

In their research (Burgher, Hamers, 2020) introduce methods of quantifying qualitative information related to market-driven program dimensions and developing the quantitative model for strategic planning in higher education for a portfolio's optimization. The output of the model is a program management schedule and development plan for the portfolio optimization process for the planning period.

Our approach – the Research Domain Portfolio Matrix (RDPM) - is different from the previous research in the following:

1) We incorporate both qualitative and quantitative approaches in our research. The quantitative angle is very useful in terms of fact-checking and benchmarking the university's strategy against financial return on allocated resources (as the trend for market-driven academic programs is growing due to financial constrains experienced by academia).

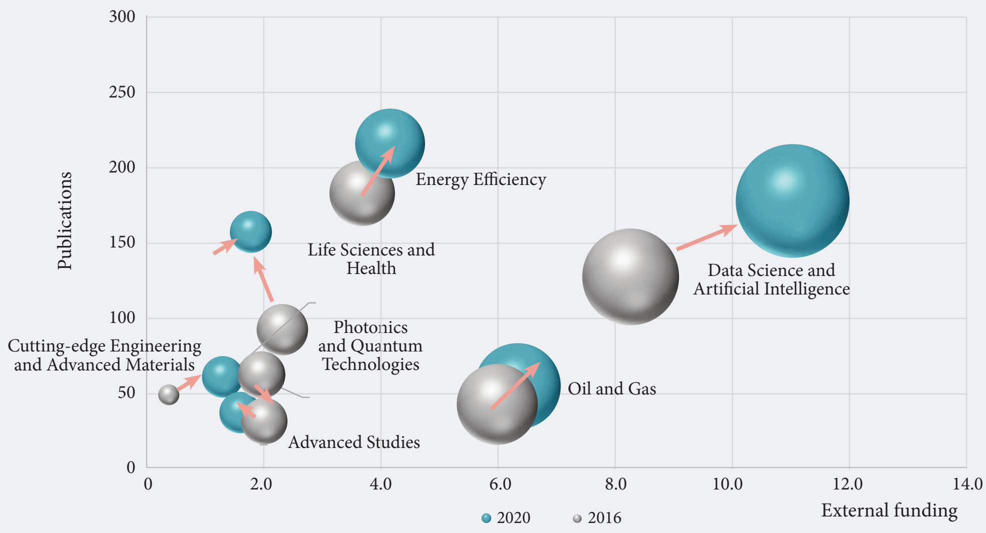
Figure 4. **The Evolution of Publications Activity and Research in 2016–2020 (USD mln)**



Note: Scientific impact is measured by publications in Q1-Q2 scientific journals (Y-axes, number of publications); external funding application is measured by attracted funding for both basic and applied research (X-axes, USD m).

Source: Composed by the authors on the basis of Skoltech Annual Reports.

Figure 5. **The Progress in Publication Activity and External Funding from 2018 to 20209 (USD mln)**



Note: Scientific impact is measured by publications in Q1-Q2 scientific journals (Y-axes; number of publications); external funding is measured by attracted funding for both basic and applied research (X-axes; USD mln); size of the bubble reflects amount of the total external funding. Yellow arrows indicate progress dynamics (change in positions from 2019 till 2020).

Source: Composed by the authors on the basis of Skoltech Annual Reports.

2) Our focus is on the finding a *right balance between the basic and applied research* since both dimensions are important and neither should be neglected.

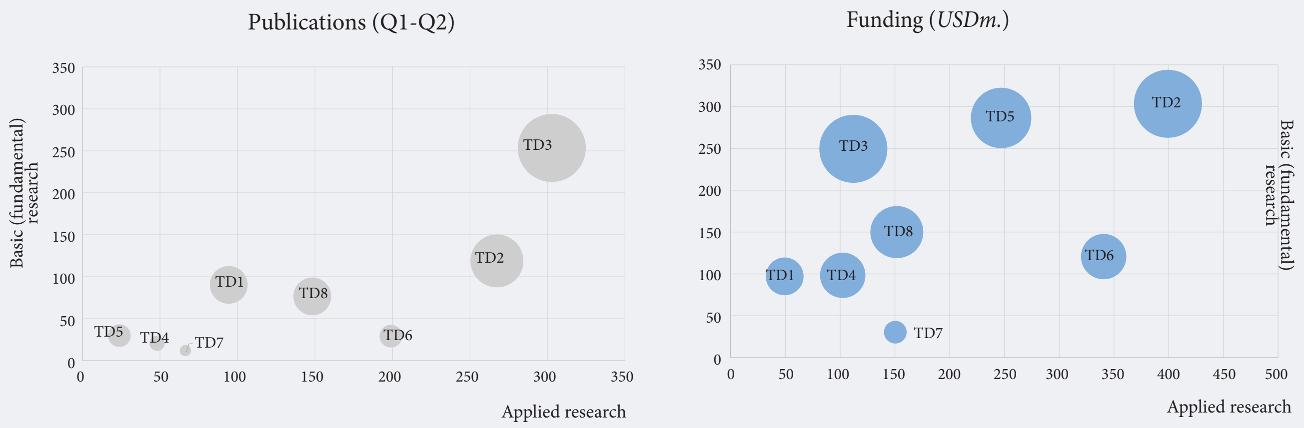
3) We suggest focusing more on the dynamics of research achievements (changes over time, i.e., Figures 4-5) rather than static measurements that are usually common for product portfolio matrixes (i.e., the approach by (Wells, Wells, 2011).

The RDPM approach maps key research areas (Target Domains) of a university according to their fundamental or applied nature. A university is treated as a portfolio of research projects. The X and Y axes of the matrix represent the level of fundamental and applied research measured by either produced publications or attracted funding (a hypothetical university research portfolio provided on Figures 6-7 for illustrative purposes). The proposed approach has been successfully used to classify more than 850 projects implemented by Skoltech over the period of 2016-2020.

The RDPM approach helps to provide a holistic view of the state of university research. Like a company balance sheet, it gives a snapshot of the current state of the research portfolio (its composition). It provides a good visualization of the top contributors across research domains to the university's scientific visibility and impact on the one hand, as well as its usefulness to industry and real-life applications. Additionally, RDPM viewed dynamically (i.e., across several years) is useful in tracking the progress of Target Domains and, therefore, providing more or less reliable estimates of 1) scientific return on investment (i.e., in the form of quality publications in Q1-Q2 journals) or 2) financial return on investment (funding from either government sponsored grants or industry sponsored research). The management of the university can "praise the winners" and "punish the laggards" by allocating the excess of internal funding to the areas with the highest scientific or industrial returns in the short- to mid-term (Figure 7). Thus, RPDM might be used as a simple and powerful tool to *rebalance research portfolio* by setting and modifying the priorities of current and future university research, which is naturally a topic of hot debate for university management given resource allocation constraints.

Overall, Skoltech maintained a good balance between basic and applied research. The judgement of whether the balance is "good" or "bad" is largely *at the discretion of the university's management*. Skoltech governance is based on the principles of collegiality. The strategy issues are overseen by the Board of Trustees. The Board of Trustees monitors Skoltech results on a regular basis (quarterly or semi-annually), reviews proposals for new initiatives of strategic importance, and approves the changes to Skoltech's overall strategy. However, Target Domains are managed by the respective centers where faculty are largely responsible for setting up directions for research. Periodically (no less than once in three years), the programs of the centers are audited by the International Advisory Committee providing valuable input on Skoltech's international scientific agenda. Most of the Target Domains also have Industrial Councils, comprised of representatives of the top management of leading Russian and international companies. Industrial

Figure 6. **Research Domain Portfolio Matrix Approach Maps Key Research Areas (Target Domains) of the Hypothetical University according to theirFundamental or Applied Nature**



Note: Considering University as a portfolio of research projects the X and Y axes of the matrix represent the level of fundamental and applied research measured by either produced publications or attracted funding.

Source: Composed by the authors on the basis of Skoltech Annual Reports.

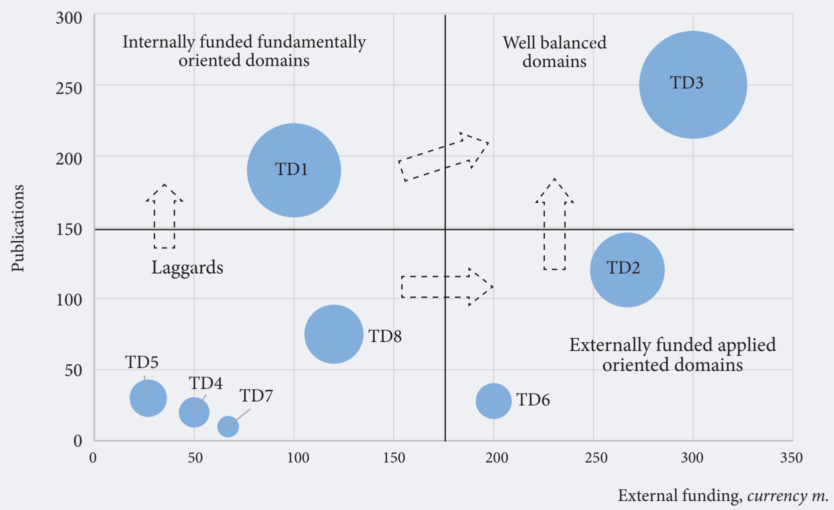
Councils together with the Industrial Programs Department under the Vice-President of Industrial Cooperation help set the direction of applied technology research.

In 2011, when the Skoltech was established, the Board of Trustees set up a rather ambitious target to get at least 30% of university funding from external sources (i.e., industrial funding or grants and subsidies from domestic or international science funding agencies) by 2020. This was included in the KPIs of Skoltech (in 2020, the share of external funding reached 29.6%[3]).

The effective allocation of resources to several Target Domains in the early years (2013-2016) – in particular, to applied areas such as Oil & Gas, Data Science & Artificial Intelligence helped to attract industrial funding and bring cutting-edge technologies to the market, while investments in Life Sciences & Health, Cutting-edge Engineering & Advanced Materials, Energy Efficiency, and Photonics & Quantum Technologies helped to gain early scientific visibility.

Some of the successful examples of Skoltech's basic research include, for instance, new methods of gene

Figure 7. **Research Domain Portfolio Matrix**



Note. Dashed arrows indicate a desired improvement trajectory for Target Domains

Source: Composed by the authors on the basis of Skoltech Annual Reports.

[3] https://www.skoltech.ru/app/data/uploads/2019/10/Skoltech-Annual-Report-2020.pdf, accessed 19.05.2022.

editing, a next generation of telecom technology (6G), prospective cathode materials with high energy density, research in photonics, new math methods, etc. Among the recent applied research projects are telecom software development (5G Open RAN), AI technology applications for various industrial and medical purposes, lightweight perforated honeycomb technology production from aluminum foil, and new technologies for exploration and production of hard-to-recover hydrocarbons. Some of these projects have been commercialized recently for the leading Russian companies, i.e., SberMed.AI (medical software), a space industry manufacturer (honeycomb technology), leading oil & gas companies, and others.

Taking into account these considerations and based on the conducted analysis of Skoltech performance in 2016-2020, we conclude that:

1. Successful applied research projects help to generate more external funding year-on-year, they attract new industrial partners, and bring cutting-edge technologies to the market. There is a positive feedback reinforcement loop when successful results of applied research are used to bring in even more partnerships and funding resulting in more future successes. We believe this positive feedback loop is an important engine of growth for academic universities especially in times of shrinking government support and limited funding for basic research.

2. Some Target Domains have made remarkable progress in both basic and applied research within the last several years while others have not shown rapid growth. We believe that the performance dynamics of each Target Domain over the past three to four years is a reliable indicator to consider some strategic decisions for administrators involving resource reallocation choices that are difficult in a resource-constrained environment.

3. A further investigation is needed to define whether there are any barriers for growth for Target Domains that have not demonstrated the expected progress.

Therefore, our RDPM approach suggests that portfolio analysis is quite helpful in facilitating a strategic discussion for the management of the university. It is a useful tool for seeing the "helicopter view" of university's achievements. Also, it can be helpful in facilitating a discussion about the strategic vision for research directions and resource allocation choices.

Figures 8-9 provide some insights into the potential strategic moves for each of Skoltech's Target Domains in the future (based on 2020 data).

A systemic representation of the typical self-reinforcing loops behind the university engine of growth is provided on Figure 10. Top international scientists attracted to the university generate high quality research that results in publications (Q1-Q2 journals) and advanced scientific projects. As the scientific reputation of the university improves, making it visible within the domestic and international arenas, it becomes easier for the university to attract industrial funding for applied projects. Industrial funding also contributes to quality publications and advanced projects that drive reputation further. Thus, strong self-reinforcing loops begin serving as growth accelerators for the university as it is the case with rapidly growing companies (i.e., Achi et al., 1995; Katalevsky, 2007).

Conclusions

This paper adds to current theory and practice by developing the Research Domain Portfolio Matrix (RDPM) approach, which considers the university portfolio of R&D technologies in diverse scientific areas and at various stages of technological maturity. We claim that it is important for universities to find a balance between basic and applied research when making decisions on launching new projects and programs or when modifying existing projects and programs.

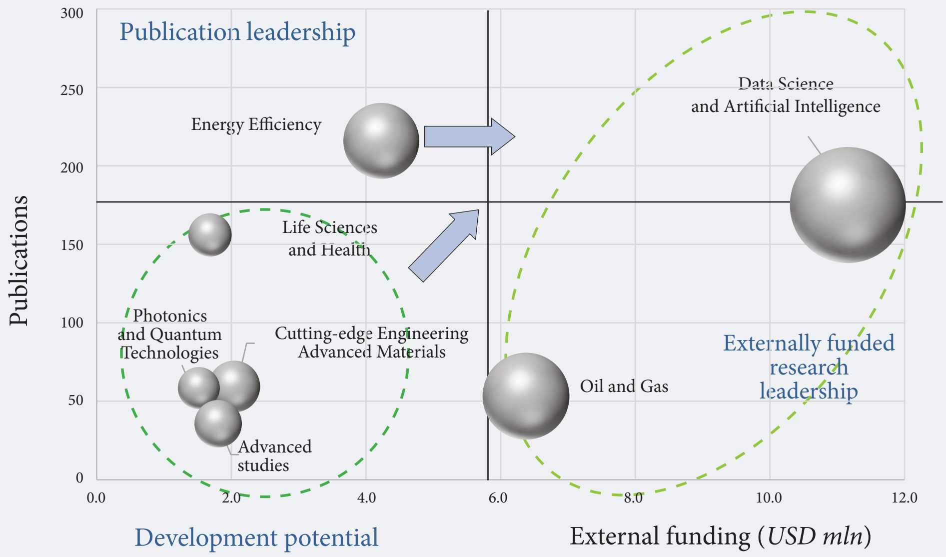
Proposing the RDPM approach to study a university's research portfolio, we conclude that an analysis of research indicators (publications in scientific journals, attracted external funding for basic and applied research) further decomposed by the specific areas of Target Domains helps to provide a clear picture of the university portfolio structure and insights into the optimal strategy for future development and investments. Unlike other approaches to R&D portfolio matrixes mentioned above, our approach is based on the assessment of real results achieved by each Target Domain whether in terms of academic excellence (publications) or industrial impact (proceeds from external funding, either basic or applied).

We analyzed key Target Domains of Skoltech research by publication activity and attracted external funding. Furthermore, we provided an assessment of Target Domains' progress in 2016-2020. This research helped us to arrive to several important conclusions.

First, the initial investments of Skoltech in relevant infrastructure and the hiring of internationally recognized faculty for the Oil & Gas and Data Science & Artificial Intelligence Domains have led to the development of strong industrial collaborations and the attraction of significant funding (2016-2020). These Target Domains currently have the greatest amount of support from industrial partners and continue to thrive even as internal funding from Skoltech is gradually diminishing due to new research areas being prioritized. Domestic and international businesses will likely support some future promising research in these Domains (i.e., various applications for Artificial Intelligence, 5G/6G technology, hydrocarbon recovery and modeling of fracking technologies for oil and gas extraction, the reduction of the carbon footprint, etc.) through long-term collaboration programs.

Second, some Target Domains (primarily Energy Efficiency, Life Sciences & Health, and Photonics &

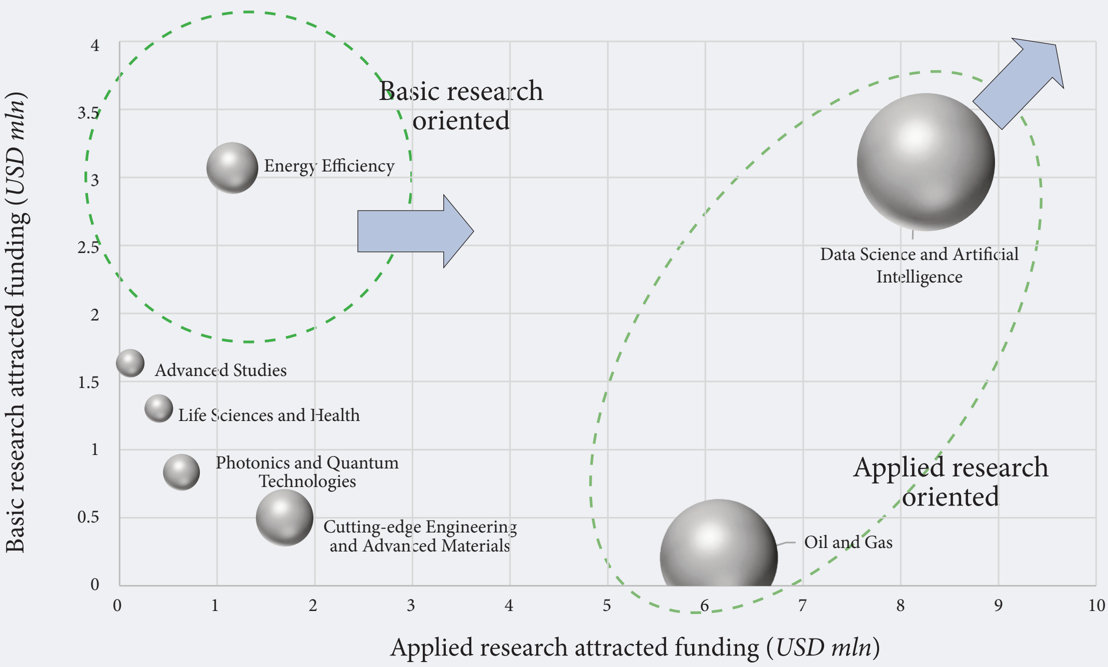
Figure 8. **Skoltech Target Domains: Strategic Future Directions (2020)**



Note: Scientific impact is measured by publications in Q1-Q2 scientific journals (Y-axes; number of publications); total external funding is measured by attracted funding for both basic and applied research (X-axes, USD mln); size of the bubble reflects amount of the total external funding; yellow arrows indicate potential strategic development directions.

Source: Composed by authors on the basis of Skoltech Annual Reports.

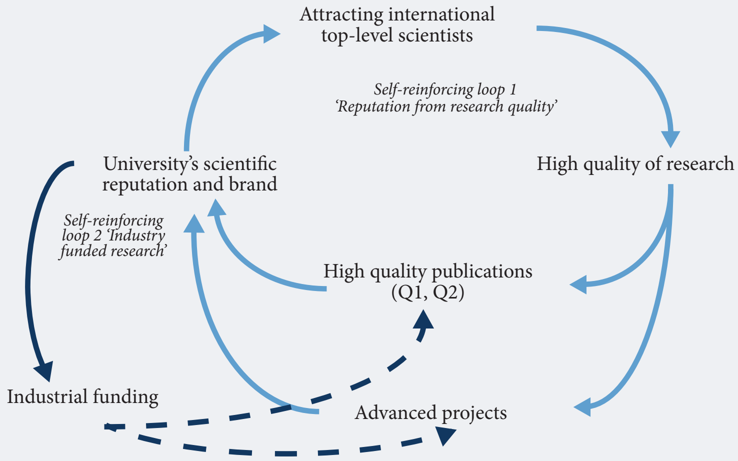
Figure 9. **Skoltech Target Domains: Basic vs Applied Research (2020)**



Note: Basic research attracted external funding (Y-axes; USD mln); applied research attracted funding X-axes, USD mln); size of the bubble reflects amount of the total external funding; yellow arrows indicate potential strategic development directions.

Source: Composed by authors on the basis of Skoltech Annual Reports.

Figure 10. **A Systemic Representation of the Self-reinforcing Loop of High Quality Research Driving Reputation and Helping to Attract Industrial Funding of the University**



Source: Composed by authors.

Quantum Technologies), represent a mixture of applied and basic research, with fundamental research prevailing. Although applied research funding levels achieved by Oil & Gas and Data Science have not been reached, these Domains were instrumental in generating a stream of quality publications. Their contributions have helped to gain valuable scientific visibility for Skoltech by 2020. Thus, in less than ten years since Skoltech was established, it was included in the top-100 Nature Index Young Universities ranking in 2019. Meanwhile, next steps should be aimed at including more industry oriented research on the agenda, i.e., quantum algorithms, THz and RF photonics, nanomaterials in the Photonics & Quantum Technology Domain, cathode materials, Li-ion batteries, conversion, and diversified energy systems in the Energy Efficiency Domain.

Third, some domains, i.e., Cutting-edge Engineering and Advanced Materials, still have to realize their potential. The same is true for the Advanced Studies Domain (theoretical math & physics), which will continue to be focused on basic research. Interestingly, Engineering can have a great impact on Skoltech since it can influence the innovation cycle of all technological domains. As shown in Figures 6 and 7, it is still in its infancy because it has been so far difficult to attract a critical mass of top engineering researchers in the fields of Product Development, Systems Engineering, and Digital Engineering, which are the key areas in Design and Systems Science, the core competency required for Cutting-edge Engineering.

Fourth, Skoltech is currently well positioned among peer technological universities in Russia being recognized as a leader in several research domains, i.e., artificial intelligence, energy storage materials, hydrocarbon extraction, and other areas. However, to sustain its position as the technology leader, it must continue attracting top international scientists to support new promising areas of basic and applied research. In addition, more efforts should be put into the early discovery of promising intellectual property from idea disclosure to active patenting of curiosity-driven research results. Thus, the RDPM portfolio matrix can be updated by using "IP/Patent application" as a vertical axis indicating the amount of IP generated over a certain period of time. When conducted, such an analysis will be able to suggest new ways for improvement.

Finally, we conclude that the proposed approach allows us to clearly formulate priorities in research development, support leaders, and decide which research directions need to be adjusted (Figure 9). The periodic adjustments to a Domain's development strategy is cause to audit a Domain's technology portfolio. We believe that the audit of a university R&D portfolio should happen at least once every three years.

To optimize funding allocation, it is important to consider the scientific area, market maturity of the technology, and the potential return for the university, economy, and society in the short- and long-term while balancing the impact of its educational programs. Investment portfolio theory provides valuable insights into how to optimize the allocation of funding (a scarce resource) in areas with the most promising risk-return profile. Further research is needed to identify the best risk-return strategies and produce mathematical models to be able to quantify the risk and payoffs of funding a particular scientific area.

It is planned that the next step should be the development of a general model for university R&D technology portfolios based on the RDPM approach. The current research is based on five years of activity at

Skoltech and we assume that the information from this subset is representative for an in-depth analysis. Meanwhile, the model should be further developed based on the analysis of case studies of different universities (both national and international) and their approaches to selecting and funding different types of R&D projects and programs. The mathematical model should include the decision alternatives, scientific domain specifics, constraints, among other elements.

It would be reasonable to investigate in further research the opportunity to rework Harry Markowitz's investment portfolio theory to apply to the area of university R&D technology portfolio management that will enable one to lower the R&D portfolio risk while maximizing its potential. A new toolbox needs to be created by further research referencing key terms suggested by investment portfolio theory.

The RDPM approach will help one leverage limited resources, establish priorities, monitor risks, and influence outcomes in the short- and long-term. Our approach might be useful for universities' leadership to facilitate strategic analysis and guide choices aimed at ensuring the desired impact of the R&D technology portfolio aligned with the universities' strategic goals, their financial stability, market needs, and potential impact on society.

Dmitry Katalevsky supervised the work, designed the study and together with Natalia Kosmodemyanskaya developed the original idea, wrote the manuscript, performed analytical calculations and derived conclusions. Arut Arutyunyan assisted with preparation of data sets and graphic representation of information. Clement Fortin reviewed the paper and provided some useful insights.

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HUMAN CAPITAL AND EDUCATION

How Susceptible are Skills to Obsolescence? A Task-Based Perspective of Human Capital Depreciation

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Abstract

This article investigates the link between human capital depreciation and job tasks, with an emphasis on potential differences between education levels. Using data from the German Socio-Economic Panel, fixed effects panel regression is applied to estimate an extended Mincer equation based on Neumann and Weiss's model. Human capital gained from higher education levels depreciates at a faster rate than other human capital. The depreciation rate is also higher for specific skills compared to general skills. Moreover, the productivity-enhancing value of education diminishes more rapidly in jobs with a high share of non-routine interactive, non-routine manual, and routine cognitive tasks. These jobs are characterized by greater technology complementarity or more frequent changes in core-skill or technology-skill requirements.

The presented results point to the urgency of elaborating combined labor market and educational and lifelong learning policies to counteract the depreciation of skills. Education should focus on equipping workers with more general skills in all education levels and adapting educational programs to take into account the rapid upgrade of production technologies and changing competency requirements.

Keywords: education; human capital; depreciation; skills; obsolescence; tasks; technological change; earnings

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Introduction

Educational organizations train workers to perform various sets of tasks in accordance with market realities. At the same time, with the proliferation of information and communication technologies (ICT) and robotics, the content of work processes is changing: machines are taking on increasingly more routine operations, while new tasks for human workers arise. As a result, qualification requirements are changing, with some of the previously acquired competencies becoming irrelevant for the labour market. This process is called human capital depreciation. If previously it mainly affected personnel employed in knowledge-intensive sectors, with the accelerated technological development this trend is becoming more broad. The ongoing digital transformation is impacting an increasing number of occupations. Relevant solutions complement or replace human skills, leading to their obsolescence. First of all, this affects jobs involving complex cognitive, interactive, and analytical tasks, where the active use of technologies complements human workers. Since workers' skills quickly become obsolete, the economic value of human capital decreases accordingly. To remain competitive, workers need to improve their skills or acquire new professions. Technological and organizational changes will obviously accelerate and affect all areas of the economy, while the risk of skill depreciation will increase. This challenge must be met and appropriate policy action taken.

Despite the stable and long-term nature of the observed effects, the topic of knowledge depreciation in the context of technological change remains poorly understood. Backes-Gellner and Janssen (2009) describe the different ways in which competencies become obsolete, pointing to the need to take into account the specific features of work tasks as a determinant of this process. However, their results are limited because they do not consider the differences in human capital depreciation depending on the level of education.

In an attempt to fill the current gap, we aim to find out how changes in the nature of work tasks affect human capital depreciation at different levels. To the best of our knowledge, this is the first study that takes into account these aspects, distinguishing between different human capital types and work task groups. Accounting for differences in competency obsolescence depending on specific features of work tasks deepens our understanding of human capital depreciation models. More effective labor market and education policies can be shaped on this basis, which is critically important to helping the workforce adapt to the changing context.

Literature Review and Theoretical Framework

Skills depreciation

The human capital concept emerged in academic discourse decades ago (Becker, 1964; Mincer, 1974; Rosen, 1975). It comprises knowledge and skills acquired both over the course of formal education at educational organizations and during practical work. Human assets' current economic value is reflected by the remuneration workers receive and by their performance indicators. As with any other type of capital, professional qualifications can depreciate over time in two dimensions: technical and economic ones (Becker, 1964; Arrazola, Hevia, 2004; De Grip, Van Loo, 2002; Neuman, Weiss, 1995). The first is caused by internal factors such as workers' age, or insufficient application of their skills. The second involves a decrease in the market value of knowledge and skills due to changes in the economic environment, which is why it is often called external depreciation. The focus of our analysis is on the economic aspect.

Innovation-based development and the growth of high-technology industries led to labor substitution, creating a serious challenge for the "established" qualifications. With the development of labor-substituting technologies capable of performing repetitive production operations, such effects are becoming increasingly more pronounced.

Measuring competence depreciation

Empirical studies focused on the quantitative aspects of human capital obsolescence remain sporadic, while their methodological approaches are less than universal. A particularly broad range of models were applied for these purposes in early studies. The analysis of the relationship between workers' earnings, age, and experience revealed that competencies of workers with secondary education become obsolete faster than those of university degrees (Rosen, 1975). The qualifications of women with tertiary education depreciate at a particularly high rate (Mincer, Ofek, 1982). A number of experts believe the level of education does not play a decisive role here (Carliner, 1982; Holtmann, 1972). The age-earnings relationship was explored in more detail for such aspects as lifecycle investment models (Becker, 1964; Haley, 1976; Heckman, 1976; Johnson, Hebein, 1974) or interruptions in women's work (Mincer, Ofek, 1982). However, the above studies do not distinguish between internal and external depreciation. Only a single general indicator is taken into account: technical obsolescence of human capital due to insufficient use of skills or advanced age (De Grip, 2006; De Grip, Van Loo, 2002).

Currently, human capital depreciation is measured either directly or by using indirect indicators. Internal and external depreciation were first distinguished by (Neuman, Weiss, 1995). Human capital depreciation is measured indirectly through, e.g., the ratio of education to potential experience, and its impact on earnings (Mincer, 1974). The relationship of the "education" and "experience" variables is estimated based on the assumption that the economic value of knowledge and skills decreases depending on the length of time between the end of formal education and potential entry onto the labor market. The advantage of an indirect approach is that it captures the decline in productivity through earnings, which is the main problem in most countries (De Grip, 2006). It was established that negative effects on earnings in relation to the level of education and work experience are more pronounced in high-technology sectors where workers tend to have more advanced qualifications (Neuman, Weiss, 1995).

An improved version of this model was applied to examine the Spanish labor market (Murillo, 2011). The education depreciation rate was estimated at 0.7% in 1995 and 0.4% in 2002 (this indicator value grows along with the education level), and the experience depreciation at 3.8% and 1.8%, respectively. Calculations based on the extended earnings equation (Mincer, 1974) showed that the skill obsolescence rate was higher for workers whose jobs involved knowledge-based tasks, rather than experience-based ones (Backes-Gellne, Janssen, 2009).

An analysis of sectoral differences in human capital depreciation in OECD countries in 1980-2005 revealed fluctuations in the range from 1% to 6%, with this indicator value being higher in the sectors requiring high level of skills, regardless of the use of technology (Lentini, Gimenez, 2019). The knowledge depreciation rate increases with higher qualifications and reaches maximum values in high-technology industries (Ramirez, 2002). Mathematical modeling based on direct estimates showed that the human capital depreciation rate in the UK and the Netherlands was at 11%-17% (Groot 1998), and at 1.2%-1.5% in Spain, depending on the sector and the duration of unemployment (Arrazola, Hevia, 2004). The case of Switzerland (Weber, 2014) shows that specialized skills depreciate faster (0.9%-1.0%) than general ones (0.6%-0.7%). The variation in depreciation levels is most likely due to differences in measurement techniques, observation periods, and source data arrays. It was established that the competency obsolescence depends on their type, but not enough attention was paid to the role of the technological development factor that determines the state of affairs in most of the leading countries. Competency obsolescence was linked to work task types (knowledge- or experience-based ones) (Backes-Gellner, Janssen 2009), but the depreciation of formal training was not taken into account. Accordingly, the obtained results are poorly compatible and of little use for evaluating modern educational systems. In other studies, specific features of this loss of relevance in different professional segments was addressed only indirectly (Weber, 2014; Lentini, Gimenez, 2019).

The technological potential of labor substitution differs for different work task types, so it can be assumed that human capital obsolescence rates vary depending on the functional portfolio of a particular profession. To test this assumption and compare the results with the findings of previous studies, we focused both on work tasks (according to the classification described in the job polarization literature) and education depreciation.

Hypotheses

The above literature review allows one to suggest a number of hypotheses and clarify the role of work tasks in human capital depreciation. As was noted, it comprises two aspects: education and experience, but the "reserves" of each are subject to depreciation - which, together with investments, determine the current human capital value. Its depreciation rate depends on the category of personnel. The depreciation rate classifications proposed in previous studies (Murillo, 2011; Neuman, Weiss, 1995) are provisional and must be revised. In our opinion, the economic obsolescence of human capital caused by changes in the external context does not affect everyone equally, but depends on personal skills (basic and specialized) and the type of tasks performed. Core competencies are universal in nature, typically acquired over the course of general secondary or tertiary education and remain relevant in the long term even as the economic landscape changes. In turn, specialized skills are developed in the course of secondary vocational education and training (VET) or higher vocational education and training (HVET). They are based on the latest knowledge and focused on making use of particular technologies. However, the accelerating substitution of some production processes with others leads to a rapid depreciation of such qualifications. Accordingly, the following hypotheses are suggested:

H1a. *The higher the level of workers' education, the higher the rate of their skill depreciation.*

H1b. *The competencies of workers with higher and secondary vocational education depreciate more rapidly than those of workers with general education.*

The next group of hypotheses concerns the relationship between work tasks and skill obsolescence. Any profession comprises a set of tasks which cannot be performed without appropriate training (Rodrigues et al., 2021). In other words, competencies are determined by the nature of the job. Technological development leads to changes in work tasks and in competency requirements, which in turn results in obsolescence of the latter. Manual or repetitive tasks are gradually transferred to machines (Autor, Dorn, 2013; Autor, Handel, 2013; Frey, Osborne, 2017). Cognitive, analytical, or interactive tasks need more advanced human capital, often enhanced by technology. Occupations with a high share of non-routine operations include, e.g., financiers or programmers. However, specialized skills acquired during formal education are intended for the use of technologies relevant at the time, and as some production processes are replaced by others these skills depreciate. Accordingly, the demand for such workers frequently changes, which accelerates human capital depreciation. In turn, professions with a high share of manual operations tend to be less dependent on technology, so the human capital obtained through education remains valuable even in the context of ongoing digital transformation. This applies, e.g., to construction and food industry workers (Muro et al., 2017), for whom the rate of knowledge depreciation will be lower.

H2a. *The depreciation rate is higher for occupations with a significant share of interactive, analytical, and cognitive tasks which rely on technology.*

Our next assumption is that the rate of human capital depreciation depends on the scale of changes in technology application. Machines perform an increasingly broad range of tasks, gradually covering non-routine operations which previously remained the prerogative of people. Therefore in the course of technological development "non-routine" professions are more likely to require new skills, which will accelerate human capital depreciation.

H2b. *The more rapidly the technological upgrading of jobs occurs, the higher the depreciation rate of relevant competencies becomes.*

Data and Methodology

We estimated the depreciation rate and the factors affecting it using the German Socio-Economic Panel[1] for 1984-2017. It was possible to establish links between control variables (education, wages, etc.) and workers' professional characteristics. The human capital depreciation rate was calculated using an extended earnings function (Neuman, Weiss 1995; Mincer, Ofek 1982), which allowed for analyzing the impact of education on wages that decline over time. The education-specific depreciation is indirectly estimated by equation (1) as the relationship between tertiary education and work experience (the period of time elapsed since the completion of formal education (Edu_i X $pexper_{it}$). The β2 coefficient indicates how skill obsolescence affects earnings.

$$\ln w_{it} = \beta_0 + \beta_1 Edu_i + \beta_2 (Edu_i \times pexper_{it}) + \beta_3 pexper_{it} + \beta_4 pexper_{it}^2 + X_{it} + \varepsilon_{it} \qquad (1)$$

The use of a panel fixed effects estimation with cluster robust standard errors allowed the authors to take into account the autocorrelation and heteroscedasticity of the error terms. Controls for personal or job-related characteristics were applied stepwise.

To test the relationship between skill obsolescence and work task types, a categorical variable was constructed based on the German classification of occupations (KldB, 1992). In accordance with the method proposed in (Dengler et al., 2014), each occupa-

[1] SOEP v34i (doi: 10.5684/soep.v34i). https://www.diw.de/sixcms/detail.php?id=diw_01.c.742267.en, accessed 07.11.2021.

tion was assigned one predominant work task type. Based on the classifications presented in (Spitz-Oener, 2006; Autor et al., 2003), we distinguish between non-routine (interactive, analytical, manual) and routine (cognitive, manual) work tasks.[2]

The categorical variable *tasks* was used to distinguish between different work task types, first added to equation (1) to take into account the possible relationship with earnings. Subsequent calculations of equation (1) for each task group allowed us to determine how the depreciation rate varies for different work task types. The main variables are presented in Table 1.

Findings

Calculations based on various specifications of fixed effect panel regression are summarized in Table 2. In the preferred specification (column 4), the coefficient of the interaction term for all levels of education (except secondary) has a negative value, which indicates human capital depreciation.

The annual depreciation rate is lowest for workers with VET degrees (1.1%), followed by university degree holders (1.2%); the highest value was established for workers with higher VET (1.4%). Our observations are consistent with previous publications (Lentini, Gimenez, 2019; Neuman, Weiss, 1995), confirming the significant vulnerability of skills acquired over the course of higher education. In support of the findings of (Weber, 2014), it was also found that competencies acquired through VET (VET versus general secondary school and higher VET versus university) depreciate more rapidly. This implies the limited applicability of specialized human capital for other work tasks, and its depreciation when the economic context changes. Compared to other studies (Murillo, 2011), our depreciation rate calculated for each additional year of potential experience is relatively low (0.01%). A possible explanation is the time when our analysis was conducted: previous studies have noted a declining experience depreciation trend.

According to the regression results for the dominant work task categories (Table 3), the depreciation rate varies depending on the education and work task type, which empirically confirms the importance of both of these factors for competency obsolescence. Skills required to perform non-routine interactive, specific manual, and generic cognitive tasks are subject to a faster decline in relevance. The highest annual depreciation rate was found for non-routine interactive tasks: 2.0% for workers with tertiary education and 1.9% for workers with higher VET. Specialized skills of workers with higher VET become obsolete even faster (2.3%), and those of workers who mainly perform non-routine analytical tasks, on the contrary, depreciate at half that rate. Furthermore, the value of experience increases in relation to tasks with a higher level of depreciation (as indicated by the potential experience variable *pexper*).

To better understand the differences in depreciation rates, we have built predictive earnings-experience profiles for different types of tasks based on the results of Model Specification 5. Figure 1 shows that earning profiles significantly vary by task types and education levels. Earnings, including education premiums, tend to be lower for those performing manual tasks and higher for analytical, interactive, and cognitive ones. Towards the end of their careers, earnings of workers with VET will exceed those of workers with higher VET. As to non-routine manual tasks, VET and higher VET provide more significant income than general tertiary education. In addition, wages of secondary school graduates quickly peak and for a certain period of time exceed those of workers with VET and higher VET, but then rapidly lose ground. Despite reduced educational qualifications, at the beginning of one's career differences in depreciation levels in some cases can offset the difference in earnings. Therefore even university graduates need to constantly update their knowledge to maintain the value of their human capital.

A detailed analysis of occupations with a high share of interactive or cognitive tasks indicates that the use of technologies by such workers changes significantly. They widely apply supplementary digital solutions, primarily to perform cognitive and analytical tasks, while the rate of such technologies' evolution remains moderate (Table 4). Perhaps this explains the increased level of skill depreciation for workers who carry out such tasks. On the contrary, with non-routine manual work tasks, the use of technology increases dramatically. For example, they make up the core of construction, hotel, catering, and logistics occupations. In 2001 digital technologies were rarely applied for these purposes

[2] Data on job-related technology use comes from (Muro et al., 2017) who provide information on the use of technology for 545 occupations between 2001 and 2016.

Table 1. **Descriptive Statistics (full-time workers > 30 hours/week)**

Variable		Observations	Mean	Std. Dev.	Min	Max
Earnings (deflated base year 2015)						
lwage15	Log gross hourly wages	266,234	2.546	0.654	-0.728	5.330
Education level (base group: only secondary education)						
2	VET	488,577	0.512	0.500	0	1
3	Higher VET	488,577	0.072	0.259	0	1
4	High School (Abitur)	488,577	0.083	0.276	0	1
5	University	488,577	0.193	0.395	0	1
Potential experience (years)						
pexper	age - years in education	510,724	35.479	17.800	1	93
Tasks						
1	Non-routine analytical	266,537	0.233	0.423	0	1
2	Non-routine interactive	266,537	0.087	0.281	0	1
3	Non-routine manual	266,537	0.175	0.380	0	1
4	Routine cognitive	266,537	0.326	0.469	0	1
5	Routine manual	266,537	0.180	0.384	0	1

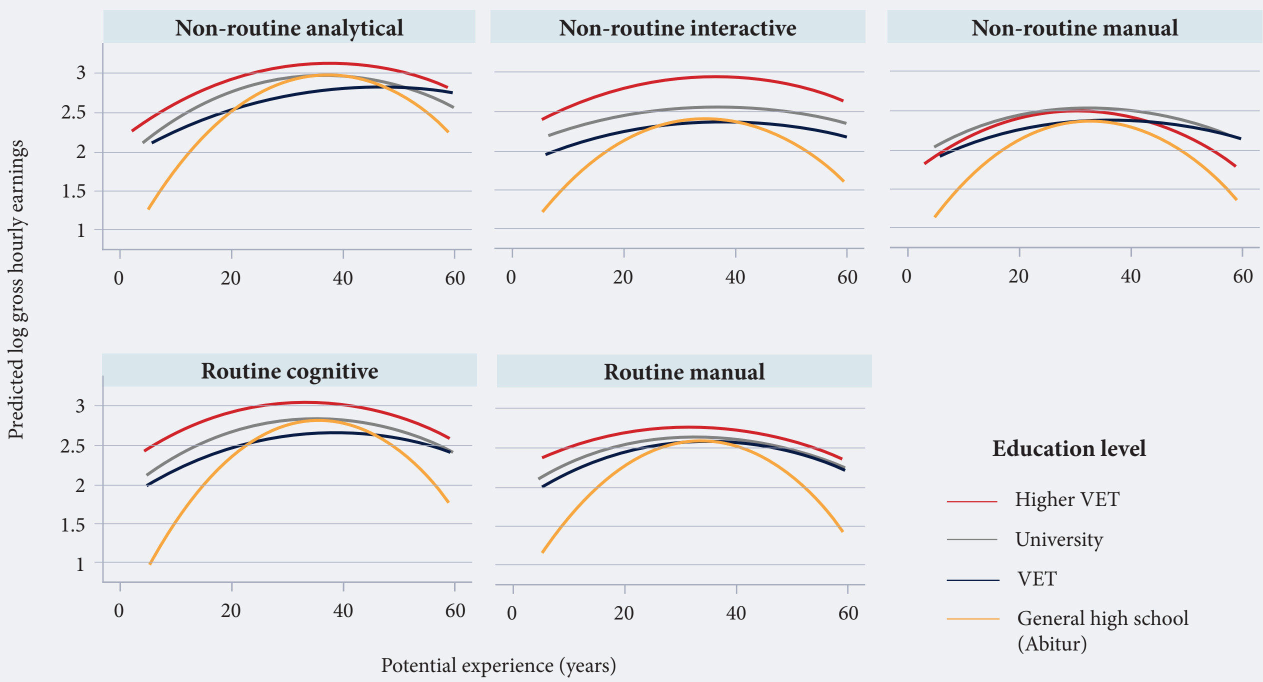
Source: composed by the authors using SOEP v34i. https://www.diw.de/sixcms/detail.php?id=diw_01.c.742267.en, accessed 07.11.2021.

(Muro et al., 2017), but by 2016, their use has doubled, accelerating competency depreciation. Thus, though the average skill obsolescence rate for the entire period is moderate, in recent years the pace of this process has increased. Compared to other professions, the use of technology here remains relatively low, but more significant changes can lead to increased competency depreciation.

Conclusion

Advances in technology development are changing the employment sphere and skill requirements, making human capital acquired through formal education obsolete. Digitalization is radically transforming the nature of work tasks and the demand for competencies, which creates new opportunities for some workers and risks for others. A deeper

Figure 1. **Predicted Earnings–Experience Profiles by Task Groups for Heterogeneous Levels of Human Capital**



Source: authors.

Table 2. **Results of Fixed Effects Regression with Deflated Log Hourly Wages as Dependent Variable**

Log hourly wages	(1)	(2)	(3)	(4)	(5)
Education level					
VET	0.718*** (27.04)	0.497*** (18.20)	0.509*** (18.35)	0.488*** (14.54)	0.495*** (14.59)
Higher VET	0.696*** (19.98)	0.597*** (15.95)	0.581*** (15.69)	0.555*** (12.67)	0.567*** (12.89)
High School (Abitur)	-0.302*** (-9.50)	-0.280*** (-9.41)	-0.218*** (-7.13)	-0.231*** (-6.21)	-0.223*** (-5.93)
University	0.649*** (16.47)	0.613*** (12.95)	0.635*** (13.97)	0.602*** (11.34)	0.609*** (11.38)
Depreciation of education					
VET*pexper	-0.015*** (-17.40)	-0.010*** (-11.51)	-0.012*** (-14.35)	-0.011*** (-11.18)	-0.011*** (-11.13)
Higher VET*pexper	-0.016*** (-13.81)	-0.013*** (-10.25)	-0.014*** (-11.52)	-0.014*** (-9.70)	-0.014*** (-9.71)
High school*pexper	0.013*** (9.22)	0.011*** (8.01)	0.009*** (6.68)	0.009*** (5.43)	0.008*** (5.21)
University*pexper	-0.010*** (-9.43)	-0.010*** (-6.25)	-0.012*** (-8.78)	-0.012*** (-6.87)	-0.012*** (-6.82)
Experience					
pexper	0.040*** (7.71)	0.070*** (9.57)	0.070*** (10.38)	0.063*** (8.05)	0.064*** (8.10)
Depreciation of experience					
pexper-squared	-0.001*** (-41.64)	-0.001*** (-12.55)	-0.001*** (-13.70)	-0.001*** (-10.90)	-0.001*** (-10.68)
_cons	0.881*** (14.36)	-3.248*** (-24.00)	-2.347*** (-16.19)	-2.382*** (-14.07)	-2.347*** (-13.69)
Controls	No	+ personal	+ job	+ industry	+ tasks
Observations	262.7780	261.101	204.689	158.561	154.792
R-squared	0.407	0.425	0.388	0.386	0.385

Note: Dependent variable is Log hourly wages in constant prices.
* p<0.05, ** p<0.01, *** p<0.001, t statistics in parentheses, cluster robust standard errors.
Source: authors.

understanding of these processes' impact on human capital depreciation is critical for employees, employers, and policy makers alike.

This study analyzes skill obsolescence over the course of economic change, taking into account technological development factors such as the rate of new tools' application and the changing nature of work tasks. It was established that the human capital of workers performing predominantly non-routine interactive, non-routine manual, and routine cognitive tasks depreciates more rapidly than for other work task types. This can be explained by the two factors presented in Table 4. New digital solutions allow one to perform the above tasks more efficiently and are applied for these purposes more actively than elsewhere. The higher the technology application level, the more radically knowledge requirements change. As a result, the rate of basic human capital depreciation increases. Also, in a number of occupations, the use of digital technologies is changing particularly fast. First of all, this applies to jobs with a large share of non-routine manual tasks, where the accelerated digitalization leads to skill obsolescence. As this process continues, the work environment is likely to change even more dramatically, with the rate of skill obsolescence increasing even further.

Though in the case of routine tasks, human capital depreciates at a slower rate, this should not be seen as a positive factor since, as labor polarization studies show, workers performing routine cognitive tasks are gradually being replaced by technology. It is expected that in their present form, occupations based on such tasks will gradually disappear, which will accelerate skill depreciation even more.

Contrary to popular belief that technology is incapable of performing non-routine tasks, our results reveal a relatively high depreciation rate for workers in such occupations, despite the fact that demand for them is growing.

Common policy measures for dealing with these issues include improving workers' skills and increasing tertiary education enrollment. However, this does not protect against skill obsolescence either.

The main goal of tertiary education is creating general human capital applicable to a variety of non-routine work tasks. However, if knowledge related to an entire task group is expected to become obsolete due to external changes, even general higher

Table 3. **Results – Human Capital Depreciation by Task Groups**

Log hourly wages	Non-routine tasks			Routine tasks	
	analytical	interactive	manual	cognitive	manual
Education level					
VET	0.394** (-3.07)	0.677*** (-7.62)	0.541*** (-8.56)	0.635*** (-10.84)	0.503*** (-8.07)
Higher VET	0.462*** (-3.4)	0.803*** (-6.49)	0.572*** (-5.73)	0.792*** (-11.08)	0.563*** (-5.27)
High school (Abitur)	-0.244 (-1.83)	-0.181 (-1.69)	-0.15 (-1.87)	-0.08 (-1.36)	-0.316*** (-4.24)
University	0.393** (-2.68)	0.931*** (-6.01)	0.646*** (-4.04)	0.869*** (-10.14)	0.411* (-2.07)
Depreciation of education					
VET*pexper	-0.010** (-2.98)	-0.019*** (-4.54)	-0.015*** (-8.42)	-0.016*** (-9.48)	-0.012*** (-7.42)
Higher VET*pexper	-0.012*** (-3.30)	-0.023*** (-4.51)	-0.019*** (-6.27)	-0.021*** (-8.62)	-0.015*** (-5.27)
High school*pexper	0.008* (-1.97)	0.008 (-1.12)	0.000 (-0.01)	0.003 (-1.63)	0.011*** (-3.48)
University*pexper	-0.009* (-2.36)	-0.020*** (-3.97)	-0.016*** (-4.76)	-0.019*** (-6.36)	-0.011* (-2.46)
Experience					
pexper	0.031* (-2.43)	0.091*** (-3.58)	0.075*** (-3.94)	0.091*** (-7.44)	0.072*** (-3.34)
Depreciation of experience					
pexper-squared	-0.001*** (-3.85)	-0.001*** (-5.22)	-0.001*** (-6.05)	-0.001*** (-6.81)	-0.001*** (-5.66)
_cons	-1.798*** (-3.70)	-1.655*** (-3.52)	-3.561*** (-10.00)	-1.620*** (-6.68)	-3.077*** (-7.26)
Observations	46,523	17,716	30,927	62,462	28,791
R-squared	0.366	0.320	0.283	0.449	0.369

* p<0.05, ** p<0.01, *** p<0.001, t statistics in parentheses, cluster robust standard errors.
Source: authors.

education does not guarantee sustainability, which means that simply raising the level of education is no longer enough. The value of human capital based on university education is annually declining for all work task types, and doing so at a significant pace. Our findings suggest that for workers who predominantly perform non-routine manual tasks, the earnings-to-experience ratio may even worsen compared to other education levels less susceptible to depreciation. In the absence of lifelong learning, the initial investment in higher education may "dissolve". To prevent serious problems, it is necessary to expand the content of education and constantly invest in it, taking into account human capital depreciation.

Creating an inclusive labor market implies an opportunity for the most vulnerable population groups to acquire digital skills, which will require significant staff training efforts. For other groups, the ability to adapt and acquire new competencies to perform tasks which cannot be substituted by machines is crucial. It is advisable to pursue an integrated labor market and education policy aimed at countering human capital obsolescence. While

Table 4. **The Link between Job Tasks and Human Capital Obsolescence**

Task type	Task example	Use of task-complementing technology	Change in job-related technology use	Human capital obsolescence
Non-routine analytical	Researching, designing	medium	low	low
Non-routine interactive	Managing, entertaining	high	high	high
Non-routine manual	Repairing, serving	low	high	medium
Routine cognitive	Bookkeeping, calculating	high	medium	medium
Routine manual	Operating machines	low	low	low

Source: author's elaboration, based on (Muro et al., 2017) for data on technology use, task groups adopted from (Spitz-Oener, 2006) many countries have recognized the importance of this approach, further action is needed in the field of education. The findings of this study may help develop effective training programs to provide workers with opportunities to periodically upgrade their existing skills and acquire those in high demand. Educational policy should provide for "upgrading" competencies, allowing workers to quickly adapt to changing market conditions in a situation of increasingly rapid and radical technological progress. Companies interested in increasing workers' productivity need to expand training opportunities for them. As to workers, they need to be aware of the current developments and periodically plan for further training. If the efforts are focused on acquiring new skills and developing the existing ones, further technological development will yield significant benefits

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The Digitalization of Human Resource Management: Present and Future

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Abstract

Information technologies are rapidly transforming the field of human resource management at organizations. The digital transformation of human resource management has become specifically important in the context of the COVID-19 pandemic, which has significantly accelerated the pace of digitalization of HR processes. Companies that are able to quickly take advantage of the opportunities of the implemented digital HRM technologies are in a better position than those in which digitalization was paid less attention. At the same time, the factors and consequences of the digitalization of human resource management, as well as its relationship with various characteristics of firms, remain unclear today. This article provides an attempt to shed light on the key components of HRM digitalization analyzed against significant characteristics of organizations (size, personnel structure, staff turnover, performance) using the data of 449 small, medium, and large businesses operating on the Russian market. The collected data indicate the presence of two key components of digitalization: quantitative (reach or breadth) and qualitative (effectiveness of digital practices). We found that the combination of wide reach and high efficiency has not always been a sign of more successful and functional companies.

Keywords: human resource management; information technology; digitalization; digital transformation; electronic human resource management; Russia

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Introduction

The digital revolution, which in recent years has been taking place in many business organization areas has not bypassed the human resource management (HRM) sphere either, which was reflected in the application of new technologies in personnel management, the change of relevant arrangements, and redistribution of functions (Ulrich, Dulebohn, 2015) . Digital technologies are transforming conventional HRM processes, the structure and functions of HR departments, the activities of relevant staff members, and, ultimately, the entire human capital-based value chain. Though the general dynamics of these processes has been described in the literature in sufficient detail, considerable disagreement remains regarding the specific forms it takes in corporate practices (Ulrich, Dulebohn, 2015; Bondarouk, Brewster, 2016; Kehoe, Collins, 2017; Huselid, Minbaeva, 2018). The correlation between applying particular management techniques and the organization's performance has not yet been proven (Bondarouk et al., 2016)[1], which results in subjectivism, bias, and the unjustified replication of decisions and reforms.

An additional challenge in the theoretical understanding of the ongoing developments is the fact that almost all modern HRM approaches were developed in a predictable environment, which makes them unsuitable for a volatile situation (Parry, Strohmeier, 2014; Stone et al., 2015). The coronavirus pandemic and the resulting economic crisis have increased the importance of HRM digitalization. Digital technologies have become the universal answer to emerging challenges. Companies capable of quickly mastering new tools gain a comparative advantage over more conservative competitors. The effectiveness of digital HRM technologies is associated with their suitability for flexible and remote employment formats, but a practical assessment of this relationship has yet to be made.

Key aspects of HRM digitalization such as coverage and performance are approached in this paper in terms of more important company characteristics including size, staff structure and turnover, and productivity. The empirical basis of the study was provided by the survey of 449 small, medium, and large companies operating on the Russian market. The survey was conducted in November–December 2019, so it reflects the pre-crisis situation.

Digitalization of Human Resource Management: Research by Academic Organizations and Consulting Companies

Digitalization as a key aspect of a digital economy based on the use of data essentially amounts to the application of digital (information and communication (ICT) and computer) technologies to significantly improve business performance indicators such as labor productivity and customer service, optimize operations, or develop new business models (Lepak, Snell, 1998; Vial, 2019; Fitzgerald et al., 2014). A number of this process's features (multidimensional in their structure and effects) were identified by analyzing a large array of sources (Strohmeier, 2020), in particular converting analogue organizational information into a digital format for subsequent automated processing. This socio-technological approach aims to unlock a company's digital potential to accomplish operational objectives and/or strategic goals.

Four types of organizations can be distinguished depending on the degree of their strategy and operational digitalization (Strohmeier, 2020). Those of the first (analogue) type do not digitize either strategic or routine activities. In the second case (digital organization type I, operational application) digitalization is applied exclusively to manage operational processes in order to increase their speed, improve quality, and reduce costs. The third type (digital organization type II, or strategic alignment) implies aligning technological capabilities with the organization's strategic goals; digitalization is applied to all business operations and some of the strategy. Organizations of the last type (digital organization type III, strategic integration) directly integrate technology into the strategy development process, while their digital potential is used to find new business development areas (Strohmeier, 2009, 2020).

The electronic HRM (e-HRM) concept was initially applied to describe the digitalization processes in the area under consideration, which includes various approaches to integrating personnel management mechanisms and ICT for target groups of line and administrative workers, to create value at individual organizations and between them (Bondarouk, Ruel, 2009). Electronic HRM is an effective tool for performing relevant corporate functions via the internet (Parry, Tyson, 2011). The rapid evolution of artificial intelligence and robotics has profoundly transformed approaches to electronic HRM; its next development stage involved the adoption of the digital HRM concept, which was first theoretically and empirically described in 2020. For the purposes of this paper, the terms "electronic" and "digital" HRM are used interchangeably.

Most of the existing studies describe digital HRM as a one-dimensional process or corporate practice (see, e.g., (Parry, Tyson, 2011)). As a result, in quantitative studies it is seen as a generalized characteristic of digital technologies' application for personnel management purposes. However, a more comprehensive analysis requires distinguishing between at least two digital HRM dimensions: coverage (or "breadth") and effectiveness. Breadth is measured as a numerical coefficient of digital HRM application (Parry, 2011). Thus, a company thatapplies digital technologies to manage a significant part of HR-related processes including recruiting, training and development, motivation, career advancement, and so on will have a wider digital HRM breadth, regardless of these technologies' actual contribution to managerial performance.

Digital HRM effectiveness is a qualitative characteristic of digitalization measuring the integration of digital practices into the company's core activities, their application to perform routine tasks, and the "strength" of digital tools (Bowen, Ostroff, 2004; Bondarouk et al., 2015). For example, a company may digitize a single aspect of personnel management and still receive significant "rent" from the adoption of the relevant technology.

If Russian businesses started to digitize HRM only relatively recently (so this phenomena still has more quantitative (breadth) than qualitative (effectiveness) characteristics), many other countries have accumulated much more extensive experience. This allows researchers of HRM transformation to not resort solely to specific case studies in their analysis, but to compare large amounts of data accumulated over several decades. Vossen, Sorgner (2019) note both the destructive (replacing human workers with machines) and transformative (increased productivity) effects of digitalization on the labor market.

Two main research areas can be identified in digital HRM studies. The first is related to the actual application of digital technologies in personnel management, while the second is concerned with the transformation of relevant corporate strategies and practices. In the first case, the object of study is the digitalization process as such, and in the second - digital technologies as a means of transforming the HRM functions in a dynamic environment.

In the scope of the first area the features of digital technologies' penetration into companies' HRM practices are analyzed, in particular their contribution to reducing personnel management costs and improving its efficiency (Bondarouk et al., 2015). Although certain authors note the positive effects of HRM digitalization, its productive impact on company performance still is not believed to be conclusively proven (Bondarouk et al., 2016). The actual issue under consideration is poorly conceptualized, which is evident in the different approaches to studying it and inconsistent assessments of the results. The aspects which have not yet received due attention include the factors and consequences of applying digital HRM.

According to the authors who follow the second approach, taking into account the strategic aspects of personnel management in meeting present-day socio-economic challenges allows one to assess the role of digital practices in companies' operations. The relevant departments need to think strategically, be agile, efficient, and customer-focused all at the same time, while providing a full range of services. Digital technologies have sufficient potential to achieve this goal and improve HRM; digitizing the latter area can help accomplish various operational, relational, and transformational corporate objectives (Lepak, Snell, 1998). At the operational level, routine activities can be automated (with less added value), such as document management, recruitment, and administration of remuneration systems. At the relational level, internal and external communications take place, ensuring the speed and quality of service for employees and customers alike (Brockbank, 1997). At the transformational level, strategic coordination and integration of specific HRM practices and initiatives is carried out on a corporate scale and in specific divisions. Factors related to the perception of new decisions by staff play a key role in implementing digital technologies at all levels; they can be broken down into those concerning the quality and usefulness of the changes being made (Kohansal et al., 2016).

HRM digitalization issues also attract the attention of consulting and analytical companies. For example, a PwC report mentions it among the priority aspects of Industry 4.0, while a low level of digital culture and lack of adequately skilled personnel are named as the main barriers hindering its implementation at companies.[2] The role of personnel and the importance of developing adequate strategies for successful digitalization are also noted in the report by McKinsey experts.[3] Deloitte's annual Human Capital Trends review highlights the most important trends in corporate HRM across countries. Digitalization remained a key personnel management trend for many years. In 2017, the authors of the aforementioned study noted that the function under consideration should not only digitize itself but also contribute to the digitalization of other areas, so that the digital transformation of an organization begins precisely with HRM.[4] The review also described the content of HRM digitalization: the adoption of relevant ICT tools and specialized applications, their automation, and the introduction of data-driven decision-making.

[1] See also: https://www.vedomosti.ru/management/articles/2020/12/15/851115-sovershenni-protsessi, accessed on 19.03.2021.

[2] https://www.pwc.ru/ru/technology/assets/global_industry-2016_rus.pdf, accessed on 19.03.2021.

[3] https://www.mckinsey.com/business-functions/organization/our-insights/the-people-power-of-transformations, accessed on 19.03.2021.

[4] https://www2.deloitte.com/us/en/insights/focus/human-capital-trends/2017/digital-transformation-in-hr.html, accessed on 19.03.2021.

If consulting companies' studies conducted in 2016-2017 describe digitalization as a priority in itself, in the reviews published in 2018-2019, it was viewed as a tool for achieving goals of a more strategic nature created by the changing socioeconomic environment. A joint SAP and Deloitte report[5] based on Russian material shows that companies with more than 10,000 employees achieved the best results in the area under consideration. They are the ones who have demand for and the ability to introduce relevant practices. Meanwhile most of small (up to 100 employees) organizations believe they can do without introducing formal HRM practices and automating them. Companies were broken down into four groups: (1) those adopting the traditional "manual" approach (paper-based HRM), (2) partial automation, (3) mature automation, and (4) intelligent HRM.

According to experts, Russian companies' digitalization is at a somewhat lower level than that of its foreign counterparts, corresponding to the fragmented automation stage. A quarter of domestic organizations belong to the "paper-based HRM" group with only 9% can be considered to have reached mature automation and none included in the "intelligent HRM" group. Digitalization levels significantly vary across sectors of the Russian economy. For example, the financial and banking sector, metallurgy and mining, IT and telecommunications are the leaders in applying best international practices in the field. Retail, pharmaceutical, consumer products (FMCG), and media companies (including online ones) also tend to show high HRM digitalization rates. The "partial HRM automation and digitalization" ("catching up") group includes oil and gas production, knowledge-intensive business services (KIBS), manufacturing, and logistics companies.

The results of open-access analytical reports generally match the conclusions of academic studies about the high importance of the transformations taking place in the HRM sphere. Having completed a number of initial stages, Russian businesses' digitalization is advancing toward numerous new areas. Against this background, identifying the key characteristics of companies involved in the abovementioned processes becomes a relevant objective.

Methodology

A series of structured telephone interviews with heads of HR departments, senior executives, and personnel managers at organizations operating in large cities was conducted to collect information about the current digitalization level of Russian companies (Table 1).

A random sample of companies from the Amadeus Bureau Van Dijk database was built using such primary criteria as having more than 50 employees and operating in Russian cities with a population of more than 800,000. The randomization allowed for building a sample similar to the general population of Russian companies in terms of key characteristics including age, size, and industry affiliation. The final sample comprised 449 companies from 16 industries (Table 2).

The goal of the study was to compare companies with differing breadth and effectiveness of the digital HRM tools they apply. To measure the first parameter, the respondents were asked to assess the use of such tools by their company on 15 Likert scales from 1 (not used at all) to 7 (actively used). The scales included the following sections: the publication of HRM information online, availability of intranet services, use of online tools for recruitment, training and development, motivation, and assessment purposes, and for the development of an HR brand (e.g., "Staff training is conducted using e-learning tools"). The effectiveness of HRM digitalization was assessed in a similar way using 25 scales measuring the following characteristics: correctness, quality, frequency, reliability and flexibility of ICT solutions, their integration into actual management practices, user and stakeholder satisfaction, the impact of ICT on accomplishing company goals, HR department objectives and staff involvement (e.g., "Digital HRM tools are reliable (available, and work without fail"). Factor analysis confirmed the robustness of both indicators (AVE > 0.5, CR > 0.8, Cronbach's alpha > 0.8).

Information from the Bureau van Dijk database was also used over the course of the analysis (number of employees in 2019, capitalization (in euros), growth in the number of company employees over three years, return on assets (ROA), return on capital employed (ROCE)), along with data collected via the questionnaire (staff structure by age and employment type, personnel turnover, use of ana-

Table 1. **Distribution of companies by city**

City	Number of companies in sample
Kazan	38
Moscow	139
Nizhny Novgorod	8
Perm	44
Samara	41
St. Petersburg	135
Ufa	42

Sourca: authors.

[5] http://obzory.hr-media.ru/cifrovaya_transformaciya_hr_russia, accessed on 19.03.2021.

Table 2. **Distribution of companies by industry**

Industry	Number of companies in sample
Manufacturing	145
Knowledge-intensive business services, R&D	71
Wholesale and retail trade; motor vehicles and motorcycles repair	51
Construction	49
Transport and storage	27
Information and communication	22
Real estate	16
Electricity, gas and steam supply; air conditioning; water supply; sewage, collection and disposal of waste, pollution management	16
Administration activities and related services	14
Hospitality and catering	10
Mining	8
Finance and insurance	7
Healthcare	5
Education	3
Sports, recreation, entertainment	2
Repair of computers, personal and household items	1

Sourca: authors.

logue HRM practices). Analogue practices were measured using a popular model which distinguishes between three interrelated HRM practices: ability, motivation, and opportunity (AMO (Gardner et al., 2011; Appelbaum et al., 2000). For example, ability is related to training and recruiting practices, motivation to compensation and evaluation, and opportunity to involvement and feedback. Relevant practices were assessed using a Likert scale from 1 (none) to 7 (widely used).

Results

The companies were broken down into clusters by the median values of breadth (3.5) and effectiveness (4.5) of their HRM digitalization. Four clusters were obtained altogether (Fig. 1)

The first cluster comprises companies that have achieved a high effectiveness and wide breadth of HRM digitalization. The second is made up of highly effective companies with a more modest coverage, i.e., those applying a limited number of technologies only to cover certain HRM processes, but with impressive results. The third cluster comprises companies with wide breadth, but low effectiveness of digital HRM practices. Here many processes are performed using digital tools, but not effectively enough. Finally, the fourth cluster is made up by organizations whose HRM practices are poorly and inefficiently covered by digital tools.

Industry analysis shows that the "high effectiveness, wide breadth" cluster has the largest share of KIBS companies, while the largest share of manufacturing, construction, and mining firms occupy the cluster representing companies with the lowest HRM digitalization level.

Further analysis was carried out in several stages. Key parameters describing the size of the four clusters' companies were analyzed first. At the second stage, their staff structure by age and employment type, and the level of personnel turnover was considered. The third stage comprised the analysis of conventional (analogue) HRM practices including those aimed at skill development, strengthening motivation, and extending professional opportunities. At the fourth and final stage, the performance of companies with different kinds of HRM digitalization was evaluated.

Company Size

Table 4 presents data on key company size parameters (number of staff and capitalization) for all four clusters. The third cluster (low effectiveness, broad coverage) comprises the smallest organizations, while the fourth one (low effectiveness, narrow coverage) includes those with the largest number of employees. The first cluster (high effectiveness, broad coverage) has companies with largest amount of total assets. Large standard deviations (dispersion) in the number of employees and the amount of assets between the first and fourth cluster companies may indicate their high internal heterogeneity.

Table 3. **Industry affiliation of companies with varying degree of HRM digitisation**

Indicator	Cluster			
	1	2	3	4
Manufacturing, construction, mining: number of companies (% of total)	83 (19%)	21 (5%)	16 (4%)	98 (22%)
KIBS: number of companies (% of total)	73 (16%)	12 (3%)	13 (3%)	53 (12%)
Trade and transport: number of companies (% of total)	31 (7%)	4 (1%)	9 (2%)	34 (8%)

Note for tables 3-7: cluster 1 - high effectiveness, broad coverage; cluster 2 - high effectiveness, narrow coverage; cluster 3 — low effectiveness, broad coverage; cluster 4 - low effectiveness, narrow coverage..

Source: authors.

Table 4. **Descriptive company size statistics**

Indicator		Cluster 1	Cluster 2	Cluster 3	Cluster 4
Number of staff, persons (average)		321.50	362.11	276.71	393.24
Number of staff, persons (standard deviation)		506.94	499.99	499.16	688.25
Company type by size (number of companies)	Large (≥250)	58	17	7	60
	Medium (100–250)	68	11	12	65
	Small (50–100)	61	9	19	60
Capitalisation, euros (average)		24167.59	17076.42	12753.17	21264.72
Capitalisation, euros (standard deviation)		66251.77	27658.61	23406.06	52691.58

Source: authors.

The obtained data reveals a correlation between company size and HRM digitalization type. Moreover, this correlation seems to be non-linear and affected by other factors.

Staff Structure and Turnover

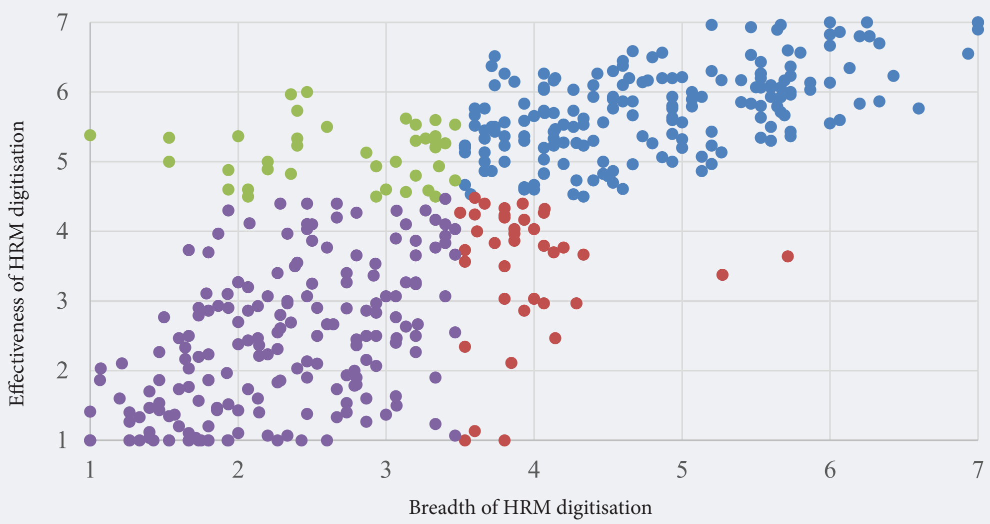
Table 5 describes the staff structure and turnover in the four company clusters. The first cluster (high effectiveness, broad coverage) stands out by age structure, with the largest share of employees under 25 and the smallest share of those aged 55 and older. Companies in the other three clusters have similar age structures, with the highest shares of employees aged 26-30 and 41-54. Companies in the third and fourth clusters (low effectiveness of HRM digitalization) have the largest share of employees aged 55 and older. These results give grounds to assume a negative correlation between the effectiveness of HRM digitalization (regardless of its breadth) and the average employee age.

The first cluster (high effectiveness, broad coverage) is also significantly different in terms of the employment type structure: these companies tend to use unconventional employment formats more often (about 19% of such employees in total). Companies in the third cluster (low effectiveness, broad coverage) have a relatively high share of WFH and part-time employees.

The first cluster companies show the highest overall staff turnover rate (at employee initiative and for other reasons). Organizations with advanced digital HRM infrastructure have a large amount of data and various mechanisms for dismissing employees at their disposal, which leads to a higher labor mobility. The lowest turnover rate for reasons beyond employee control is demonstrated by the third cluster companies (low effectiveness, broad coverage).

Table 6 presents averaged-out indicator values for the use of various conventional (analogue) HRM

Figure 1. **Clustering companies by breadth and effectiveness of HRM digitisation**



Note: colours indicate companies' affiliation with HRM digitisation clusters.
Source: authors.

Table 5. **Descriptive staff structure and turnover statistics**

Indicator		Cluster 1	Cluster 2	Cluster 3	Cluster 4
Average number of employees, persons		321.50	362.11	276.71	393.24
Staff structure by age groups, %	25 and younger	17.83	11.73	10.80	9.82
	26-40	40.92	38.70	45.79	40.14
	41-54	29.24	36.97	31.58	34.39
	55 and older	15.06	15.28	19.03	19.33
Staff structure by employment type, %	Remote employment	11.07	1.67	4.44	2.92
	Part-time employment	11.20	3.91	5	4.43
	Freelance	8.65	0	0	1.42
	Full-time employment	80.80	96.62	97.89	95.30
Staff turnover	Employee initiative	5.51	6.47	5.59	4.76
	Other reasons	4.19	2.46	1.00	2.53

Source: authors.

practices such as skills development, motivation, and opportunity. The first cluster companies (high effectiveness, broad coverage) most actively apply all three types of practices. A relatively high use of opportunity enhancement practices (5.2) singles out the third cluster (low effectiveness, broad coverage). These practices are least common in companies with low effectiveness and narrow coverage of HRM digitalization.

Thus, digital tools do not replace, but rather complement analogue HRM practices.

Company Performance

Table 7 summarizes various company performance indicators: growth over the last three years, ROA, and ROCE. We can see that the allegedly beneficial effect of applying digital HRM tools noted in numerous studies is not confirmed empirically. Companies in the fourth cluster (low effectiveness, narrow coverage) turned out to be the highest performers in the sample. This can be explained by their heterogeneity (evident in the high standard deviation values) due to many players' long presence on the market, which ensured their competitiveness without the use of digital tools. Another possible explanation is the generally low level of digital HRM development in Russia. Companies committed to its implementation are looking for new sources of competitiveness, for ways to convert technology into business results. Companies in the first cluster have achieved relative success in this regard, in terms of growth and profitability alike.

"Half-way" HRM digitalization strategies turned out to be the least effective in terms of performance. The second (high effectiveness, narrow coverage) and third (low effectiveness, broad coverage) clusters demonstrate similarly low growth and profitability rates.

Table 6. **Descriptive HRM practices statistics**

Indicator (average value)	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Use of skill development practices	5.43	4.55	4.22	3.63
Use of motivation strengthening practices	5.54	4.42	3.99	3.77
Use of opportunity enhancement practices	5.76	4.45	5.20	4.07

Source: authors.

Conclusion and Discussion of Results

Our study of HRM digitalization at 449 small, medium, and large businesses in 16 sectors of the Russian economy was based on existing academic studies and reports published by leading consulting companies (Deloitte, PwC, McKinsey) in the area under consideration. In contrast to the prevailing approach in the literature, a comprehensive view of HRM digitalization is proposed, using at least two characteristics to describe it: quantitative (breadth) and qualitative (effectiveness). The breadth of HRM digitalization measures the application of digital technologies in HRM, i.e., digital HRM as such, while effectiveness reflects the level of digital practices' integration into actual HRM, i.e., how easy such practices are to apply to accomplish operational objectives.

Using these characteristics on the one hand allows one to take a fresh look at the uneven HRM digitalization process, by expanding its coverage or, conversely, by focusing on a particular aspect. On the other hand, this approach helps to more clearly operationalize HRM digitalization taking into account not its "overall level" but specific meaningful parameters.

Table 7. **Descriptive company performance statistics**

Indicator	Cluster			
	1	2	3	4
Company growth over 3 years (average)	3.06	0.64	0.90	4.48
Company growth over 3 years (standard deviation)	11.53	1.85	2.24	24.52
ROA (operational revenue/total assets) (average)	2.21	2.15	2.09	5.93
ROA (operational revenue/total assets) (standard deviation)	3.13	1.94	1.79	53.10
ROCE (average)	40.61	31.10	37.63	48.18
ROCE (standard deviation)	102.21	43.68	34.68	86.89

Source: authors.

The collected empirical data confirms the existence of two HRM digitalization modes, on the basis of which the companies in the sample can be broken down into four clusters characterised by (1) high effectiveness of digital HRM practices and broad coverage of relevant processes' digitalization, (2) high effectiveness of such practices but narrow coverage of digitalization, (3) low effectiveness of digital practices but broad coverage of digitalization, and (4) low effectiveness and narrow coverage of digital HRM practices. In addition to existing studies of the relationship between HRM digitalization and various company characteristics (see, e.g., (Bondarouk et al., 2016)), the analysis of these clusters revealed patterns and features specific to companies with different levels of HRM digitalization.

The findings suggest that companies more successful in digitalization have greater flexibility in managing their workforce structure: they more often use unconventional employment formats and on average tend to have younger staff. This is facilitated by the use of ICT tools to strengthen the HR brand, which increases job seekers' interest in vacancies. Companies with broader and more effective HRM digitalization also demonstrate higher levels of employee turnover, including at the employer's initiative, which may reflect not so much the shortcomings of HR management as its flexibility and dynamism (Siebert, Zubanov, 2009). These findings add to the controversy of previous evidence that digital technologies affect company personnel's work experience in an exclusively positive way (Malik et al., 2020).

Another confirmed hypothesis is the absence of a direct correlation between the digitalization level and business performance, which contradicts the conventional wisdom but is consistent with the findings of some studies that questioned whether HRM digitalization yields quick returns in the form of economic indicators. Though technology does relieve HR managers of much of the routine tasks (Ruel et al., 2004) and makes it easier for front-line employees to manage HR (Malik et al., 2020), its impact on company performance requires further study. The obtained data indicates that companies with the lowest digitalization level (narrow coverage, low effectiveness) were leaders in key performance indicators including growth rate. This may mean that the effects of HRM digitalization are not necessarily beneficial for all kinds of businesses and that some organizations seem to be managing very well without relevant ICT tools. We are talking about the fourth cluster companies, which also use conventional (analogue) HRM practices. These findings somewhat reinforce the earlier conclusions that HRM yields sustainable economic performance gains only when it is deeply integrated into the business and supports the strategic HRM function (Njoku, 2016).

As to practical recommendations, we would like to note the need to thoroughly analyze and identify the HRM functions that require ICT solutions. Organizations should carefully estimate the expected results of applying such tools and soberly evaluate the economic return on relevant investments. Managers should take into account the structural features of their company, including those related to the workforce and the extent of applying HRM practices when they plan relevant digital projects.

Further research could focus on the nature and factors of digitalization at Russian and foreign companies. Despite the progress made in identifying incentives for and barriers to the introduction of digital technologies in the field of HRM, the actual mechanism of their impact still remains unclear. Qualitative research of companies with high and low degrees of HRM digitalization may help fill this gap. Assessing the relationship between these processes' parameters and Russian companies' performance indicators on the basis of a larger array of data and using specialized statistical tools also remains relevant. An analysis of, among other things, non-economic performance indicators could be valuable as well. Thus, there is reason to believe that digital HRM technologies are particularly effective in overcoming the crisis and reorienting companies toward remote work. Accordingly, HRM digitalization can be viewed as a crisis management tool, even if it does not guarantee short-term economic results.

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Factors Influencing Satisfaction and Future Intention to Use E-Learning at the University Level

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Abstract

With the growing interest in e-education, particularly in the context of the pandemic, more scientific studies have been undertaken recently to analyze and identify factors influencing e-learning acceptance. Indeed, e-learning acceptance depends on many different factors, but no consensus has been reached on factors that contribute most to the acceptance of e-learning solutions. Consequently, this article ascertains the factors and their relationships behind the satisfaction and the future intention to use e-learning among Polish university students. From among the factors analyzed in the literature, the author examined the relationship between computer self-efficacy (CSE), facilitating conditions (FC), satisfaction (S), and the future intention to use e-learning (FI). Data were gathered using structured questionnaires and computer-assisted web interviewing (CAWI). Students at Bialystok University of Technology (Poland) were sent an electronic link to the questionnaires using the internal e-mail system. A total of 803 forms were returned fully filled out. Aiming to ascertain the extent to which measured variables describe the number of constructs, the author conducted a Confirmatory Factor Analysis (CFA). The Generalized Least Squares (GLS) estimator was used to calculate the values of model parameters.

The results confirmed that higher computer self-efficacy and better facilitation conditions result in greater user satisfaction with e-learning. However, facilitating conditions impact user satisfaction more than computer self-efficacy construct variables. Based on the findings, user satisfaction is a strong antecedent of the future intention to use e-learning.

Keywords: e-learning; consumer satisfaction; future intension to use; computer self-efficacy; university students

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Introduction

Dynamically developing ICT significantly changed every aspect of social life, including education. E-learning erases time and space limitations, thus allowing one to meet the increasing needs of contemporary education. The outbreak and rapid spread of COVID-19 exacerbated the need to focus on directing human activities towards ICT (Fritsch et al., 2021). In many countries, limitations faced by educational institutions functioned as a motivator in boosting the digitalization of education. Based on (UNESCO, 2020), this decision affected 72.4% of learners in 177 countries. The proper functioning and effectiveness of distance learning is a challenge for educational institutions, which requires more complex and often different measures compared to traditional, stationary education. Despite the effort and commitment of educational institutions to promote new ICTs, the successful implementation of e-learning tools mainly depends on the final users, i.e., their level of acceptance and satisfaction (Arteaga Sánchez, Duarte Hueros, 2010; Recker, 2016).

The recent growing interest in e-education, particularly in the context of the pandemic, is reflected in more studies undertaken to analyze and identify factors determining the adoption of e-learning tools. It seems that one essential element is the identification of critical success factors at all stages of the e-learning technology adoption process (Yi, Hwang, 2003; Emelyanova, Voronina, 2014).

Despite many efforts to promote the use of e-learning technologies, users determine the scope of solutions or their complete rejection (Recker, 2016). Indeed, e-learning acceptance depends on many different factors, but no consensus has been reached on the factors that contribute most to the acceptance of e-learning solutions (Weerathunga et al., 2021). Thus, a study of the factors that motivate and engage the recipients of e-learning solutions remains an area of scientific interest (Jung, Lee, 2018; Emelyanova, Voronina, 2014).

Consequently, this article ascertains the factors and their relationships behind the satisfaction and future intention to use e-learning among Polish university students. From among the factors analyzed in the literature, the author examined the relationship between computer self-efficacy (CSE), facilitating conditions (FC), satisfaction (S), and the future intention to use e-learning (FI).

The studied variables for the model determining the future intention to use e-learning were selected based on a literature review into technology adaptation models used for e-learning. The evaluation focused on the influence of two variables, i.e., facilitating conditions (FC) and computer self-efficacy (CSE), on user satisfaction with e-learning tools and the influence of satisfaction (S) on the future intention to use (FI) e-learning at the university level. The elaborated model allowed the author to consider, on the one hand, the internal factor that reflects user self-efficacy with IT tools and, on the other hand, the external factor of user-support by administration and IT staff.

Literature Review

E-learning (electronic learning) refers to the use of digital tools to support the learning process (OECD, 2020). The adaptation of any new technological solution, including e-learning, is a multifaceted problem that, apart from technological aspects, must also consider economic, social, ethical, or legal factors.

During the pandemic, the usual teaching process, its approaches, tools, and methods for the verification of effects had to change quickly, although many teachers and students were unprepared for such an unexpected situation. E-learning research demand is also driven by the anticipated growth in the global share of this form of studies. Based on global forecasts, the e-learning market will exceed USD 243 billion by 2022 (Duffin, 2020).

The diversity of research on e-learning stems from a wide range of stakeholders involved in the e-learning process that comprises planning, teaching, technology supply, and the improvement of quality and evaluation. The stakeholders include students, employees, teachers, educational and accreditation institutions, educational content providers, responsible ministries, e-learning technology providers, teacher associations, and student organizations.

Research on the application of e-learning technologies is particularly concerned with the perceived benefits for users and providers of educational services (Kimiloglu et al., 2017; Milićević et al., 2021; Mathivanan et al., 2021; OECD, 2020; Al-Azawei et al., 2017; Chen, Tseng, 2012; Ozdamli, Uzunboylu, 2014), the weaknesses of and barriers to e-learning (Olum et al., 2020; Yang et al., 2018; Buckley, 2003), and the analysis of factors determining the wider use and success factors of an e-learning application (Kurfal et al., 2017; Dečman, 2015; Hsiao, Yang, 2011).

E-learning systems also interest researchers in the context of technology acceptance models used to explain elements that determine the current and future extent of use of technological solutions. Such models have also been used for e-learning technologies, e.g., the D&M IS Success Model — DeLone–McLean Information System Success Model, UTAUT — Unified Theory of Acceptance and Use of Technology, and TAM — the Technology Acceptance Model (Weerathunga et al., 2021; Ejdys, 2018). The technology acceptance concept model developed by Fred Davis (Davis, 1985) served as the prototype for all the models.

Dedicated technology acceptance models were also developed considering the specifics of e-learning solutions, e.g., the E-learning Acceptance Model (Islam, Selim, 2006), the user-experience UX-based e-learning acceptance framework (Zardari et al., 2021), or the EESS model — Evaluating E-learning Systems Success

(Al-Fraihat et al., 2020). Based on the original TAM, researchers have expanded their models to include new constructs and examined their interrelationships (Bharadwaj, Deka, 2021). The constructs considered by other authors in e-learning technology acceptance models are shown in Table 1.

In nearly all analyzed e-learning TAMs, their authors considered the constructs included in the original TAM model and its modifications, namely, the perceived ease of use, the perceived usability (functionality), attitudes toward using the technology, behavioral intentions, and the extent of the system's actual use. Many researchers have developed models that include constructs reflecting hedonic characteristics of e-learning tools, such as enjoyment, pleasure, or fun. Other important model elements were constructs expressing characteristics in the field of e-learning, such as self-efficacy, fear, and concerns about computers as well asrequired user effort. In recent studies conducted during the COVID-19 pandemic, new variables have emerged in TAMs, such as the fear of vaccinations and concerns about facilitating the spread of COVID.

The literature review conducted on the application of the UTAUT model for studying the acceptance of e-learning solutions allows us to conclude that most researchers consider six basic constructs in their original models, i.e., the expected performance, the expected effort, social image, support conditions, behavioral intentions, and the system's use. Given the specific areas of interest of a particular researcher, the initial model is modified by including additional constructs. In the era of the pandemic of 2019–2020, an increase in interest can be observed among authors regarding the variables relating to social isolation or fear of contracting COVID-19 on the acceptance of e-learning solutions. Similar to TAMs, UTAUT model variables frequently reflect teacher (instructor) characteristics and the quality of the curriculum content, teaching materials, or the way the classes are conducted.

The variables added to the initial D&M IS Success Model were user experience with the analyzed technology and experience of using the Internet. An interesting new construct added to the D&M IS Success Model refers to learner's character attributes, i.e., student grit, defined as the constancy of interest, persistence, and passion for achieving long-term goals (Aparicio et al., 2017).

Most studies deal with the use of e-learning solutions from the perspective of two user groups — teachers/instructors/trainers of training/courses and the participants in the e-learning process (students, pupils, employees). However, most studies refer to the second group of e-learning system users. Such research aims to establish success factors for the implementation of e-learning technologies; analyze the relationships between the e-learning systems' quality and their use and user satisfaction; measure the effect of individual characteristics and the skills of teachers and students on other elements considered in models addressing the acceptance of e-learning solutions.

The conducted literature studies allowed for distinguishing between two main categories of factors determining the satisfaction with e-learning tools, i.e., internal factors related to individual attributes, such as user competences, skills, motivation, and attitudes, and external factors resulting from general user support and assistance. Computer self-efficacy seems to be the most important among the internal factors, reflecting the user-perceived level to perform a certain task using a computer. According to the literature review, computer self-efficacy and facilitating conditions belong to the most used external variables in TAM applications (Jimenez et al., 2021). Computer self-efficacy reflecting individual characteristics was the most widely employed external factor of technology acceptance models (Salloum et al., 2019; Al-Emran et al., 2018; Abdullah et al., 2016; Williams et al., 2015). Self-efficacy is one of the factors that determine the level of student motivation and commitment towards using e-learning (Baber, 2021). During the COVID-19 pandemic, self-efficiency could play a protective role and may create a more flexible atmosphere that encourages technology acceptance (Al-Maroof et al., 2021). The areas for future research include the need to study the variable "support for e-learning" and its relationship to self-efficacy (Alamri et al., 2020).

The variable "facilitating conditions" is another important external factor, which reflects user satisfaction with the technology/system that the existing organizational and technical infrastructure provides in support of the technology to overcome use-related barriers. The COVID-19 situation forced the Bialystok University of Technology (Poland) to make an urgent transition to remote learning. In the early stages of remote learning, the extent of support from the university was a determining factor for user satisfaction with e-learning.

Research Model and Hypotheses

The literature review resulted in four variables that were included in the proposed model: computer self-efficacy (CSE), facilitating conditions (FC), satisfaction (S), and the future intention to use (FI).

Self-efficacy is the confidence in one's ability to perform certain learning tasks using an e-learning system (Pituch, Lee, 2006) or reflect one's beliefs about one's ability to use computers effectively (Compeau, Higgins, 1995). Otherwise, computer self-efficacy refers to a person's assessment of their capacity to use a PC and the trust in their own ability to handle related challenges (Venkatesh, Davis, 1996).

Facilitating conditions refer to the degree to which the user of the technology/system believes that the existing organizational and technical infrastructure provides support for the technology to remove its use-related barriers. Otherwise, facilitating conditions concern the technical assistance and available resources and infrastructure that facilitate the use of a technology (Venkatesh et al., 2003).

User satisfaction defines the degree of user contentment with his or her ability to use the system. Sanchez-Franco defined satisfaction as the level of user perception about their necessities, objectives, and expectations related to the system (Sanchez-Franco, 2009).

The future intention to use refers to the predicted decision to use a system in the future in advance of doing so (Petter, McLean, 2009). In the proposed model, the future use of e-learning refers to the planned extended use of e-learning and the encouragement of its use by others.

The object of interest was the relationship between the indicated variables.

Computer self-efficacy vs. satisfaction

Self-efficacy is the ability to use an e-learning system while carrying out specific learning tasks (Pituch, Lee, 2006) or user-perceived trust in their own ability to use a PC effectively (Compeau, Higgins, 1995).. Low self-efficacy levels can result in a user's inability to handle problems, especially when systems are complex, and discourage users from continued use of the device. Many previous studies confirmed that computer self-efficacy significantly affected the student's intention to use an e-learning system (Zardari et al., 2021; Ahmad et al., 2020; Ameen et al., 2019). Based on the findings by Al-Fraihat et al. (2020), computer self-efficacy was one of the primary determinants of student learning satisfaction. Based on the authors, the student experience and grasp of the system and the ability to use it to perform tasks (self-efficacy) can promote positive attitudes toward the e-learning system and overall satisfaction (Al-Fraihat et al., 2020). According to Hsiao and Yang (2011), if e-learning systems are recognized as task-related information systems, self-efficacy is considered to have stronger positive effects on the use (Hsiao, Yang, 2011). Based on Alenezi and Karim (2010), computer self-efficacy can promote a high level of use of an e-learning system among students. An increase in the level of computer self-efficacy leads to the improvement of student acceptance of learning systems (Mouakket, Bettayeb, 2015).

Thus, H1 is formulated as follows:

Hypothesis 1: Computer self-efficacy (CSE) has a positive impact upon satisfaction with e-learning (S)

Facilitating conditions vs. satisfaction

Technology acceptance models refer to this variable differently, but the meaning is the same. The UTAUT model has the variable "support conditions", the D&M IS Success Model uses a service quality variable. Service quality means effective support provided to system users (Wang, Wang, 2009).

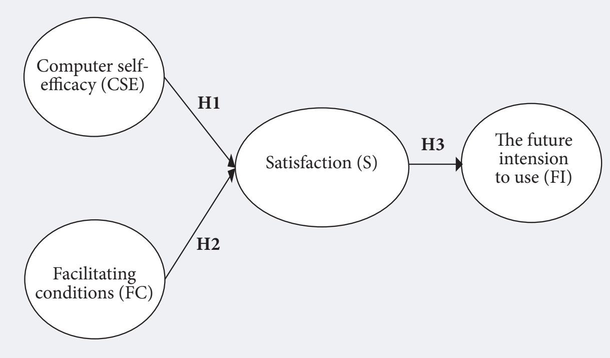
According to Passmore (2000), the satisfaction and progress of students in virtual learning depend on technology and support facilities and infrastructure provided by their institutions (Passmore, 2000). Venkatesh et al. (2003) also argued that the facilitating conditions could reflect user perception and behavior, and the individual use of a system is largely determined by facilitating conditions (Venkatesh et al., 2012; Karaali et al., 2011). Also, Al-Fraihat et al. (2020) confirmed that service quality reflecting facilitating conditions has a significant positive impact on student satisfaction with e-learning tools. Therefore, the following hypothesis was formulated:

Hypothesis 2: Facilitating conditions (FC) have a positive impact upon satisfaction with e-learning (S)

Satisfaction vs. the future intention to use

Technology users can express their level of satisfaction resulting from the quality of information and the system (Gulc, 2020, 2021). User satisfaction with e-learning is often used to measure learners' attitudes (Wu et al., 2010). User satisfaction in the D&M IS Success Model is a key determinant in using technology systems (DeLone, McLean, 2003). Many authors agreed that satisfaction is a key factor for the intention to use e-learning (Aldammagh et al., 2021; Ejdys, Gulc, 2020; Arain et al., 2019; Chang, 2013; Hassanzadeh et al., 2012). Satisfaction as the key antecedent for predicting students' intention to use e-learning is confirmed by Rajeh et al. (2021) and Yekefallah et al. (2021). In the model developed by Kim et al. (2010), measurement variables reflecting user satisfaction were included within the attitude construct (e.g., "All things considered, using the IT system is a pleasant idea, I am satisfied with using the IT system"). The results of the study confirmed that variables related to user satisfaction are

Figure 1. **Theoretical model**



Source: author.

Table 1. **Constructs Included in the e-Learning Technology Acceptance Model – Literature Review**

Authors	Basic model	E-learning tools	Research sample	Country	Theoretical constructs
Arteaga Sánchez, Duarte Hueros, 2010	TAM	Moodle	226	Spain	Perceived usefulness, perceived ease of use, perceived self-efficacy, technical support, attitude, and the use of the system
Al-Maroof et al., 2021	TAM	M-learning	630	United Arab Emirates	Perceived routine use, perceived usefulness, perceived ease of use, perceived enjoyment, the self-efficacy theory, perceived critical mass, fear of vaccination, post-acceptance of the e-learning platform
Weerathunga et al., 2021	TAM	E-learning	1039	Sri Lanka	Subjective norm, relevance, self-efficacy, computer anxiety, experience, perceived usefulness, facilitating the precipitating events of COVID, conditions, perceived ease of use, attitude towards e-learning, behavioral intention to use e-learning, actual use of e-learning
Abdullah at el., 2016	TAM	E-portfolios	242	UK	Perceived usefulness, perceived ease of use, self-efficacy, experience, enjoyment, computer anxiety, subjective norm, behavioral intention to use
Ibrahim et al., 2017	TAM	Blackboard e-learning systems	95	Malaysia	Computer self-efficacy, instructor characteristics, course design, perceived ease of use, perceived usefulness, the future intention to use
Al-Azawei et al., 2017	TAM	Blended e-learning	210	Iraq	Perceived satisfaction, e-learning self-efficacy, learning styles, perceived usefulness, perceived ease of use, intention to use
Cheng, 2019	TAM	WIKI for group work	174	Hong Kong	Subjective norms, self-esteem, perceived behavioral control, perceived ease of use, perceived usefulness, attitude towards using, intention to use behavior
Raza et al., 2021	UTAUT	e-learning	516	Pakistan	Expected performance and effort, social image, facilitating conditions, social isolation (COVID), behavioral intentions, fear of COVID
Mohan et al., 2020	UTAUT	MOOC	412	India	Expected performance and effort, social image, support conditions, hedonic motivation, habits, course content, behavioral intentions
Odegbesan et al., 2019	UTAUT	e-learning	574	Nigeria	Expected performance and effort, social image, support conditions, behavioral intentions, system use, experience
Almaiah, Alyoussef, 2019	UTAUT	e-learning	507	Saudi Arabia	Expected performance and effort, social image, support conditions, behavioral intentions, system use, teacher characteristics, course support tools (chat, multimedia, forums, animations), course evaluation tools, course design (structure, content)
Fianu et al., 2020	UTAUT	MOOC	204	Ghana	Expected performance and effort, social, support conditions, self-efficacy in computer use, quality of the system, quality of teaching
Al-Azawei, 2019	D&M IS	Facebook, Moodle	143	Iraq	Quality of information and system, system use, user satisfaction, impact on users and on the organization, experience with the technology, experience with the Internet
Yakubu, Dasuki, 2018	D&M IS	e-learning CANVAS system	366	Nigeria	Quality of the system, information and services, user satisfaction, behavioral intention to use the system, current level of use of the system
Mohammadi, 2015b	D&M IS	e-learning	420	Iran	Quality of education, services, technical system and content and information, perceived ease of use, perceived functionality, user satisfaction, intention to use, the current scope of use
Al-Fraihat et al., 2020	D&M IS	Moodle	563	Great Britain	Quality of the technical system, information, services, education and support system, quality of participants and teachers, perceived satisfaction, perceived functionality, use of the system, benefits
Aparicio et al., 2017	D&M IS	e-learning	383	Portugal	Quality of information, system and services, user satisfaction levels, system utilization system, impact on the individual, fortitude participants

Source: author.

Table 2. **Summary of the Literature on Variables Included in the Theoretical Model**

Concept (variable)	Literature
Computer Self-Efficacy (CSE)	Arteaga Sánchez, Duarte Hueros, 2010; Agudo-Peregrina et al., 2014; Mohammadi, 2015a; Abdullah et al., 2016; Ibrahim et al., 2017; Al-Azawei et al., 2017; Muyesser Eraslan Yalcin, Birgul Kutlu, 2019
Facilitating conditions (FC)	Mohammadi, 2015a; Asher Irfan Saroia, Shang Gao, 2019; Arteaga Sánchez, Duarte Hueros, 2010; Karaali et al., 2011; Agudo-Peregrina et al., 2014; Dečman, 2015
Satisfaction (S)	Mohammadi, 2015a, 2015b; Abdullah et al., 2016; Salloum et al., 2019
Future intention to use (FI)	Karaali et al., 2011; Ibrahim et al., 2017; Salloum et al., 2019; Venkatesh et al., 2003
Source: author.	

statistically significant for the users' future intention to use the system (Kim et al., 2010). This led to hypothesis H3:

Hypothesis 3: *User satisfaction (S) has a positive impact upon the future intention to use e-learning (FI)*

The theoretical model reflecting the links between all the variables is presented in Figure 1, while the summary of the sources that describe each variable is reflected at Table 1.

Research Method

Data

Data were collected using structured questionnaires and computer-assisted web interviewing (CAWI). In February–March 2021, students at Bialystok University of Technology (Poland) were sent an electronic link to the questionnaires using the internal e-mail system. The form was distributed to 5,779 potential respondents. The return rate was 13.9% (803 completed

Table 3. **Constructs and Items — Results of the Confirmatory Factor Analysis**

№	Constructs and items	Standardized regression weights before and after CFA		Variable symbol
		before	after	
	Computer Self-Efficacy (CSE)			
1	I can sort out any problems arising during the use of e-learning tools by myself	0.799		Removed
2	I can use e-learning tools without the support of the third parties	0.841	0.810	CSE1
3	I can use e-learning tools even if I do not have a user guide	0.920	0.959	CSE2
4	I can use e-learning tools even if I have not used them before	0.877	0.878	CSE3
5	I have sufficient technical resources to use e-learning tools	0.668		Removed
	Facilitating conditions (FC)			
6	During the e-learning process, I can rely on technical support from the University	0.843	0.856	FC1
7	During the e-learning process, I can rely on technical support from my colleagues	0.393		Removed
8	In the case of any problems concerning the functioning of e-learning tools, I can count on feedback	0.782	0.808	FC2
9	The University provides professional assistance to users of e-learning tools through clear and understandable user instructions and guides available on the website	0.829	0.834	FC3
	Satisfaction (S)			
10	I enjoy using e-learning tools	0.897	0.895	S1
11	The use of e-learning tools is more satisfying than traditional forms of learning	0.916		Removed
12	The use of e-learning tools makes me more creative	0.889	0.893	S2
13	The use of e-learning tools gives me self-confidence	0.859	0.843	S3
14	The use of e-learning tools gives me the feeling that I am competent and able to perform important activities	0.911	0.896	S4
	Future intention to use (FI)			
15	I intend to use e-learning to a greater extent	0.872	0.888	PI1
16	I intend to encourage others to use e-learning	0.911	0.922	PI2
17	Thanks to e-learning, I am more open to new technological solutions	0.846		Removed
18	I prefer the traditional way of teaching in direct contact with the teacher	0.694		Removed

* Variable removed due to absolute value of covariance for standardized residuals being greater than 2 or regression coefficient less than 0.7

Source: author.

Table 4. **CFA Model Fit Summary**

Indicator	Model fit	
	Before removing reduction	After removing reduction
NPAR	42	31
CMIN Chi-square	586.498	145.044
Degrees of freedom (DF)	129	47
P	0.000	0.000
CMIN/DF	4.546	3.086
RMR	0.305	0.134
GFI	0.919	0.970
AGFI	0.892	0.950
PGFI	0.693	0.584
NFI Delta1	0.601	0.878
RFI rho1	0.527	0.829
IFI Delta2	0.659	0.914
TLI rho2	0.588	0.877
CFI	0.652	0.913
RMSEA	0.066	0.051
LO 90	0.061	0.042
HI 90	0.072	0.061
PCLOSE	0.000	0.414
HOELTER 05	215	354
HOELTER 01	232	401

Source: author.

forms); 463 (42.8%) of respondents were women, and 459 (57.2%) were men.

Measures

Variables included in the theoretical model (computer self-efficacy, facilitating conditions, satisfaction, and the future intention to use) are not directly observable. Therefore, several observable variables were used for their measurement. Based on the literature review, 18 items were initially considered: five items were identified for measuring computer self-efficacy, four — facilitating conditions, five — satisfaction, and four — the future intention to use. A seven-point Likert scale (with 1 as "totally disagree" and 7 — "totally agree") was applied in the measurement of the constructs.

Afterward, the fit of the measured variables with the number of constructs was determined with the help of Confirmatory Factor Analysis (CFA). As it is less sensitive to assumptions concerning normal distribution, the Generalized Least Squares (GLS) estimator was used to determine values of model parameters. Observable variables, for which the value of regression coefficient was lower than 0.7, and absolute values of Standardized Residual Covariances were greater than 2, were removed from the original set (Ejdys, Halicka, 2018). Eventually, 12 items were used for further analysis. The list of variables resulting from the confirmatory factor analysis is presented in Table 2. Table 3 gives the model fit summary.

Cronbach's alpha coefficients were used to verify the consistency of the items in the scale. It is assumed that Cronbach's alpha above 0.7 is acceptable, and less than 0.7 suggests that the item of the scale needs to be revised. For convergence validity, two indicators were used, i.e., Average Variance Extracted (AVE) (Fornell, Larcker, 1981) and Composite Reliability (CR). AVE above 0.5 shows the better capacity of the measurement to indicate characteristics of each model's research variables. CR above 0.7 indicates a higher inherent consistency of the measurement (Hair et al., 2013).

The scale reliability reflected by Cronbach's alpha ranged from 0.873 to 0.934. Composite Reliability (CR) and Average Variance Extracted (AVE) were also higher than expected, which confirmed the convergence validity of scale. Table 4 provides mean, factor loading, Cronbach's alpha, CR, and AVE for the items.

The removal of selected variables improved the fit measures of the CFA model (Table 3). Descriptive statistics, Cronbach's alpha, Average Variance Extracted, and Composite Reliability values are represented in Table 4

Results

The measurement model was evaluated for appropriateness by using the chi-square statistics. The $\chi2$ value was statistically significant ($\chi2=136{,}262$, $p<0.001$), indicating a good model fit to the data. Also, ratio chi-square divided by the degrees of freedom ($\chi2/df$) was used as a measure of model fit, where values of 3 or less indicate a good model fit. Ratio $\chi2/df$ achieved the value of 2.839, which proved a good model fit as well. Several other disparate indices had been considered to evaluate an overall model fit. The indices adopted to assess the SEM model fit and their desired values are presented in Table 5.

To verify the hypotheses, the author used Generalized Least Squares (GLS) Modeling (GLS-SEM). All tested relationships were found to be statistically significant. Thus, these positive relationships confirmed three hypotheses H1, H2, and H3. The results of the hypotheses' verification and model fit measures are presented in Table 6. Figure 2 presents the individual structural path estimates between constructs and variables.

Results of hypothesis testing using AMOS software are presented in Figure 2.

Discussion

The obtained results allowed for verifying hypotheses H1 and H2 examining the relationship between three variables: computer self-efficacy (CSE), facilitating conditions (FC), and satisfaction (S). The research confirmed the statistically significant role of the computer self-efficacy construct in creating satisfaction with e-learning (H1) and the statistically significant role of the facilitating conditions construct in creating

Table 5. **Descriptive Statistics, Cronbach's Alpha, Average Variance Extracted and Composite Reliability**

Constructs and Items	Mean (M)	Factor Loading	Cronbach's α	Composite Reliability (CR)	Average Variance Extracted (AVE)
Facilitating conditions (FC)					
FC1	4.56	0.854	0.873	0.872	0.695
FC2	4.88	0.806			
FC3	4.65	0.835			
Computer self-efficacy (CSE)					
CSE 1	6.24	0.809	0.911	0.915	0.782
CSE 2	6.16	0.959			
CSE 3	5.94	0.875			
Satisfaction (S)					
S1	4.32	0.896	0.934	0.933	0.778
S2	3.76	0.893			
S3	3.85	0.842			
S4	3.93	0.896			
Future intention to use (FI)					
FI1	4.55	0.888	0.902	0.901	0.819
FI2	4.00	0.923			

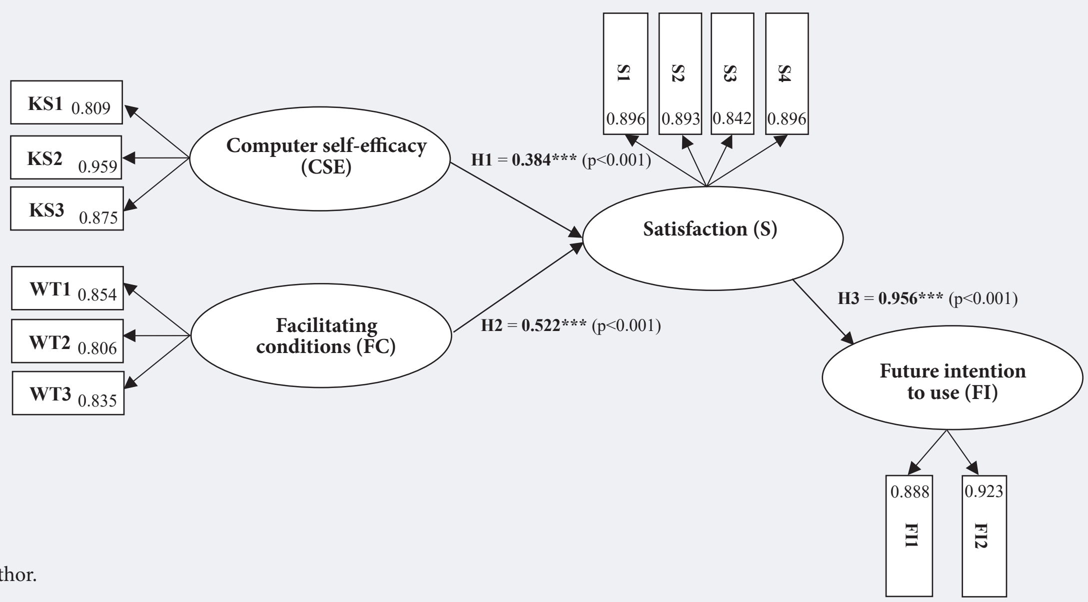
Source: author.

satisfaction (H2). In particular, the effect of facilitating conditions is more profound than that of computer self-efficacy on user satisfaction.

Higher levels of computer self-efficacy result in greater user satisfaction with e-learning. Computer self-efficacy means that users can use tools without external support also if they have never used them before. This is because the respondents belong to the Net Generation, representing young people raised while constantly exposed to computer-based technology.

Particular variables within computer self-efficacy received high scores based on the employed seven-point Likert scale. The average scores for variables were as follows: SCE1 (statement: I can use e-learning tools without the support of the third parties) - 6.24; SCE2 (statement: I can use e-learning tools even if I do not have a user guide) -6.16, and CSE3 (statement: I can use e-learning tools even if I have not used them before) - 5.94. The results confirm that the students feel confident and their digital skills allow them to use new e-learning tools without any problem or additional stress. Previous user experience with digital tools makes them more confident with the new tools, which are very often built on earlier solutions and are often intuitive. Findings regarding the relationship between computer self-efficacy and satisfaction are consistent

Figure 2. **Measurement Model**



Source: author.

Table 6. **Results of the Verification of the Hypotheses**

Hypothesis	Estimate	S.E.	C.R.	P	Test results
Hypothesis (H1). Computer self-efficacy (CSE) has a positive impact upon satisfaction with e-learning (S)	0.384	0.058	6.608	***	Support
Hypothesis (H2). Facilitating conditions (FC) have a positive impact upon the satisfaction with e-learning (S)	0.511	0.051	9.992	***	Support
Hypothesis (H3). User satisfaction (S) has a positive impact upon the future intention to use e-learning (FI)	0.956	0.029	33.153	***	Support

χ^2= 136.262; d.f. = 48; χ^2/d.f. = 2.839; p < 0.005; RMSEA = 0.048; GFI = 0.972; AGFI = 0.954 *** p < 0.001, Hoelter - 384. Adopted level of the statistical significance was 0.001.

Source: author.

with previous studies. Zardari et al. (2021) and Ahmad et al. (2020) proved that computer self-efficacy had a significant effect on students' intention to use the e-learning system. Also, the findings of the study conducted by Al-Fraihat et al. (2020) indicated that computer self-efficacy was one of the primary determinants of student learning satisfaction.

Facilitating conditions (FC) is the second variable determining the level of user satisfaction with e-learning. It concerns the external environment and reflects the conditions created by the university for organizational and technical support. Individual questionnaire statements received lower scores on the used seven-point Likert scale compared to variables of the computer self-efficacy (CSE) construct. The average scores for variables were as follow: FC1 (statement: During the e-learning process, I can rely on technical support from the university) - 4.56, FC2 (statement: In the case of any problems concerning the functioning of e-learning tools, I can count on feedback) -4.88, and FC3 (statement: The university provides professional assistance to users of e-learning tools through clear and understandable user instructions and guides available on the website) - 4.65. Findings regarding the relationship between facilitating conditions and satisfaction were consistent with previous studies. Many authors agreed that technology and support facilities and infrastructure provided by their institutions influenced the satisfaction and progress of students in e-learning (Passmore, 2000; Venkatesh et al., 2003; Venkatesh et al., 2012). Results obtained by Al-Fraihat et al. (2020) confirmed that providing quality services (facilitating conditions) to students may potentially increase their level of satisfaction with an e-learning system. Also, Al-Sabawy et al. (2013) proved that the effect of the system's quality on user satisfaction was significant for students and academic staff.

Analyzing the effect of both variables, i.e., computer self-efficacy (SCE) and facilitating conditions (FC) on the variable "user satisfaction", the standardized regression weight confirms that the facilitating conditions (standardized regression weight - 0.511) have a significantly higher impact than the computer self-efficacy construct variables (standardized regression weight - 0.384) on user satisfaction. This allows for concluding that relatively lower rated variables characterizing facilitating conditions (FC) need further improvement by the university, which will definitely affect the level of user satisfaction.

Results in examining the relationship between satisfaction (S) and the future intention to use e-learning (FI) are consistent with previous studies. The findings regarding the effects of satisfaction on the future intention to use indicated that user satisfaction was a strong predictor of the future intention to use e-learning. According to Zardari et al. (2021), satisfaction significantly influences the intention to use e-learning. Also, research conducted by Alyoussef (2021) confirmed

Table 7. **Model Fit Indices**

Model fit indices	Level of acceptance	Sources
Chi-square/Degrees of freedom (χ2/df)	desire < 3, acceptable < 5	Hwang, Kim, 2007; Choudhury, Karahanna, 2008; Iacobucci, 2010
Comparative fit index (CFI)	0.9, 0.95 desire	Hwang, Kim, 2007; Choudhury, Karahanna, 2008
Root mean square error of approximation (RMSEA)	0.05 (0.08)	Konarski, 2010; Choudhury, Karahanna, 2008
GFI - The goodness-of-fit index	>0.9	Jöreskog, Sörbom, 1979; Hwang, Kim, 2007;
AGFI - The adjusted goodness-of-fit index	>0.9	Jöreskog, Sörbom, 1979; Hwang, Kim, 2007

Source: author.

that student satisfaction had a positive impact on the use of e-learning as a tool ensuring the sustainability of education and the academic performance of students.

Conclusion

This study mostly focused on examining the causal determinants of e-learning user satisfaction and their future intention to use the tool. Considering the literature review results, two constructs determining user satisfaction with e-learning were adopted. One factor was taken from the group related to individual characteristics of users, i.e., computer self-efficacy (CSE), and the other was related to external factors, i.e., facilitating conditions (FC). Thus, the author's intention was to investigate which factors play a more significant role in creating user satisfaction.

All tested relationships were found to be statistically significant. Thus, they confirmed hypotheses H1, H2, and H3. Higher levels of computer self-efficacy and facilitating conditions result in greater user satisfaction with e-learning. But facilitating conditions have a significantly higher impact than the computer self-efficacy variables on user satisfaction.

The conducted research allowed for drawing methodological and practical conclusions. The confirmed reliability of the constructed measurement scales indicates their practical usefulness for future studies of the constructs by other researchers.

The achieved results provide practical implications for e-learning users, namely, in making e-learning tools more effective and widely used. Since the conditions of e-learning support have a significant impact on the level of student satisfaction with e-learning, it is, therefore, necessary to organize appropriately trained personnel available to students who would control the tools and support students during e-learning. Such support should include the provision of tutorials on the use of the tools but also direct contact with students in the case of technical problems. University support should have a positive impact on the students' feelings, satisfying their needs. A student should be treated as any customer, and the university's goal should be to ensure customer satisfaction.

This study provides novel knowledge yet has limitations. The main limitation is the sample, which comprised one university. The study did not include the university teachers and did not research factors influencing their satisfaction and future intention to use e-learning. The number of constructs was limited, aiming to simplify the model and examine relationships between the main factors under the assumption that the other elements determining the acceptance of e-learning technologies were constant. On the other hand, the small number of constructs may restrict the model's application in the future. Yet other limitations are related to the fact that the respondents, while evaluating two factors determining their level of satisfaction with the use of e-learning, gave a higher rating to the factor relating to their characteristics (computer self-efficacy) than an external factor over which they had no influence (facilitating conditions).

The research findings indicate directions for future research. University teachers and ICT staff should be included in studies of factors impacting satisfaction with e-learning systems and the future intention to use.

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Vocational Education and Training and Knowledge Intensive Business Services: A Promising Relationship in the Digital Era

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Abstract

Knowledge intensive business services (KIBS) act as bridges of innovation in the productive fabric. Given this growing importance, the occupational structure and demand for skills in KIBS activities need to be reflected upon. This paper examines the occupational structures of KIBS, looks at the role that vocational training profiles can play within them. The focus of this analysis is the case of the Basque Country, to which the mismatch approach was applied. Beyond merely understanding the current role of vocational education workers, this approach makes it possible to explore the potential of VET graduates in KIBS. Three types of mismatches are studied here: vertical mismatch, horizontal mismatch, and skills mismatch. The results show that the relevance of VET workers varies within the different types of KIBS, being particularly important in T-KIBS. This leads to the conclusion that VET graduates can play a key role in digital transformation processes, both at manufacturing and services companies.

Keywords: KIBS; vocational education and training; occupational structure; digitalisation; Industry 4.0; innovation

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Introduction

The literature on KIBS has taken as a given that highly qualified workers provide services without clarifying their educational background. It has been assumed, whether explicitly or tacitly, that they are primarily university-educated. At the same time, as a consequence of the new emerging technologies in work processes, new medium-skilled jobs linked to Vocational Education and Training (VET) are rising (Autor, 2015), especially in fields like IT and Industry 4.0 (Becker, Spöttl, 2019; Goller et al., 2021; Spöttl, Windelband, 2021), two key areas of potential development for KIBS in the coming years (Vaillant et al., 2021).

On this basis, this paper disentangles the role of VET workers in KIBS. The focus of the analysis here is the Basque Country's VET system, considered by Cedefop (2019) to be a model of excellence in Europe. The research is conducted on the one hand by considering the share of VET graduates employed in KIBS activities and on the other hand, by analyzing the mismatches between the skills supplied by KIBS employees and their occupations, according to three types of mismatch: vertical, horizontal, and skills. This approach helps one to understand the current role of VET in KIBS and its potential to correct the university bias from which the sector suffers. The case is analyzed using a combination of quantitative (descriptive analysis of secondary data and a survey with KIBS employers carried out by the authors) and qualitative methods (interviews with several KIBS employers). Thus, in order to explore the importance of VET graduates in KIBS, this paper addresses the following research question: are there any vertical, horizontal, or skills mismatches between KIBS occupational demand and the supply of VET graduates? While there are several classifications of KIBS, this paper uses the one established by Miles et al. (2018), who divided KIBS into those related to legal, financial, marketing, and consulting (P-KIBS), those concerning science, engineering, and new technologies (T-KIBS), and those centered on cultural and creative activities (C-KIBS) (Table 1).

Consequently, the paper contributes to two strands in the literature. The first is related to examining the occupational structure of KIBS and the internal nature of this sector (Consoli, Elche, 2010, 2013; Miles et al., 2019) by focusing on its employees' educational background and, more particularly, on the role of vocational education in KIBS, which was previously unexplored. The second contribution, based on the conclusions related to the research question, is connected to the emergence of new medium-skilled profiles as a consequence of the rise of new technologies associated with digitalization and Industry 4.0 (Becker, Spöttl, 2019; Spöttl, Windelband, 2021).

Theoretical and Analytical Framework

KIBS as a driver of innovation in the digital era

Ever since the seminal publication by Miles et al. (1995) brought the relationship between KIBS and innovation to the fore, this topic has continued to receive noteworthy attention in the literature. As economies develop, there is an increasing demand for more sophisticated knowledge inputs and for private suppliers who can offer specialized knowledge, such as KIBS (Consoli, Elche, 2013; Den Hertog, 2000; Muller, Zenker, 2001). KIBS are typically described as "bridges of innovation" (Wood, 2009) since they fulfill an essential strategic function in firms' competitiveness by providing knowledge (Antonelli, 1998; Corrocher, Cusmano, 2014; Czarnitzki, Spielkamp, 2003; Muller, Doloreux, 2009). Through interactive customization andcollaboration processes between customers and suppliers, KIBS develop ad hoc solutions (Bettencourt et al., 2002; Cabigiosu, Campagnolo, 2019; Landry et al., 2012; Miles, 2008). While these processes could be carried out remotely through new technologies nowadays, face-to-face contact and communication are crucial (Chichkanov et al., 2021). And their outcomes, which become both technological and non-technological innovations (Amara et al., 2009; Muller, Zenker, 2001), have a high impact on the productive performance of the customer. The role of KIBS in boosting innovation appears to be particularly important in manufacturing regions (Corrocher, Cusmano, 2014; Savic, 2016; Wyrwich, 2018).

Most of today's current regional development strategies that include smart manufacturing as a priority also involve developing a strong KIBS sector (De Propris, Bailey, 2020). However, the innovative propensity of KIBS is not limited to the manufacturing sector; they can be providers of innovation, especially in ICT, in the service sector, including KIBS themselves (Cabigiosu, 2019; Kamp, Sisti, 2018). This paper follows Miles et al. (2019) when arguing that it is essential to study the occupational structure of KIBS to be able to reflect on the future of employment in this sector. Likewise, Consoli and Elche (2013) pointed out that this analysis is useful for understanding the internal structure of KIBS, as well as the competences and knowledge they demand. And according to Cabigiosu (2019), KIBS have to rethink the different professional roles, occupations, and skills needed to make effective use of the increasing opportunities offered by the new technologies. Such roles are unlikely to be homogeneous and will depend more upon the type of activity undertaken.

Vocational education and training, innovation and KIBS

KIBS are nurtured with high-skilled workers (Freel, 2006; Den Hertog, 2000), yet their qualifications are often not specified. In many cases, whether tacitly or explicitly, it has been assumed that KIBS employees have a university background. Proof of this is the large number of articles that relate KIBS to universities (Jacobs et al., 2014; Lee, Miozzo, 2019; Pinto et al., 2015). These works contend that universities are their main workforce supplier and can also act as collaborators within regional innovation systems that feed back into their capacity to acquire and operationalize the knowledge upon which they base their business model. Moreover, they can even serve as incubators that generate KIBS (Koschatzky, Stahlecker, 2006). Given the importance that the literature has placed on KIBS as boosters of innovation for other companies, the explanation as to why KIBS and VET have not been linked so far may be related to a reductionist view of the innovation economy. In general, and particularly within the literature stream of regional innovation systems, the importance of VET is still largely ignored (Navarro, 2014; Porto, Doloreux, 2018; Moso-Díez, 2020) and the fact that firms' ability to apply knowledge and technologies depends on both their high-skilled and medium-skilled workers is lost from sight (Retegi, Navarro, 2018). Indeed, many key support functions, commonly associated with vocational education, are carried out by technical staff in areas such as design, product development, and improvement of production processes (Tether et al., 2005; Toner, Woolley, 2016). Along these lines, Cedefop (2014) showed that in countries with strong apprenticeship systems, highly skilled employees are complemented by medium-skilled technical workers, thus improving a country's productivity and innovation capacity. Furthermore, remaining at the technological forefront will involve relying on a different and specific combination of human capital inputs to achieve growth, where university education will still be crucial for the more specialized tasks of implementing technology and innovation, and medium-level vocational training will be increasingly necessary to complement this work (Manca, 2012). For instance, the VET workforce is key in the deployment of Industry 4.0 and ICT (Becker, Spöttl, 2019; Spöttl, Windelband, 2021; Goller et al., 2021).

Nonetheless, few studies have established any direct links between KIBS and vocational training. The research carried out by Eurofund (2006) opened the door by drawing attention to the impact of medium-skilled workers in the creation of practical solutions for KIBS. Consoli and Elche (2010) went a step further, arguing that vocational skills will gain importance within KIBS because of the need to simultaneously adapt and effectively use the emerging technologies. Moreover, the analysis of the occupational structure of KIBS conducted by Miles et al. (2019) used the ISCO classification (International Standards Classification of Occupations) to examine the evolution of the occupational structures of KIBS and to identify different trends associated with professional support work (ISCO 3 and ISCO 4), such as the declining ratio of those groups compared to professionals (ISCO 2) within KIBS. These ISCO occupational categories, according to ILO (2012), are linked to vocational studies. Another exception is the study by Marttila et al. (2008) which explored the role of Finnish polytechnic schools as providers of KIBS. SMEs were found to be their main customers, with innovation activities more based on practical solutions to specific problems than advances in science. However, none of these contributions directly focus on the presence of employees with VET studies within KIBS. In this regard, this paper contributes by connecting the occupational structure of KIBS to the educational background of employees, seeking to identify any possible imbalances or mismatches that may exist and examining their relevance in relation to their core activities.

Table 1. **KIBS Typologies according to the NACE Classification**

KIBS type	NACE code	Activities
P-KIBS	69	Legal and accounting activities
	70	Head office and business management consultancy activities
T-KIBS	62	Computer programming and consultancy and related activities
	71	Architectural and engineering activities; technical testing and analysis
	72	Scientific research and development
C-KIBS	73	Advertising and market research
	74	Other professional, scientific, and technical activities

Source: (Miles et al., 2018).

The mismatch approach for understanding the role of VET in KIBS

The mismatch adjustment framework makes it possible to determine which function is currently performed by people with VET in KIBS, as well as the one they should perform, avoiding the bias towards workers with a university background. This can enhance firms' productivity because, when individuals are well matched to their occupations, the knowledge and skills that are acquired through education are optimally utilized on the labor market (Somers et al., 2019). As underlined by Green (2016) and McGuinness et al. (2018), there are three main types of mismatches: the vertical mismatch, the horizontal mismatch, and the skill mismatch.

- The first type of mismatch occurs when the individual's qualifications either exceed or fall short of what is required for the job. In the first case, the individual is overqualified and, in the latter, underqualified. This type of mismatch is referred to as "vertical mismatch" (Chevalier, 2003; McGuinness, 2006; Quintini, 2011).
- The second type of mismatch, known as "horizontal mismatch" (Somers et al., 2019; Robst, 2007a), occurs when the occupation held by an employee is not related to his or her field of study. This type of imbalance is also called 'field-of-study mismatch'.

- The third type of mismatch is referred to as the "skills mismatch" or "skills gap" and describes the situation in which the employer believes that a worker does not possess the adequate competences to successfully implement his or her current tasks and functions. According to McGuinness and Ortiz (2016), the literature on firm-level skills mismatch is less developed than other sorts of mismatch.

Methodology

This paper examines the case of the Basque Country (Spain) which is particularly relevant for this study for several reasons. The region is one of the most industrialized in Europe and has been considered an interesting example to use for the analysis of industrial policy (Navarro, Sabalza, 2016).[1] Moreover, within the frame of the regional Smart Specialisation Strategy, smart manufacturing and KIBS are viewed as priorities for regional competitiveness. Finally, surveys of graduates in the Basque Country provide a highly valuable source of information at the regional level that allows the educational background of recent graduates employed in KIBS to be investigated in greater detail.

The methodological approach combines quantitative and qualitative research methods. The quantitative analysis starts with exploring the educational background, occupational structure, and vertical mismatch in Spanish KIBS, as well as the extent of horizontal mismatch in Basque KIBS, all based on the secondary sources presented below. The results from a primary survey are combined with a qualitative approach through interviews with KIBS employers to analyze the skills mismatch and the relevance of VET workers within KIBS.Using microdata from the 2019 Spanish Labour Force Survey (LFS), the role of VET workers within KIBS is studied by comparing KIBS educational background with the rest of economic activities. The Spanish LFS was used again to examine the occupational structure of KIBS and how it compares with the rest of economic activities, based on the International Standard Classification of Occupations (ISCO). The Spanish LFS uses the National Classification of Occupations (CNO), a Spanish adaptation of the ISCO. Both are the same in the one-digit classification, with slight differences between the two-digit occupational categories. We have chosen to present the results using ISCO codes because they are well known internationally and can be compared with other territories. The focus is on the occupations that are considered more relevant for KIBS. According to Miles et al. (2019), the first three levels of the ISCO (ISCO-1: management occupations; ISCO-2: technicians and professionals, both scientific and intellectual; and ISCO-3: support technicians and professionals) correspond to occupations whose main tasks include knowledge-intensive activities. The occupations included in the fourth category (ISCO-4, accounting, administrative and office occupations) can also perform knowledge-intensive tasks but to a lesser extent.

To analyze the vertical mismatch, the correspondence table (see Table 2) has been adapted. This tool matches the occupational levels with the levels of education as organized by the International Standard Classification of Education (ISCED). The levels where VET is present have been divided in two to identify clearly where

Table 2. **Occupational and Educational Level Correspondence**

ISCO categories	ISCED categories										
	0	1	2	3-1	3-2	4	5-1	5-2	6	7	8
1	Under-educated	Under-educated	Under-educated	Under-educated	Under-educated	Under-educated	Correctly matched	Correctly matched	Correctly matched	Correctly matched	Correctly matched
2	Under-educated	Under-educated	Under-educated	Under-educated	Under-educated	Under-educated	Under-educated	Under-educated	Correctly matched	Correctly matched	Correctly matched
3	Under-educated	Under-educated	Under-educated	Under-educated	Under-educated	Under-educated	Correctly matched	Correctly matched	Over-educated	Over-educated	Over-educated
4	Under-educated	Under-educated	Correctly matched	Correctly matched	Correctly matched	Correctly matched	Over-educated	Over-educated	Over-educated	Over-educated	Over-educated
5	Under-educated	Under-educated	Correctly matched	Correctly matched	Correctly matched	Correctly matched	Over-educated	Over-educated	Over-educated	Over-educated	Over-educated
6	Under-educated	Under-educated	Correctly matched	Correctly matched	Correctly matched	Correctly matched	Over-educated	Over-educated	Over-educated	Over-educated	Over-educated
7	Under-educated	Under-educated	Correctly matched	Correctly matched	Correctly matched	Correctly matched	Over-educated	Over-educated	Over-educated	Over-educated	Over-educated
8	Under-educated	Under-educated	Correctly matched	Correctly matched	Correctly matched	Correctly matched	Over-educated	Over-educated	Over-educated	Over-educated	Over-educated
9	Correctly matched	Correctly matched	Over-educated	Over-educated	Over-educated	Over-educated	Over-educated	Over-educated	Over-educated	Over-educated	Over-educated

ISCO codes
ISCO-1: Managers
ISCO-2: Professionals
ISCO-3: Technicians and Associate Professionals
ISCO-4: Clerical Workers
ISCO-5: Services, Sales Workers
ISCO-6: Skilled Agricultural Workers
ISCO-7: Craft and Related Trades Workers
ISCO-8: Plant Machine and Operators and Assemblers
ISCO-9: Elementary Occupations

ISCED Codes
ISCED 0: Early childhood education
ISCED 1: Primary Education
ISCED 2: Lower secondary education
ISCED 3-1: Medium-level VET
ISCED 3-2: Other upper secondary qualifications
ISCED 4: Post-secondary non-tertiary education
ISCED 5-1: Higher VET
ISCED 5-2: Other short-cycle education
ISCED 6: Bachelor's or equivalent level
ISCED 7: Master's or equivalent level
ISCED 8: Doctoral or equivalent level

Skills in the job and educational level
Correctly matched
Under-educated
Over-educated

Source: Adapted from ILO (2012). See also: https://dev-ilostat.pantheonsite.io/258-million-workers-in-the-world-are-over-educated-for-their-jobs/ accessed 15.03.2020.

[1] See also: http://en.eustat.eus/estadisticas/tema_473/opt_0/temas.html, accessed 14.01.2022.

Table 3. **Correspondence between KIBS' NACE Activities and VET Fields of Knowledge**

KIBS type	NACE code	VET field of knowledge
P-KIBS	69	Administration and Management
	70	Administration and Management
T-KIBS	62	Information and Communication Technology
	71	Construction and Civil Work; Mechanical Manufacturing
	72	Chemistry; SSC
C-KIBS	73	Administration and Management; Trade and Marketing
	74	Administration and Management; Image and Sound; Textiles, Clothing Industry and Leather
Source: Extracted from INCUAL (2014)..		

it stands. According to this correspondence table, the ISCO-2 occupational category refers to university education, while the ISCO-3 and ISCO-4 categories, considered more technical occupations, are linked to vocational education and training. ISCO-3 corresponds to higher VET and ISCO-4 corresponds to medium-level VET along with other types of education. ISCO-1 occupations are filled by people with both university and higher vocational education levels (ISCED categories 5-8). By computing the share of people according to educational level in each occupation in the KIBS sector, the level of vertical mismatch can be observed. In particular, the ISCO-3 and ISCO-4 occupations filled by university graduates indicate a mismatch on the labor market due to overqualification.

The analysis of the horizontal mismatch is based on the classification developed by the Spanish Qualifications Institute (INCUAL, 2014) in which the Spanish VET fields of knowledge, also known as professional branches[2], are connected with the appropriately matched NACE codes (Table 3). Given this reference, the annual survey conducted by the Basque Employment Service on all graduates from VET[3] has been used. The survey, which offers information about the activities (at the NACE 2-digit level) of the companies where the graduates are employed, makes it possible to identify the field of knowledge and the occupation (ISCO 2-digit level) of VET graduates employed in each of the KIBS. Using the surveys from the 2015-2019 period, with a total of 1,805 graduates working in KIBS, their fields of knowledge and occupations can be examined to assess whether their qualifications and the job they hold correspond with what they are expected to be and, hence, to determine the share of qualifications that are horizontally matched.

Finally, the skill mismatch is examined to obtain a complete picture of the role and importance of the tasks performed by vocationally trained people within KIBS, combining descriptive analysis from a primary survey and qualitative analysis from semi-structured interviews. To understand this potential gap, a survey was conducted with 36 KIBS employers. This survey was launched within a research project in collaboration with the Bilbao City Council and Basque KIBS. The Bilbao City Council has made KIBS a priority in Bilbao's Smart Specialisation Strategy. The survey included seven different sections (see Box 1). Furthermore, ten semi-structured interviews[4] were carried out with KIBS employers.

Results

Analysis of KIBS occupational and educational structure

KIBS employ 7% of the workers in the Basque Country, which is the same percentage as in Spain and the EU 27.[5] The analysis of the educational background of people employed in KIBS shows that university graduates do the majority of jobs in all types of KIBS, more so than the average in all industries. This is especially the case in P-KIBS (73%) and T-KIBS (71%) (See Figure 1), while university-educated employees in the whole of the economy reach 31%, a substantially lower percentage than in KIBS.

Based on this first approach, it can be concluded that KIBS are a type of activity where employees mostly have a university background. Yet, despite this high percentage of profiles with university studies, Figure 1 shows that vocationally-trained people also account for a considerable percentage within KIBS; specifically, 16% in P-KIBS, 19% in T-KIBS, and 23% in C-KIBS. Except in the latter case, these percentages are smaller than in the whole of the economy. This is mainly due to the lower presence of workers with medium-level voca-

[2] The fields of knowledge, also known as professional branches, are the set of qualifications into which the Spanish National System For Qualifications and Vocational Education and Training are structured. There are 26 different fields of knowledge and these are: Physical and Sports Activity; Administration and Management; Agriculture; Graphic Arts; Arts and Crafts; Trade and Marketing; Construction and Civil work; Electricity and Electronics; Energy and Water; Mechanical Manufacturing; Hospitality and tourism; Personal Image; Image and Sound; Food Industry; Extraction Industry; Information and Communication Technology; Installation and Maintenance; Wood, Furniture and Cork ; Maritime and Fishing Industry; Chemistry; Health; Security and Environment; Sociocultural and Community Services; Textiles, Clothing Industry and Leather; Transport and Vehicles Maintenance; and Glass and Ceramics.

[3] This yearly survey is carried out with vocationally-trained people a year after their graduation. It presents data by employment status, sex, region, industry, and occupation. Microdata has been used for this paper, but general information can be found at the following link: https://www.lanbide.euskadi.eus/estudios-estadisticas/#stats5_clStats, accessed 27.02.2022.

[4] As specified by Singh (2008), such interviews start with structured questions and their possible responses, which can then evolve into unstructured or probing questions leading to different answers.

[5] Within the EU, the country, with the highest percentage of workers in KIBS is Sweden with 11%, followed by Luxembourg and Finland, both with 10%. The countries with the lowest share of workers in KIBS are Romania employing the 3% of the workforce, and Hungary and Bulgaria with a 5%.

Box 1. KIBS Employers' Survey and Semi-Structured Interview Script

1.Description of the company/organization
- What is the legal nature of the company?
- How many people are employed at the company (including the employer)?
- What is the company's business activity? [I]

2. Education of the workforce
- How many employees in the workforce have completed UNIVERSITY STUDIES (diploma, degree, master's degree, etc.)?
- How many employees have a HIGHER VET qualification?
- How many employees have a MEDIUM-LEVEL VET qualification?
- How many employees have completed OTHER STUDIES?
- How many types of jobs in the company are held by people with a VET qualification?

3. VET jobs [II]
- Field of knowledge of the person with a VET qualification
- What is the position? (marketing technician, clinic analysis technician, IT technician...)
- Do you consider the KNOWLEDGE/ SKILLS acquired in VET ADEQUATE for the job the employee has to do? (Please answer from 0 to 10 with 0 being «very unsuitable» and 10 being «totally suitable»).*
- Is there any particular SKILL OR KNOWLEDGE that you think should be part of VET that the worker DOES NOT HAVE?
- Do you think there is any particular SKILL OR KNOWLEDGE that will be KEY in the NEXT ten YEARS that is currently unavailable?
- Do you think there is any TECHNOLOGY / SOFTWARE that will be KEY in the NEXT ten years that should be studied at VET institutions?
- To what extent is there the possibility to GROW PROFESSIONALLY (job promotion, salary, etc.) within the company from this position (with 0 being «remote» and 10 being «very strong»).*
- To what extent do you consider this job RELEVANT for the COMPANY'S GROWTH? (with 0 being «not relevant for the company's growth» and 10 being «totally relevant»).*
- Does your company have more VET jobs?

4. Companies with no employees with a VET qualification [III]
- Why are there no employees with VET studies in the company?
- Do you consider that any of the positions in your company could be filled by a person with VET?
- Which position could he/she occupy?

5. VET
- Do staff, in general, participate in training courses?
- What type of training is provided?
- What type of training is considered most important?
- Which training providers are used?

6. Dual VET [IV]
- Do you know what Dual VET is?
- Do you have Dual VET apprentices?**
- Do you consider that they generate added value in the company? To what extent?**

7. VET Ecosystem
- Have you had any vocational contact with a VET institution?
- What was the reason for this contact?

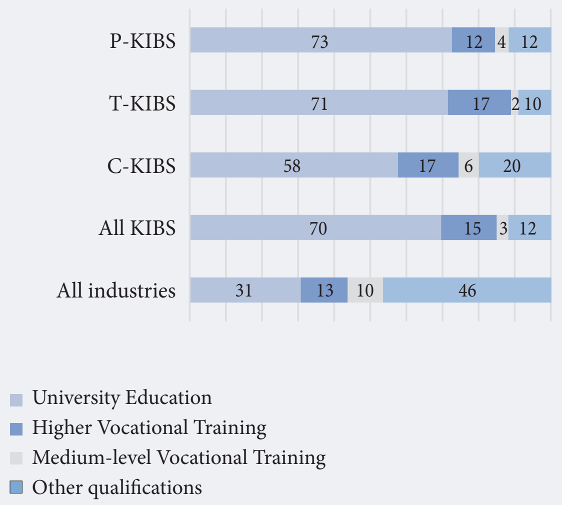
Notes:
[I] This question was absent in the questionnaire for semi-structured interviews.
[II] In the survey questionnaire, this section was completed for each type of job carried out by a VET worker at the company. For the questions marked by *, the part of the quesion in brackets was absent in the questionnaire for semi-structured interviews
[III] This section was absent from the questionnaire for semi-structured interviews.
[IV] The questions marked by ** were added for the goals of the semi-structured interviews.

Source: authors.

tional training, thus confirming that even within VET, higher qualifications are preferred when all industries are considered. Personnel with other qualifications, all of which are lower, represent a much smaller share in all types of KIBS than in the economy as a whole. Figure 2 shows that the predominant occupational level is ISCO 2 (Professionals).

Nevertheless, employees in ISCO 3 (technicians and associate professionals) and ISCO 4 (clerical workers), which, as mentioned above, are the levels mainly associated with vocational studies, also account for a significant percentage, with 39% in both P-KIBS and T-KIBS and 43% in C-KIBS. In T-KIBS and C-KIBS, technicians (ISCO 3) account for a higher percentage than clerical workers (ISCO 4), but the opposite is the case in P-KIBS, where the percentage of clerical workers (ISCO 4) is higher. Technicians (ISCO 3) are linked to higher VET qualifications and clerical workers (ISCO 4) to medium-level VET. Consequently, the tacit assumption that KIBS are provided only by university graduates becomes somewhat more nuanced when observing the results in Figure 2. The combined

Figure 1. KIBS Educational Structure in Spain by Type of Qualification (2019)



Note: Calculated as annual averages from quarterly data.
Source: Spanish Labour Force Survey (INE).

presence of occupations linked to VET backgrounds (technicians and clerical workers) is much lower in the rest of the region's economic activities.

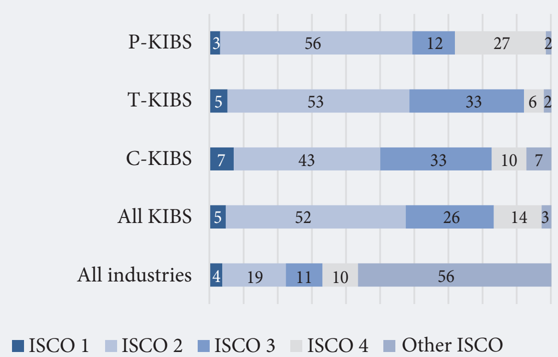
Vertical mismatch

In order to explore vertical mismatches, and following the correspondence table adapted from Gammanaro (2020) and ILO (2012) (Table 2), the share of employment has been computed by educational background in ISCO levels 3 and 4, and is shown in Table 4. It can be observed that, for technicians (ISCO 3), the level of employees who are correctly matched is higher in all KIBS than in all industries (36% vs 28%), while the opposite happens for clerical workers (ISCO 4). However, for either type of occupation, the extent of overqualification is 5 percentage points higher in all KIBS than in other industries, indicating that overqualification is more prevalent in this sector than in the rest of the economy. By type of KIBS, and starting with P-KIBS, it can be seen that the level of overqualification for technicians (ISCO 3) is quite close to that of all KIBS. Likewise, there are fewer technicians that are correctly matched because the level of underqualification is higher (35% in P-KIBS vs 25% in all-KIBS). This is, in fact, quite similar to the level for all industries (37%). Given that according to Figure 2, the share of employment in this occupation is quite similar in P-KIBS (12%) and all industries (11%), we can conclude that there are no significant differences between P-KIBS and the rest of the economy for this occupation. However, when it comes to clerical workers (ISCO 4), who account for 27% of the P-KIBS workforce, which is significantly higher than in the whole economy and the average of all KIBS, the percentage of overqualification is even greater than in all KIBS reaching 66%. This includes 30% of workers with a higher VET background. With regards to T-KIBS, the occupational level that accounts for the second highest share of employment after professionals (ISCO 2) is that of technicians (ISCO 3) (Figure 2). While 38% of them are found to be overqualified, in between the levels of all KIBS and all industries, only 19% are underqualified.

Therefore, T-KIBS is the sector with the highest level of correctly matched employees (42%) in this type of occupation. In the case of clerical workers, the level of overqualification, at 62%, is quite similar to that of all KIBS, but only 18% have higher VET qualifications, as compared to 26% in all KIBS or 22% in all industries. Finally, in C-KIBS, where 33% of the workforce are technicians (Figure 2), the level of overqualification is the highest among all activities reaching 45%, while only 23% are correctly matched by higher VET graduates (see Table 4). On the contrary, for clerical workers, the level of overqualification (48%, with 18% higher VET graduates) is the lowest among all activities, and, consequently is the activity where the level of correctly matched workers in this occupational level is the highest. This indicates that all the types of KIBS suffer from vertical mismatch in the occupations associated with VET and, therefore, the capacity to provide KIBS with VET workers is greater than currently. In the case of P-KIBS, it is more prominent in clerical occupations as they account for 27% of its workforce, and a large proportion of the positions (2 out of 3) are filled by workers with either higher VET or university qualifications, where medium-level VET or other less advanced qualifications would have sufficed.

Meanwhile, in T-KIBS and C-KIBS, the mismatch is more relevant in technician occupations. Whereas the level of overqualification (38%) in this occupation in T-

Figure 2. KIBS Occupational Structure in Spain by Occupational Category (ISCO) (2019)



Note: Calculated as annual averages from quarterly data.
Source: Spanish Labour Force Survey (INE).

KIBS is more similar to the rest of the economy (35%) than in other KIBS, it is relevant because it constitutes a larger proportion of its workforce (33% in T-KIBS vs 11% in all industries). C-KIBS technicians, 33% of its workforce (Figure 2), present the highest level of overqualification (46%). On the contrary, clerical workers present the lowest (48%). In C-KIBS, 45% are found to be overqualified, while only 23% are correctly matched by higher VET graduates (see Table 4). The level of overqualification is quite similar for clerical workers (48%), with 18% higher VET graduates, and half of the workers correctly matched, including 14% with a medium-level VET background.

While the above has focused on vertical mismatches and the occupations considered to be matched with a VET educational background, it could also be analyzed whether VET workers are in fact employed in such activities or whether they undertake occupations for which they are considered to be either overqualified or underqualified. This is shown in Table 5, where it can be observed that Medium VET graduates are highly matched in P-KIBS (in a similar way to what happens in all industries), and substantially underqualified for their occupations in T-KIBS and C-KIBS, mainly employed in ISCO-3 occupations. Regarding higher VET profiles, they are much more correctly matched in T-KIBS than in the rest of KIBS and in all industries. On the contrary, higher VET graduates in P-KIBS are significantly overqualified, mainly employed as clerical workers. This raises the question of whether they are really carrying out tasks for which they are overqualified and should be done by medium level VET workers or whether their tasks require a higher level of qualification and should, in fact, be considered as ISCO 3, but are incorrectly classified as ISCO 4. Concerning C-KIBS, what is significant is the high level of underqualification, with 33% of the higher VET workforce working as professionals (ISCO 2).

Horizontal mismatch

This section analyzes the level of horizontal mismatch by presenting, on the one hand, the fields of knowledge that recent Basque VET graduates employed in KIBS have studied and, on the other hand, the occupations they hold. Following INCUAL's (2014) correspondence table presented in Table 3, the shaded cells in each of the NACE activities in Table 6 represent the activities that are horizontally matched, disaggregated by occupational level at a single-digit level.

Appendix 1 includes more disaggregated details at ISCO 2-digit level.[6] As indicated in the table, the matching of the knowledge and professional skills they acquire during their educational/training period varies depending on the type of KIBS, and substantial differences can be seen in this respect. Regarding P-KIBS, graduates that are correctly matched reach 77% in legal and accounting activities (NACE 69). The main occupations they hold, more than 90%, are directly related to clerical work (ISCO 43, 41, 42, 34, 44, 33 and 24). In head office and business management consultancy activities (NACE 70), the level of

Table 4. Vertical Mismatch in ISCO 3 and ISCO 4 Occupations in Spain, 2019 (%)

ISCO codes	KIBS types	ISCED codes										Skills mismatching degree		
		ISCED-1	ISCED-2	ISCED-3-1	ISCED-3-2	ISCED-4	ISCED-5-1	ISCED-5-2	ISCED-6	ISCED-7	ISCED-8	Underqualified	Matched	Overqualified
ISCO-3	P-KIBS	1	5	4	26	0	26	0	14	25	0	35	26	39
	T-KIBS	0	3	4	13	0	42	0	17	20	1	19	42	38
	C-KIBS	0	7	6	18	0	23	0	21	24	0	32	23	46
	All KIBS	0	4	6	15	0	35	0	18	20	1	25	36	40
	All-Industries	1	12	6	18	0	28	0	15	20	0	37	28	35
ISCO-4	P-KIBS	1	5	11	17	0	30	0	17	19	0	1	33	66
	T-KIBS	0	11	7	19	0	18	1	18	24	0	0	38	62
	C-KIBS	2	12	14	24	0	18	0	11	19	0	2	50	48
	All KIBS	1	7	11	18	0	26	0	16	20	0	1	36	62
	All-Industries	1	13	10	20	0	22	0	16	18	0	1	42	57

Note: see Table 2 for the ISCO and ISCED codes legend, as well as for color codes.

Source: Spanish Labour Force Survey (INE).

6 Given to the volume limitations for this print-oriented version of the paper, the Appendix 1 is available at the separate file via: https://foresight-journal.hse.ru/data/2022/05/16/1823721366/Appendix%201.docx

Table 5. Vertical Mismatch of VET Graduates in Spain, 2019 (%)

ISCO codes	ISCED 3-1 Medium-level VET					ISCED 5-1 Higher-level VET				
	P-KIBS	T-KIBS	C-KIBS	All KIBS	All-Industries	P-KIBS	T-KIBS	C-KIBS	All KIBS	All-Industries
ISCO-1	3	2	2	2	1	1	1	4	2	3
ISCO-2	0	1	16	5	1	4	8	33	11	5
ISCO-3	12	62	34	33	7	27	81	44	59	23
ISCO-4	79	21	25	47	10	67	6	11	24	18
ISCO-5	0	1	7	2	38	0	0	3	1	21
ISCO-6	0	2	0	0	2	0	0	0	0	1
ISCO-7	0	8	5	4	18	0	3	4	2	15
ISCO-8	0	0	4	1	10	0	0	0	0	7
ISCO-9	6	4	7	6	12	1	0	2	0	6
Underqualified	15	65	53	40	9	4	8	33	11	5
Matched	79	31	41	54	78	28	82	48	61	26
Overqualified	6	4	7	6	12	68	9	19	28	68

Note: see Table 2 for the ISCO and ISCED codes legend, as well as for color codes.

Source: Spanish Labour Force Survey (INE).

correctly matched graduates is lower at 38%. Nonetheless, even taking into consideration that the match is not perfect, most of the working graduates belong to VET fields of knowledge that might be considered related or transversal, such as IT and communications or trade and marketing. If those activities were to be considered matched, the percentages would be over 75%. In this type of activity, VET graduates hold a greater range of occupations and, in fact, the occupation that employs a higher number of graduates is ISCO 35 (Information and communication technicians). In any case, the occupations related to clerical work are prevalent accounting for 49% (ISCO 41, 43, 42, 33 and 24).

Concerning T-KIBS, computer programming, consultancy and related activities (NACE 62) have recruited mostly graduates from the ICT professional field of knowledge (77%), who are correctly matched. Remarkably, this type of activity has recruited more VET graduates (754) between 2014 and 2019 than any other type of KIBS, concretely 42% of the total of VET graduates employed. A total of 72% of them work as information and communications technicians (ISCO 35) or information and communications technology professionals (ISCO 25) that account for 9% of the graduates within this activity. Most of those that are not horizontally matched come from the related area of electricity and electronics and also work in ISCO 35, ISCO 25, or ISCO-4 occupations, with few exceptions, mainly working as electrical and electronic trades workers (ISCO-74) and thus have occupations that are related to their studies.

In architectural and engineering activities, technical testing and analysis (NACE 71), 40% of the graduates are correctly matched but, as in P-KIBS, related or transversal VET fields of knowledge are present, some of them connected to manufacturing activities like electricity and electronics or transport and vehicles maintenance. The main occupation held by the VET graduates are science and engineering associate professionals (ISCO 31) that account for 50% of the total occupations. This is followed by both health associate professionals (ISCO 32) and metal, machinery and related trade workers (ISCO 72), accounting for 7% respectively. Science and engineering professionals account for 6%.

In scientific research and development (NACE 72), while only 28% of VET graduates seem to have qualifications that match the activity (all specialized in chemistry), there is a related field of knowledge (health) with a large percentage of graduates. Health is field of knowledge divided into two main branches, one focused on personal care and assistance and the other on technical laboratory assistance, the latter is highly related to the activity of scientific research. The main occupations are technical and closely linked to the activity (ISCO 31 and 33). Yet, some IT technicians (ISCO 35) and clerical workers (ISCO 43) are present. Finally, the percentage of correctly matched employees in C-KIBS is substantially lower, reaching 21%. In NACE 73, this share is 29% and in NACE 74, it is particularly low, only amounting to 18%. Likewise, it can be highlighted that the fields of knowledge of VET graduates in C-KIBS are quite diverse. Finally, in NACE 74 some occupations held by VET graduates such as ISCO 92 (Cleaners) or ISCO 59 (Protective services workers) are far from being associated with the core activities carried out in C-KIBS.

Table 6. Horizontal Mismatch in Recent Basque VET Graduates (2014-2019) Employed in KIBS, Disaggregated by Occupation at ISCO 1-Digit Level

NACE code	ISCO code	Occupation																							VET Graduates		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Total	By occupation per activity (%)	Matched (%)
69	ISCO-3	0	10	0	0	4	0	1	0	1	1	0	0	0	6	1	0	0	0	0	0	0	0	0	24	11	42
	ISCO-4	0	156	0	0	7	0	0	0	0	3	0	0	0	6	2	0	0	0	3	0	6	0	0	183	83	85
	Other ISCO	1	4	0	0	2	1	0	0	0	0	0	0	0	3	1	0	0	0	1	0	0	0	0	13	6	31
	TOTAL	1	170	0	0	13	1	1	0	1	4	0	0	0	15	4	0	0	0	4	0	6	0	0	220	100	77
70	ISCO-3	0	3	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	2	0	0	0	0	14	38	21
	ISCO-4	0	10	0	0	2	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0	15	41	67
	Other ISCO	0	1	0	0	2	0	1	0	0	0	0	0	0	3	0	0	0	0	1	0	0	0	0	8	22	13
	TOTAL	0	14	0	0	4	0	1	0	0	1	1	0	0	12	0	0	0	0	4	0	0	0	0	37	100	38
	P-KIBS	1	184	0	0	17	1	2	0	1	5	1	0	0	27	4	0	0	0	8	0	6	0	0	257	100	72
62	ISCO-3	0	7	0	6	1	0	53	1	5	2	0	12	0	476	3	0	1	0	1	0	1	0	0	569	75	84
	ISCO-4	0	19	0	0	1	0	4	0	0	1	0	0	0	4	0	0	1	0	1	0	0	0	0	31	4	13
	Other ISCO	0	2	0	2	1	0	30	0	3	0	0	11	0	103	0	1	0	0	0	0	0	0		153	20	67
	TOTAL	0	28	0	8	3	0	87	1	8	3	0	23	0	583	3	1	2	0	2	0	1	0	1	754	100	77
71	ISCO-3	0	9	4	1	1	30	26	1	50	0	0	0	1	9	15	0	0	20	7	5	0	0	15	194	63	52
	ISCO-4	0	33	0	0	1	0	0	0	3	0	0	0	0	1	0	0	0	0	0	1	1	0	0	40	13	8
	Other ISCO	0	2	2	2	1	5	20	3	12	2	0	1	0	4	6	0	0	2	1	1	1	0	8	73	24	26
	TOTAL	0	44	6	3	3	35	46	4	65	2	0	1	1	14	21	0	0	22	8	7	2	0	23	307	100	40
72	ISCO-3	0	1	0	0	0	0	7	0	7	1	0	0	0	8	1	0	0	38	38	3	0	0	1	105	77	36
	ISCO-4	0	10	0	0	3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	10	0
	Other ISCO	0	0	0	1	2	0	2	1	3	0	1	2	0	3	0	0	0	0	2	0	0	0	0	17	13	0
	TOTAL	0	11	0	1	5	0	10	1	10	1	1	2	0	11	1	0	0	38	40	3	0	0	1	136	100	28
	T-KIBS	0	83	6	12	11	35	143	6	83	6	1	26	1	608	25	1	2	60	50	10	3	0	25	1197	100	62
73	ISCO-3	0	0	0	1	11	0	2	0	0	0	0	4	0	21	1	1	0	0	1	0	1	0	0	43	40	26
	ISCO-4	0	4	0	1	1	1	0	0	0	1	0	1	0	0	0	0	0	0	1	0	3	0	0	13	12	38
	Other ISCO	0	2	0	11	13	0	2	0	0	2	1	4	0	5	2	2	0	1	3	0	2	1	1	52	48	29
	TOTAL	0	6	0	13	25	1	4	0	0	3	1	9	0	26	3	3	0	1	5	0	6	1	1	108	100	29
74	ISCO-3	0	0	1	6	0	1	2	0	6	0	0	3	0	4	11	0	0	2	3	2	0	0	0	41	17	7
	ISCO-4	0	21	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	1	1	0	25	10	88
	Other ISCO	7	12	6	10	3	1	17	0	16	4	5	5	1	11	16	4	1	0	33	1	21	1	2	177	73	10
	TOTAL	7	33	7	16	3	2	19	0	24	4	5	8	1	15	27	4	1	2	36	3	22	2	2	243	100	18
	C-KIBS	7	39	7	29	28	3	23	0	24	7	6	17	1	41	30	7	1	3	41	3	28	3	3	351	100	17
	TOTAL KIBS	8	306	13	41	56	39	168	6	108	18	8	43	2	676	59	8	3	63	99	13	37	3	28	1805	100	56

Note: see Table 2 for the ISCO and ISCED codes legend.

Occupations: 1 — Physical and Sports Activity; 2 — Administration and Management; 3 – Agriculture; 4 — Graphic Arts; 5 — Trade and marketing; 6 — Construction and Civil work; 7 — Electricity and Electronics; 8 — Energy and Water; 9 — Mechanical manufacturing; 10 — Hospitality and tourism; 11 — Personal image; 12 — Image and Sound; 13 — Food Industry; 14 — Information and Communication Technology; 15 — Installation and Maintenance; 16 — Wood, Furniture and Cork; 17 — Maritime and Fishing Industry; 18 – Chemistry; 19 – Health; 20 — Security and Environment; 21 — Sociocultural and Community Services; 22 — Textiles, Clothing Industry and Leather; 23 — Transport and Vehicles Maintenance.

Source: Lanbide VET graduate survey (2014-2019). https://www.lanbide.euskadi.eus/estudios-estadisticas/#stats5_clStats, accessed 19.04.2021.

While the analysis seems to indicate that the level of horizontal mismatch varies between different types of KIBS, it also casts some doubts about the accuracy of the correspondence table. This suggests that some fields of knowledge (such as ICT) might be considered transversal to almost all activities and that certain activities (such as creative ones) could benefit from incorporating graduates from diverse fields of knowledge.

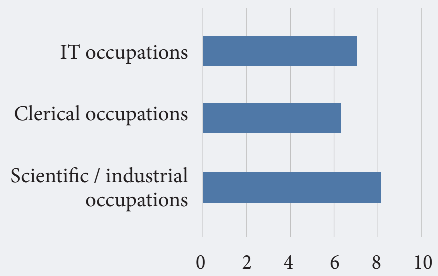
Skills mismatch

The survey and semi-structured interviews with employers shed light on the functions and the tasks performed by vocationally trained people and their relevance concerning the core activities of firms, i.e., those that bring value to customers. In the survey, the profiles of the VET workers were first defined (position, field of knowledge, and VET level). The occupations were grouped into three categories: clerical, IT, and scientific/industrial.[7]

As can be seen from the results in Figure 3, clerical occupations show the most significant skills mismatch, followed by IT occupations. Meanwhile, scientific/industrial occupations, strongly related to the installation and maintenance, and draftsman fields, stand out as the ones closest to the employers' expectations

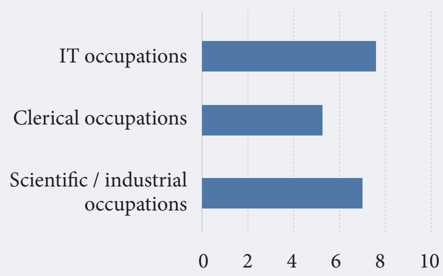
[7] A specific question was asked to be able to compute the skills mismatch: Do you consider that the knowledge/skills acquired in VET are suitable for the work they have to do? Please answer from 0 to 10, with 0 being "very unsuitable" and 10 "totally suitable".

Figure 3. **Average Level of Suitability of VET Acquired Skills by Occupational Category**



Source: Authors' own survey given to KIBS employers.

Figure 4. **Average Level of Relevance of Jobs Undertaken by VET Graduates by Occupational Category**



Source: Authors' own survey given to KIBS employers.

with regards to competences. The employers asserted during the interviews that IT occupations involve programming and computer system management tasks in different areas (full stack development, cloud computing, big data, cybersecurity, among others) where it is particularly difficult to keep up to date with what is new in the field. Likewise, in this evolving working environment, the attitudinal disposition was highlighted as a key factor when it comes to a worker's performance. In this regard, employers said that skills such as the ability to adapt to change as well as to acquire new knowledge are becoming particularly relevant to KIBS. Finally, according to employers, one evident skill gap can be found in English language skills, which do not seem to be mastered by VET graduates in comparison to their university-educated colleagues.

The role of VET workers within KIBS

In order to explore the relevance of VET workers, the survey asked the following question to KIBS employers: To what extent do you consider this job to be relevant for the growth of the company?[8] The results presented in Figure 4 show that IT occupations and scientific/industrial occupations are considered equally relevant in relation to the core activities performed in KIBS. The added value generated by clerical occupations is clearly lower since they do not participate directly in KIBS' main productive activities. This is in line with what was observed in Figure 4, which illustrates that the type of occupation carried out by people with VET in clerical profiles is, for the most part, ISCO 4. According to Miles et al. (2019), this occupational level involves lower cognitive tasks than required in other levels like ISCO-3 (Technicians).

The interviewed employers confirmed that the technological profiles are currently providing the greatest added value to the KIBS sector. Indeed, these types of profiles are becoming increasingly important for certain companies. Strikingly, several employers reported that they employed VET graduates as IT technicians because of the lack of university graduates, who are very difficult to recruit due to their high demand on the labor market. The employers asserted that they *"have discovered"* that the knowledge and skills of VET profiles are remarkable, and they are able to perform tasks that had been carried out by university graduates until that moment. Moreover, some employers even pointed out that vocationally trained people can be promoted within the firm to the same level as university graduates once given the appropriate in-house training, specifically in the Big Data field. Hence, certain tasks performed in this sector could be optimized under the principle of complementarity between workers with different educational backgrounds.

Conclusions

The literature on KIBS has pointed out that these types of services are mainly provided by highly skilled workers, usually university graduates. However, as this paper has demonstrated, the role VET graduates play in the sector cannot be overlooked. The data shows that despite the significant percentage of workers with VET training within KIBS, they are under-represented due to a mismatch problem. A vertical mismatch has been detected in the two occupational categories associated with VET qualifications: technicians (ISCO 3) and clerical workers (ISCO 4). This level of mismatch can be related to the whole Spanish labor market but KIBS present singular results, especially in P-KIBS and T-KIBS. The extent of overqualification indicates that some university graduates are being employed in occupa-

[8] The answers were measured from 0 to 10, with 0 being "not relevant for the company's growth" and 10 being "totally relevant".

tions suited for VET graduates and, therefore, the share of VET graduates could be potentially higher. Similarly, overqualification also affects different VET levels, in that some higher VET graduates are employed in clerical occupations that could be undertaken by medium-level VET graduates. Likewise, overqualification may coexist with underqualification, with technician occupations being carried out by medium-level VET workers. These results indicate differences among the various types of KIBS: P-KIBS tend to recruit clerical workers while T-KIBS and C-KIBS recruit mainly technicians. This coincides with other studies in the literature which underline the internal heterogeneity of KIBS (Consoli, Elche, 2010, 2013; Pina, Tether, 2016). As to the horizontal mismatch analysis, overall, P-KIBS and T-KIBS are found to be properly matched, especially if considering not only the fields of knowledge directly linked to them but also related or transversal ones. In particular, certain economic activities like computer programming, consultancy and related activities (NACE 62) and legal and accounting activities (NACE 69) are highly matched. Conversely, C-KIBS present a considerable horizontal mismatch where, moreover, the range of occupations carried out by VET graduates is broader and, in some cases, even unrelated. As a general conclusion, related to all sorts of KIBS, a future research topic could be to refine the fields of knowledge that are best suited for them. Regarding the skills mismatch, the survey shows that the best-matched occupations as far as VET graduates are concerned are those belonging to IT and scientific/industrial areas, while a mismatch is detected in the case of clerical occupations. In terms of relevance, once again IT and the scientific/industrial occupations are deemed particularly important as they are involved in the core activities of KIBS firms. On the contrary, clerical workers are not considered to be instrumental in those activities. These conclusions are reinforced by the opinion of the employers. According to them, VET graduates in IT and scientific/industrial occupations are playing crucial roles that are not only highly complementary to those of university graduates in the development and implementation of technological solutions but could even replace them. Likewise, the need for skills that allow VET graduates to adapt to an evolving work environment has been raised. Therefore, the role of VET graduates varies according to the type of KIBS: in both P-KIBS and C-KIBS, it is found to be less important, whereas in T-KIBS, it is more relevant. Notably, the IT and scientific/industrial profiles associated with VET stand out.

These conclusions open opportunities for further discussion and suggest future research topics related to the role of VET graduates in the current digital transition era where the application of new technologies in economic productive processes is a growing tendency. On the one hand, technological profiles related to ICT are in demand. This profile appears to be particularly important for the deployment of knowledge-intensive solutions, both to the industrial and services sector (including KIBS themselves) in areas such as cybersecurity, big data, and cloud computing. Given the growing demand for such profiles and how critical they are (Castellaci et al., 2020), being aware of the capacity of graduates with vocational training can benefit the productivity of companies that until now have tended to hire people with university profiles. This also has implications for the skills provision system that can train new learners, through VET, in emerging areas of employment in fields of knowledge related to current ones but with the potential for development in new and emerging areas of knowledge.

The findings in this paper illustrate that this first profile can be offered by VET graduates and reinforces the argument of Autor (2015), who suggests that a significant stratum of medium-skilled jobs combining specific vocational skills with foundational middle-skill levels of literacy, numeracy, adaptability, problem-solving, and common sense will be essential in the coming decades. As Cabigiosu (2019) states, the rapid evolution and proliferation of ICT technologies represents not only a considerable opportunity for KIBS but also a challenge for firms trying to make effective use of these technologies. Having teams that are made up of VET graduates together with university graduates could be an answer to such challenges.

As to the limitations of this work and further research opportunities, the paper presents a study conducted using the specific case of the Basque Country. Given that VET systems differ substantially across countries and regions in Europe, future research could include other cases. Moreover, another limitation comes from the methodological approach. Due to the novelty of the topic and the difficulty in finding reliable sources for an in-depth analysis of the nature of KIBS from an educational perspective, this paper has adopted an exploratory and descriptive approach. Nevertheless, sufficient evidence has been gathered to affirm that the role of VET in KIBS is of growing relevance in areas such as IT and Industry 4.0, which opens new avenues for this promising relationship to be further examined.

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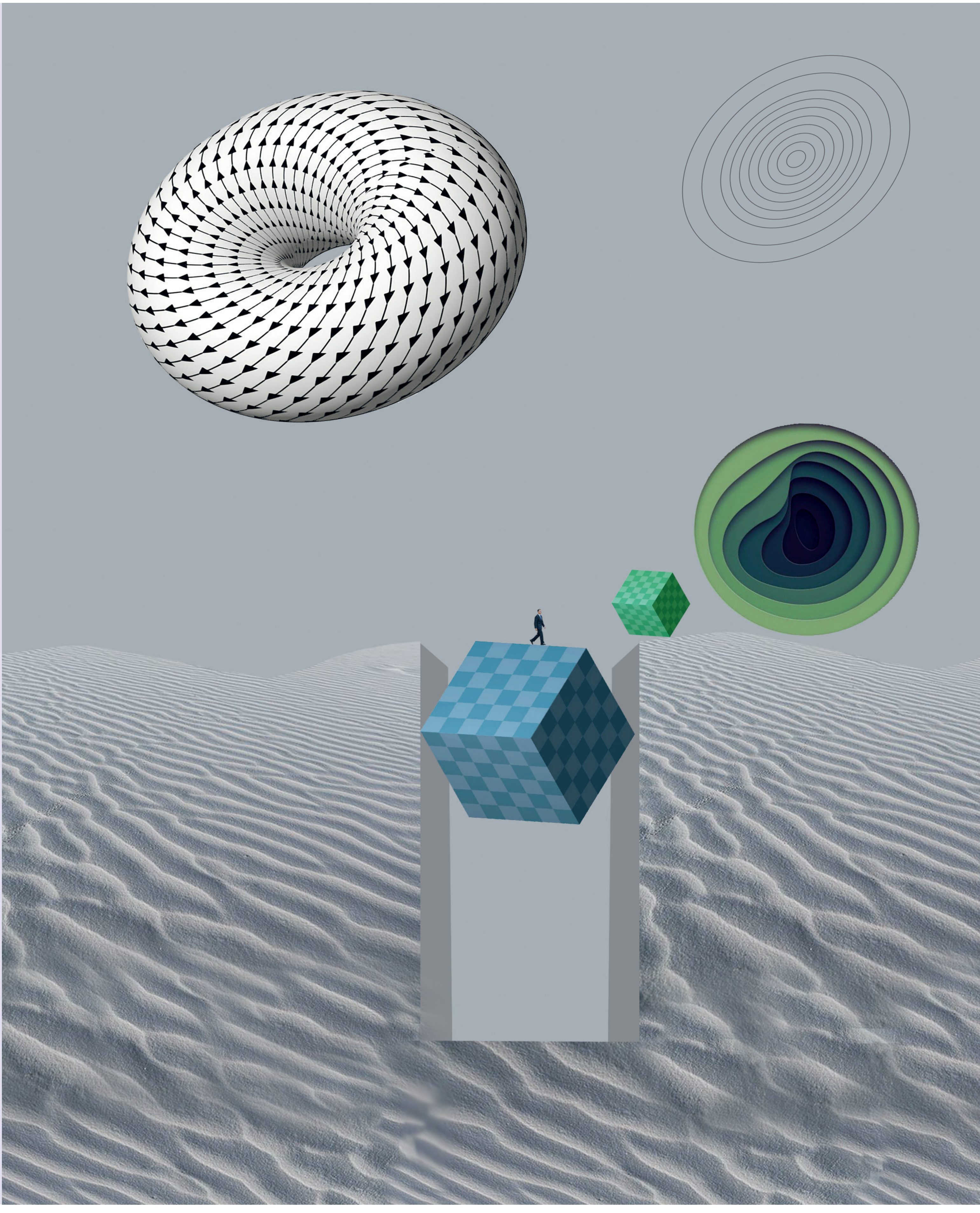

Epidemiological Informing of the Population in Cities: Models and Their Application

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Abstract

With an increase in population density and contacts between people and the emergence of new biological viruses, the threat of various epidemics is growing. Countering these threats involves the implementation of large-scale preventive, therapeutic, and other measures, both before the start of and during the epidemic. Epidemiological informing of the population plays an important role in such counteraction. The currently used models of sharing epidemiological information of the population of cities largely do not meet the needs of practice. This negatively affects the effectiveness of the response to epidemics. The purpose of the study is to develop new models and justify their applicability for understanding the processes in public health, the impact of epidemics on the economy and business. For the quantitative substantiation of epidemiological information spreading programs (scenarios), a method based on new models of epidemic development in related cities is proposed. The method is characterized by a new target function that links economic efficiency with the state of health of the population in an epidemic. The models differ from the known solutions both in the space of the selected states of the processes under study and in the connections between them.

Using the developed method, seven possible programs of sharing epidemiological information with the population of related cities were analyzed and the best of them werefound for specific conditions. New regularities have been established between the parameters of the programs being implemented and the results of the impact on the health and performance capability of the population. It is shown that an epidemic can develop in cities that are differently connected to one another by vehicles. The proposed method allows for quicklying the best epidemiological information sharing programs for the population. The models underlying this method make it possible to predict public health and the impact of epidemics on the economy and businesses, depending on the planned measures to counteract epidemics. They are also applicable for determining the sources and time of an infection's onset. The obtained simulation results are in good agreement with the known facts. The method can be applied in advanced information systems to support the adoption of far-sighted decisions to counteract epidemics.

Keywords: epidemiological informing; programmes; forecasting; health; economic losses; epidemic development models

Paper type: Research Article

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Introduction

A key aspect of forecasting public health and assessing the impact of epidemics on the economy and businesses, is the sharing of epidemiological information with the population in cities connected by large passenger flows (further on referred to as "connected cities"). The success of a comprehensive response to epidemics largely depends upon the effectiveness of such information programs and underlying models and approaches which allow one to build alternative scenarios (Papa et al., 2020; Abdulai et al., 2021).

General issues of informing people about possible threats to life and health have been studied in sufficient detail (Liu et al., 2020; Lukyanovich, Aflyatunov, 2015). Attempts have been made to assess the impact of information sources on people's situational awareness and social distancing (Wu et al., 2012; Qazi et al., 2020; Tiwari et al., 2021), including in the context of media coverage of the COVID-19 pandemic and early proliferation of the infection in China (Liu et al., 2020; Zhou et al., 2020). A number of models exist, each with its own advantages and disadvantages under particular conditions (Chubb, Jacobsen, 2009; Nadella et al., 2020), which help predict the development of epidemics (Newbold, Granger, 1974; Holko et al., 2016; Holko et al., 2020; Hu et al., 2020; Levashkin et al., 2021; Medrek, Pastuszak, 2021; Katris, 2021; Osipov et al., 2021).[1] Various approaches are applied to monitor the situation and process statistical data in order to set parameters and initial states for the application of these models, but little attention is paid to assessing the potential impact of sharing epidemiological information on public health. Methods for assessing the associated potential economic risks are also insufficiently developed. The imperfection of existing approaches makes it difficult to develop effective programs to inform the public about epidemics, which negatively affects the response to them.

The proposed new method of substantiating epidemiological information programs (scenarios) for the population of connected cities, and the associated models are designed to more effectively respond to pandemics by taking into account the informational aspect of their development and economic losses. Such models will help one to more accurately assess the efforts to counter epidemics through the prism of information policy and population response, which affect the natural dynamics of disease proliferation.

Materials and Methods

Method

Epidemiological information programs are based on the analysis of public health, economic and business data, features of the epidemic specific to connected cities, and possible response measures. Such information sharing is conducted regularly, according to the prevailing conditions. The program design, which should take into account potential effects on public health and the economic costs, should be aimed at developing an optimal epidemiological information program. Based on the evaluation results, programs that do not meet the requirements are excluded, and alternative ones are presented for consideration. Then all programs meeting acceptable public health criteria are evaluated in terms of economic indicators to select the most efficient ones. When the optimal program is identified, it is translated into specific actions. The substantiated program is communicated to the public via media in the form of instructions to overcome the epidemic.

Thus, the objective is to design an epidemiological information program (PRG_o) whose implementation would create the highest economic effect ($W_o(PRG_o, \Delta T)$) during the given time interval ΔT, which would meet the relevant public health and implementation cost requirements.

The effects ($W_s(PRG_s, \Delta T)$ of implementing program PRG_s during the interval $\Delta T = T_K - T_0$ can be defined as follows:

$$W_s(PRG_s, \Delta T) = \sum_{k=0}^{K} \int_{T_k}^{T_{k+1}} \sum_{i=1}^{L} V_{ki}(PRG_s, \Delta T_k) \cdot P_{ki}(PRG_s, T_k \leq t < T_{k+1})\, dt,$$

where

$V_{ki}\ (PRG_s, \Delta T_k) = V_{io}/(1 + \Delta t_{ki}\ (I_{ks} \in PRG_s)/\tau)$ is the economic performance of the population per unit of time in the i-th state during the k-th interval $\Delta T_k = T_{K+1} - T_k$ of the implementation of the s-th epidemiological information program;

V_{io} is the average economic performance of the population in the i-th state without the restrictive measures;

τ is the time interval for estimating V_{io};

$\Delta t_{ki}\ (I_{ks} \in PRG_s)$ is the additional time needed to achieve the same result when restrictive measures are in place;

I_{ks} are the elements of program PRG_s implemented during the k-th interval.

[1] See also: https://docs.idmod.org/projects/emod-environmental/en/latest/model-seir.html, accessed 22.01.2022.

P_{ki} $(PRG_s,\ T_k \leq t < T_{k+1})$ is the probability that the population would be in the i state during the k-th interval of implementation of the s-th epidemiological information program.

The desired program $PRG_s = PRG_s\ (I_{ks};\ k = 0.1,\ \ldots,$ K) may comprise K information blocks I_{ks}, and must belong in the set of effective programs which meet the given requirements.

The algorithm for solving this problem comprises the following steps:

1. Assessing the initial state of public health, the current dynamics of the epidemic, the employment in manufacturing and service sector, and the scope for informing the public.

2. Designing effective epidemiological information programs meeting the specified requirements.

3. Assessing each program's impact upon the resulting performance indicator and identifying the optimal one.

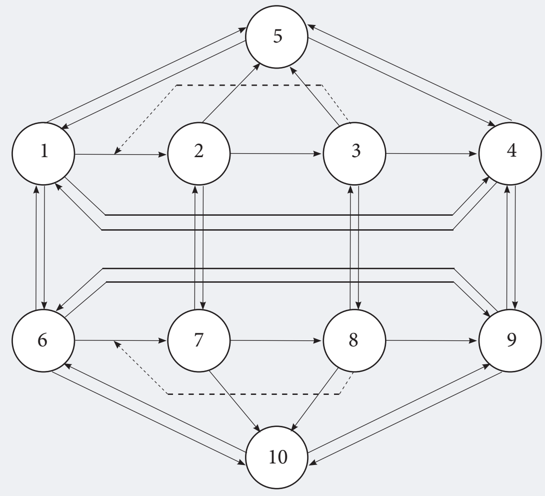
For the purposes of this assessment, the impact of PRG_s programs on the development model parameters and the course of the epidemic must be determined for each considered time interval. Then with the help of this model and taking into account its initial states, probabilities P_{ki} $(PRG_s,\ t)$ can be estimated. Knowing these probabilities and $V_{ki}(PRG_s,t)$, it is possible to estimate the damage prevented over the relevant time interval. $V_{ki}(PRG_s,t)$ values can significantly vary for different population states and strongly depend upon PRG_s parameters. To estimate the damage prevented during the next $k + 1$ time interval, the previous calculation of P_{ki} $(PRG_s,$ $t)$ should be taken into account.

Epidemic Development Models in Connected Cities

New models that take into account an extended range of possible factors affecting epidemiological development are suggested to determine P_{ki} $(PRG_s,$ $t)$. One of them is a state graph of epidemiological development in two connected cities (Figure 1). The graph vertices in Figure 1 corresponds to the population states of the first (1-5) and second (6-10) cities. The arcs in the graph presented in Figure 1 reflect the transitions of the epidemic from one state to another. These transitions are described in Table. 1. This model is different from known solutions (Browne et al., 2015) primarily due to its taking into account additional important correlations.

In line with the probability theory limit theorem for event flows, the graph in Figure 1 can correspond to a system of 10 differential equations relating the probabilities of the selected states (Box 1). Rates of transition from one state to another λ_{ij} serve as these equations' parameters, which depend upon the characteristics of the implemented

Figure 1. **State graph of epidemic development in two connected cities**



Note: vertices 1, 6 - healthy population susceptible to the infection; 2, 7 - infected population displaying no symptoms (infection carriers); 3, 8 - infected population with symptoms; 4, 9 — healthy population with immunity; 5, 10 - dead population. Each state is associated with the relative number of people in that state. Normalisation is performed in relation to the entire population of both cities.

Source: authors.

epidemiological information programs. This dependence is manifested in the form of negative and positive adjustments of λ_{ij} reflecting the change in the nature of transitions between the model states corresponding to each control action.

As a result of communicating epidemiological information to the population of the first city in the scope of the program being implemented, the parameters of transitions 1→2, 3→4, 1→6, 2→7, 3→8, and 4→9 may change. For the second city, the same applies to transitions 6→7, 8→9, 6→1, 7→2, 8→3, and 9→4.

The epidemic development can be scaled up to cover multiple cities (or countries) simultaneously, by enlarging the states presented in Figure 1. For example, states 2, 3 and 1, 5 can be combined, since new births compensate for population decline. State 4 remains unchanged. Thus, the epidemiological model of each individual city in a generalized form can be formalized by three related population states. By combining individual city models on the basis of the population's infection state, higher-level epidemic development models can be developed (Figure 2).

The models presented in Figures 2a and 2b can be incorporated in differential equation systems to analyze the process dynamics relative to the initial

Box 1. **Differential equations of the model**

$$\begin{cases}
\frac{dP_1(t)}{dt} = \lambda_{51}P_5(t) + \lambda_{61}P_6(t) - (\lambda_{12}P_3(t) + \lambda_{16} + \lambda_{15} + \lambda_{14})P_1(t) + \lambda_{41}P_4(t) \\
\frac{dP_2(t)}{dt} = \lambda_{12}P_3(t)P_1(t) + \lambda_{72}P_7(t) - (\lambda_{23} + \lambda_{25} + \lambda_{27})P_2(t) \\
\frac{dP_3(t)}{dt} = \lambda_{23}P_2(t) + \lambda_{83}P_8(t) - (\lambda_{34} + \lambda_{35} + \lambda_{38})P_3(t) \\
\frac{dP_4(t)}{dt} = \lambda_{14}P_1(t) + \lambda_{34}P_3(t) + \lambda_{94}P_9(t) - (\lambda_{45} + \lambda_{49} + \lambda_{41})P_4(t) + \lambda_{54}P_5(t) \\
\frac{dP_5(t)}{dt} = \lambda_{15}P_1(t) + \lambda_{25}P_2(t) + \lambda_{35}P_3(t) + \lambda_{45}P_4(t) - \lambda_{51}P_5(t) - \lambda_{54}P_5(t) \\
\frac{dP_6(t)}{dt} = \lambda_{16}P_1(t) + \lambda_{10,6}P_{10}(t) - \left(\lambda_{67}P_8(t) + \lambda_{61} + \lambda_{6,10} + \lambda_{69}\right)P_6(t) + \lambda_{96}P_9(t) \\
\frac{dP_7(t)}{dt} = \lambda_{67}P_8(t)P_6(t) + \lambda_{27}P_2(t) - \left(\lambda_{72} + \lambda_{78} + \lambda_{7,10}\right)P_7(t) \\
\frac{dP_8(t)}{dt} = \lambda_{78}P_7(t) + \lambda_{38}P_3(t) - \left(\lambda_{83} + \lambda_{89} + \lambda_{8,10}\right)P_8(t) \\
\frac{dP_9(t)}{dt} = \lambda_{69}P_6(t) + \lambda_{89}P_8(t) + \lambda_{49}P_4(t) - \left(\lambda_{94} + \lambda_{9,10} + \lambda_{96}\right)P_9(t) + \lambda_{10,9}P_{10}(t) \\
\frac{dP_{10}(t)}{dt} = \lambda_{6,10}P_6(t) + \lambda_{7,10}P_7(t) + \lambda_{8,10}P_8(t) + \lambda_{9,10}P_9(t) - \lambda_{10,6}P_{10}(t) - \lambda_{10,9}P_{10}(t)
\end{cases}$$

Source: authors.

states. Such models allow for predicting epidemic proliferation across multiple cities depending on the epidemiological information programs implemented there. Forecasting of this kind requires data on the model parameters and on the initial process states determined by the probabilities $P_i(t = 0)$ that at the time $t = 0$, the process would be in the i-th states. Since the period of time is divided into intervals, the relevant times are $T_k = 0$. Each of the probabilities $P_i(t = 0)$ can be defined as the relative number of people in the i-th state at a given time.

Since model parameters such as rate of transition from one state to another λ_{ij} depend on epidemic response measures, the impact of the epidemiological information program PRG_s on changes in λ_{ij} can be estimated according to the rule:

$$\lambda_{ij} = \lambda_{ij}^{*} \pm \beta_{ij} g_{ij}\ (PRG_s),$$

where

β_{ij} is the maximum possible change in the transition rate ij depending on the epidemic response measures taken;

$g_{ij}\ (PRG_s)$ is the probability that the implementation of the PRG_s program will achieve changes in λ_{ij} equal to β_{ij}.

Thus, knowing the initial process states and the parameters of the applied model allows one, by resolving the corresponding system of differential

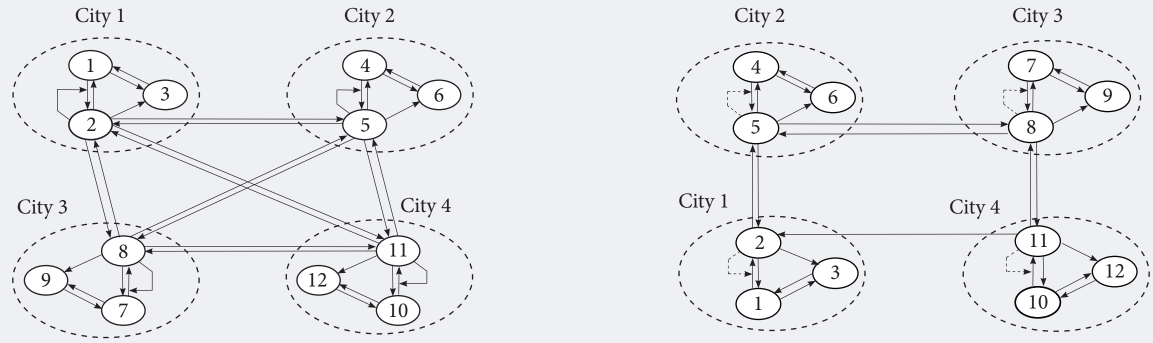
Table 1. **Transitions of the epidemic from one state to another**

Transitions	Description
1→2, 6→7	Healthy population vulnerable to the infection (states 1, 6) over time can move on to states 2, 7 (asymptomatic disease). The transition rate depends on the probabilities of states 3, 8. This dependence is shown in Fig. 1 by dash-dotted arrows.
2→3, 7→8	Infected population of the cities displaying no symptoms (states 2, 7) move on to states 3, 8 - infected population with symptoms of the disease.
3→4, 8→9	After treatment, infected population with symptoms (states 3, 8) move on to states 4, 9 - healthy population with immunity.
1→4, 6→9	After vaccination, healthy population vulnerable to the infection (states 1, 6) move on to states 4, 9.
4→1, 9→6	After losing the immunity, population of the cities in states 4, 9, return to states 1, 6.
1→6, 6→1, 2→7, 7→2, 3→8, 8→3, 4→9, 9→4	Transitions caused by people's travelling between the cities using different modes of transport.
1→5, 2→5, 3→5, 4→5, 6→10, 7→10, 8→10, 9→10	Transitions caused by mortality.
5→1, 4→4, 10→6, 10→9	Transitions caused by births.

Source: authors.

Figure 2. **Epidemic development models in connected cities**

a) epidemic development in fully connected cities ***b) sequential cyclic proliferation of the epidemic***



Note: selected population states in individual cities are shown by dotted circles; 1, 4, 7, 10 - healthy population vulnerable to infection; 2, 5, 8, 11 - infected population; 3, 6, 9, 12 - healthy population with immunity. Transitions 3→1, 6→4, 9→7, 12→10 primarily depend on the duration of immunity. When it disappears, the population moves from states 3, 6, 9, 12 to states 1, 4, 7, and 10.

Source: authors.

equations using known methods, to achieve predictive probabilities P_{ki} (PRG_s, $T_k \le t < T_{k+1}$) = P_{ki} ($\lambda_{ij}^* \pm \beta_{ij}\, g_{ij}$ (PRG_s), $T_k \le t < T_{k+1}$) that the population would be in the i-th state during the k-th time interval if the s-th epidemiological information program is implemented. Given these probabilities, it becomes feasible to forecast the economic effects W_s $(PRG_s, \Delta T)$ of implementing programs (PRG_s) over the interval $\Delta T = T_K - T_0$.

Based on the simulation results, morbidity proliferation in cities over time can be estimated. Changing the initial model conditions and implementing various administrative measures in the scope of PRG_s allow one to build alternative epidemic development scenarios and predict the programs' impact upon public health and the economy. A particular benefit of the described models (Figures 2a and 2b) may be associated with the ability to identify the place and time of the onset of the infection, i.e., to conduct a reverse analysis of the epidemic development in connected cities.

Initial Data

The statistics of COVID-19 proliferation in Russian regions and federal-level cities (Table 2) for the period from March 6 to December 30, 2020 was used as the initial data for modeling the impact of epidemiological information programs. To analyze the impact of epidemiological information sharing of the population with the system of equations presented in Figure 2, the values given in Table 3 were applied as initial transition rates. Average values of population performance in the i-th state with no restrictive measures in place were set in relative units, based on known examples (Bellman, 1983): (1; 0.75; 0.3; 1; 0; 0; 0; 0; 0; 0).

Results and Discussion

Problems (1) - (5) were solved using the MatLab software package. To begin with, let us consider the example of the interaction between two cities with a heavy passenger flow in both directions, in which, despite the different population size, similar epidemiological information programs are being implemented along with typical "safe period" preventive measures. In one of the cities, an infection source emerges and the epidemic begins to spread. How quickly will the situation develop in the first and second cities if epidemiological information sharing with the public is not adjusted?

To answer this question, the epidemic's development was modeled for a period of 150 weeks (Figure 3). The initial states in the equations system of the model presented in Figure 2 were set as (0.39888; 0.001; 0.00; 0.00; 0.00; 0.00012; 0.59982; 0.0; 0.0; 0.0; 0.0; 0.00018). Table 3 was used to set the transition rate values. Figure 3a shows the change in the relative number of healthy people

Table 2. **Online resources for monitoring the proliferation of COVID-19 pandemic**

Name	URL
An interactive web-based dashboard to track COVID-19 in real time.	https://www.thelancet.com/journals/laninf/article/PIIS1473-3099(20)30120-1/fulltext, accessed 20.01.2022.
Our World in Data. Coronavirus Pandemic (COVID-19)	https://ourworldindata.org/coronavirus, accessed 20.01.2022.
Online COVID-19 Coronavirus Map	https://coronavirus-monitor.info/, accessed 20.01.2022.
Source: authors.	

Table 3. **Initial transition rates**

Transitions	Transition rates	Transitions	Transition rates
1→2	$0.750 \cdot P_3(t)$	9→6	0.0007
6→7	$0.750 \cdot P_8(t)$	4→5	0.000235
1→4	0.0007	9→10	
6→9		5→1	0.39
2→3	0.21	10→6	
7→8		5→4	0.39
3→4	0.1	10→9	
8→9		1→6	0.00084
1→5	0.000235	6→1	0.00056
6→10		2→7	0.00084
2→5	0.000235	7→2	0.00056
7→10		3→8	0.00084
3→5	0.0011	8→3	0.00056
8→10		4→9	0.00084
4→1	0.0007	9→4	0.00056

Source: authors.

vulnerable to the infection in the first and second cities over time. Figure 3b, 3c, 3d, and 3e show the probabilities that the populations of the two cities are in states 2, 7 (infected, no symptoms); 3, 8 (infected with symptoms); 4, 9 (healthy with immunity); and 5, 10 (dead). Figure 3f presents the dependencies and the economic performance of the population in the analyzed cities when the initial epidemiological information program is implemented:

$$V_{\Sigma 1}(PRG_s, t) = \sum_{i \in 1,2,3,4} V_i(PRG_s, t) \cdot P_i(PRG_s, t),$$

$$V_{\Sigma 2}(PRG_s, t) = \sum_{i \in 6,7,8,9} V_i(PRG_s, t) \cdot P_i(PRG_s, t).$$

The expected total economic effect $W_Z(PRG_s, \Delta T)$ for the case under consideration during a 150-week interval was 143.5 conventional economic units (CEU), of which 57.5 CEU fell to the first city, and 86.0 CEU to the second one.

As shown in Figure 3, over time the number of healthy people vulnerable to the infection rapidly declines, while the number of infected people increases. However, in the first city, the highest number of infected people with symptoms falls in the 70th week, and in the second in the 80th. In the second city, infection is transmitted by people crossing the border between the cities by air, land, and water. Relative mortality in the second city peaks at 0.00036, which is 1.94 times higher than the initial one. With the input data used, the largest economic downturn occurs in week 80.

Note that at the time $t = 0$, the number of infected in the first city amounted to 0.1% of the total population of both cities. The number of infected with symptoms in this city peaked only after 14 months, while in the second city it happened after 16.5 months.

The overall impact of the epidemiological information program under consideration (*PRG1*) on the health and economic indicators of the population in connected cities is presented in Table 4. The table also shows the estimated effect of alternative epidemiological information programs designated PRG 2–7. Brief descriptions of these programs (without specific effects on model parameters) are given in Table 5.

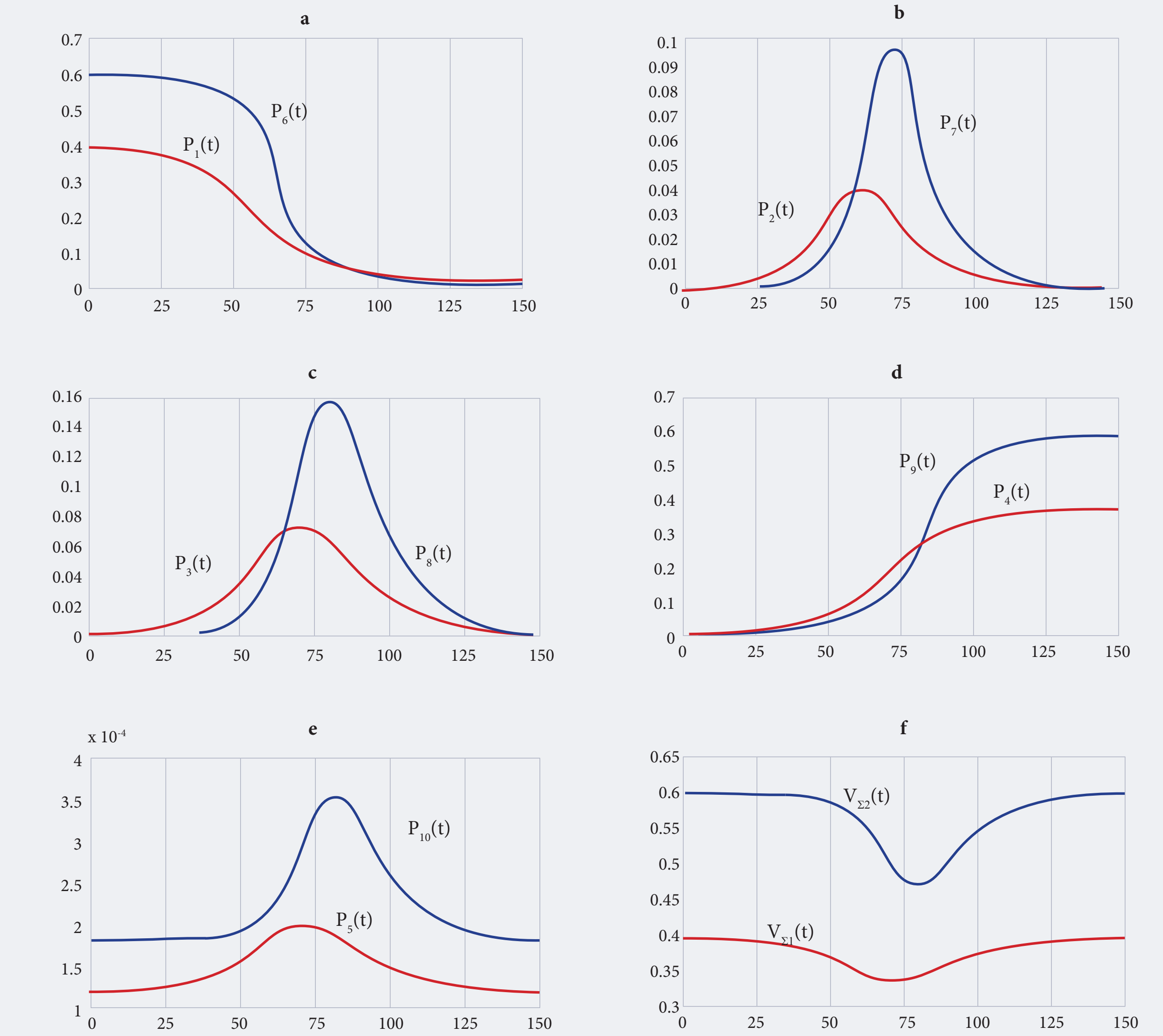
When, in contrast to *PRG1*, the *PRG2* program informs the population of the first city about the need to wear protective masks and maintain social distance, the rate of the transition 1 → 2 in the model decreases. At the same time additional time costs Δt_{ki} ($I_{ks(Z)} \in PRG_{s(Z)}$) arise, which in the example under consideration amount to 0.1 of τ. *PRG3* differs from *PRG2* in that similar protective measures are taken in the first and second cities simultaneously. If protective measures are taken only in the first city (*PRG2*), the total economic effect amounts to 138.8 CEU, but when such measures are implemented in the two cities at the same time (*PRG3*), it amounts to 131.5 CEU. According to these estimates, economic performance compared to *PRG1* declines, while peak infection rates in both cities shift to the right and decrease, along with mortality. If the implemented programs provide for vaccination (*PRG4,5*), in the first (*PRG4*) or in both cities (*PRG5*), the simulation results suggest higher values of public health indicators can be achieved during the epidemic along with higher productivity.

If epidemiological information sharing programs limit the links between the cities, infection rates differ from the above examples. *PRG6* provides for informing the public about restrictions on travel between the first and second cities starting from week 50. According to *PRG7*, people are informed about the restrictions (and the latter are introduced) starting from the time $t = 0$. An analysis of Table 5 shows that introducing these measures with a shift of 50 weeks does not lead to any appreciable results. A significant effect in the form of morbidity peaks shifting to the right is observed only when restrictions are introduced from the time $t = 0$.

Modeling the impact of epidemiological information programs on the economic performance of the population suggested that *PRG5* was the best one: the effect of its implementation to inform the population of both cities about the need for vaccination was 149.3 CEU. *PRG7* (which provided for severe restrictions on travel) was the least effective in this regard.

Let us consider the features of the epidemic's development in four cities (Figure 2a) taking into

Figure 3. Epidemic development in connected cities if no additional epidemiological informing measures are taken



Source: authors.

account the response measures. According to the model, population in each city can be in three states: 1, 4, 7, 10 (healthy population vulnerable to the infection); 2, 5, 8, 11 (infected population); and 3, 6, 9, 12 (recovered population). Let us assume immunity after recovery or vaccination will last for two years. The infection originated in the first city. The population distribution by city is (0.3, 0.2, 0.2, 0.3). The conditions for countering the pandemic through epidemiological information sharing with the public in the first, third, and fourth cities are the same. In the second city, the possibilities of treating the sick are more limited. The results of modeling the development of the epidemic using this model are shown in Figure 4.

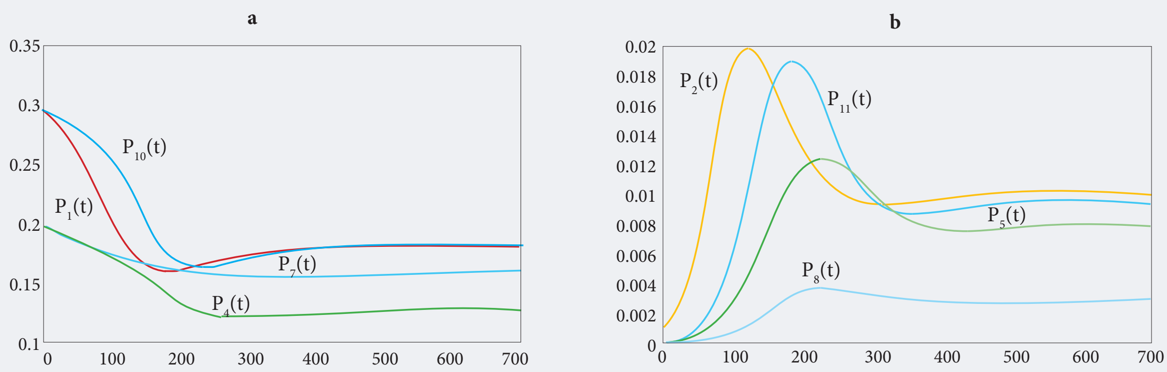
Figure 4a shows the time dependencies of the probability that cities are in states 1, 4, 7, 10 (healthy population vulnerable to the infection). Similar dependencies for states 2, 5, 8, 11 (infected population) are shown in Figure 4b. If the epidemic develops this way, and the population have limited immunity, pronounced waves can be observed during a 700-week interval (see Figures 4a and 4b). An analysis of Figure 4 reveals that without special measures, the infection can persist in the cities for many years. The duration depends upon the structure of passenger flows, the distance between the cities, population density, the epidemiological response measures implemented, virus mutations, weakening of immunity over time, and so on. Since

Table **4. Impact of epidemiological information programmes on health and economic performance of population in two connected cities**

Epidemiological informing programme	City 1			City 2			Cities1, 2
	$P_3(t^*)$ / t^*	$P_5(t^*)$ / t^*	$V_{\Sigma 1}(0)/V_{\Sigma 1}(t^*)$ / t^*	$P_8(t^*)$ / t^*	$P_{10}(t^*)$ / t^*	$V_{\Sigma 2}(0)/V_{\Sigma 2}(t^*)$ / t^*	$W_s(PRG_s, \Delta T)$
PRG 1	0.073 / 70	2.00×10^{-4} / 70	0.40/0.34 / 70	0.158 / 80	3.60×10^{-4} / 80	0.60/0.47 / 80	143.5
PRG 2	0.044 / 94	1.70×10^{-4} / 94	0.37/0.33 / 94	0.158 / 83	3.50×10^{-4} / 83	0.60/0.47 / 83	138.8
PRG 3	0.040 / 96	1.65×10^{-4} / 96	0.37/0.33 / 96	0.114 / 105	3.05×10^{-4} / 105	0.55/0.46 / 105	131.5
PRG 4	0.015 / 70	1.35×10^{-4} / 70	0.40/0.38 / 70	0.15 / 82	3.50×10^{-4} / 82	0.60/0.47 / 80	145.6
PRG 5	0.0142 / 70	1.35×10^{-4} / 70	0.40/0.38 / 70	0.0155 / 100	1.98×10^{-4} / 100	0.60/0.58 / 100	149.3
PRG 6	0.073 / 70	2.00×10^{-4} / 70	0.40/0.34 / 70	0.0156 / 80	3.50×10^{-4} / 80	3.50×10^{-4} / 80	131.5
PRG 7	0.073 / 70	2.00×10^{-4} / 70	0.40/0.34 / 70	0.0156 / 95	3.50×10^{-4} / 95	0.60/0.45 / 95	130.6

Source: authors.

Figure 4. Assessment of epidemic development in connected cities using the model in Fig. 3a



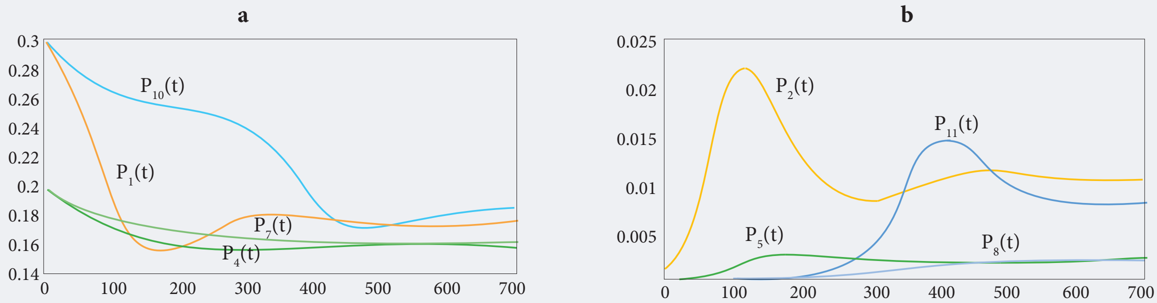
Source: authors.

Table **5. Alternative epidemiological information programmes**

Programme code	Description
PRG1	Ongoing (basic) programme to inform the public, not really tailored to the actual epidemic specifics.
PRG2	Additional programme to further inform the population of the first city about the need to wear protective masks and maintain social distance. The second city is informed in the usual way.
PRG3	A programme to inform the population of both cities about the need to wear protective masks and maintain social distance.
PRG4	A programme to inform the population of the first city about the need for vaccination.
PRG5	A programme to inform the population of both cities about the need for vaccination.
PRG6	Awareness programme on restrictions on travel between the first and second cities starting from week 50.
PRG7	A programme to inform the population about the restrictions on travel between the first and second cities starting from time t = 0.

Source: authors.

Figure 5. Assessment of epidemic development in connected cities using the model in Fig. 3b



Source: authors.

the pace of epidemiological development in large cities is much higher than in small towns, this alone can create wave patterns.

When additional epidemiological measures are implemented, the model in Figure 2a can be changed as shown in Figure 2b, where the infection proliferates sequentially from the first to the fourth city and then returns to the first one. Simulation results (Figure 5) for this model are more undulatory than those in Figure 4. Following the epidemic response measures, the incidence rates in the second, third, and fourth cities (Figure 5b) decreased compared with Figure 4b, while the incidence peaks significantly shifted over time.

Table **6. Period of time 1% infection rate was achieved in selected Russian regions**

Cities and regions	Date in 2020
Moscow	14 May
Murmansk	13 July
Nizhny Novgorod	26 September
Khabarovsk region	11 October
St. Petersburg	21 October
Voronezh region	26 October
Krasnoyarsk region	5 November
Primorsky region	15 November
Sverdlovsk region	20 November
Rostov region	5 December
Novosibirsk	30 December
Chelyabinsk region	30 December

Source: authors.

To compare the modeling results with the existing statistical data (see Table 2), Table 6 was compiled showing the dates when a number of Russian regions reached the 1% COVID-19 infection rate. An analysis of this data shows that the obtained simulation results do not contradict the available statistics.

Conclusion

This study presents a method for quantifying epidemiological information programs in connected cities and new epidemic development and response models. New correlations have been revealed between the indicators describing public information programs, the state of public health, and economic performance. The results obtained allow one to confirm a strong correlation between the three above elements. The economic costs of epidemics that can be taken into account in forecasting include the costs of medical and preventive measures, informing the public about epidemic response, temporary disability compensation, etc.

The proposed method helps one find evidence-based epidemiological response solutions by estimating the effectiveness of planned measures. The developed models can be applied to assess current and future waves of epidemics, and their impact upon the economy and businesses. The models the presented method is based upon are also suitable for determining the location and time of the onset of an infection. The method is applicable to advanced epidemiological policy decision support information systems.

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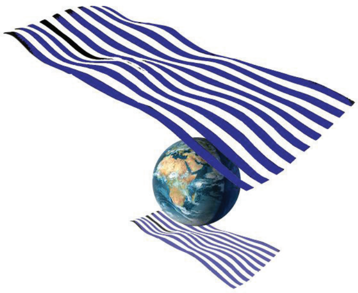

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