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Evolution of the regional innovation system in terms of the Covid-19 pandemic, financial and economic crisis: The long term perspective from Central European region

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Abstract

Research background: The evolution of the innovation system is not easy to explore due to the small number or selective nature of the international research about it. The natural trajectory is well known in a long time period but differs between regions and countries — more or less developed. If the impact of the external shocks on regional innovation system (RIS) is added here, the situation is even more complicated. The answer for the crises depends on the development level of a country and region, the maturity of the relationships between actors of the Triple Helix (entrepreneurship, science, government) — their strength and stability over time, some endogenous conditions specific to it. The knowledge about the evolution of the

innovation system is crucial to understand how the system works, where it was, is and will be at the evolution trajectory.
Purpose of the article: Therefore, the purpose of this paper is to identify the evolution of the RIS in the one of Central Europe's regions (Lower Silesian in Poland) including the impact of the global financial crisis and the Covid-19 pandemic on the innovation technology there.
Methods: Using microdata collected by the authors and the stepwise logit modelling, industrial enterprises were analysed in three time periods: 2004–2006, 2010–2012 and 2019–2021. Total 1649 questionnaires forms were collected. The research was made in the one of Poland's well advanced regional innovation systems — the Lower Silesian. The matrix of success and fail was used as long as the AUC curve and some statistical indicators to prove the usefulness of models. The dependent variables were the new technology pushed by R&D and the investment in new machinery and equipment.
Findings & value added: The nature of RIS evolution in the one of the regions in Central Europe in a catching-up country in the context of financial crises and Covid-19 was examined. The analyses identified two alternative groups of conditions — high or low resilience to various market shocks. To the first group belongs: R&D and equipment interactions (the growing competence effect) and a cooperation along the supply chain in the industry. The low resilience is observed in the other categories, as follows: the cooperation with science institutes and business support organizations (the isolation effect), the lack of external sources of funding (the sinking effect), the short time reaction of entrepreneurs (the adaptation effect). As was pointed above in the catching-up country, some elements of the Triple Helix are more sensitive to external shocks, while others are not. The crisis situation can radically slow down an evolutionary development or change its direction. Knowing them will allow the local authority to react on time or with a low delay to reduce negative consequences of it to the regional economy. Authors have shown a new approach to the evolution process of regional innovation system. It could be useful to learn how, where and when the system is going to.

Introduction

Building a strong and effective environment for innovation creation requires a holistic view of all determinants that are involved in the process. This applies to both the national and regional levels, with the national innovation system invariably influenced by regional systems and the factors that determine them (Zarebski *et al.*, 2022; Ciołek *et al.*, 2021; Park *et al.*, 2021; Chung, 2002). The variables that play a role in this process are closely related to the specific characteristics of the countries that focus on stimulating innovation (Munoz & Encinar, 2014). This means that the architecture of tools to support the implementation of new solutions must take into account the specificities and technological sophistication of countries and regions (Kuczewska & Tomaszewski, 2022; Puangpronpitaga, 2019; Lee & Kim, 2016), rather than simply focusing on copying solutions that have contributed to success in highly developed countries. In this context, policies need to be consistent in terms of the structural and institutional arrangements available to facilitate the adoption of new technologies by firms (Khan, 2022).

The concept of innovation systems (whether national or regional) involves the interactions taking place between the different actors in the system (Seker, 2022; Cooke & Morgan, 1993). Creating the right framework for building support mechanisms for innovation systems requires an understanding of the functioning of the different system elements and their interactions. In this context, the determinants established by the Triple Helix model prove useful as a starting point (Ravic *et al.*, 2023; Galvao *et al.*, 2019). This model indicates that the elements influencing the functioning of innovation systems are three groups of actors: enterprises, public administrations and scientific institutes (Cai & Etzkowitz, 2020; Leydesdorff & Etzkowitz, 2001). The state of these institutions and the relationships between them are closely related to the level of advancement of the country in which they occur, i.e. in emerging countries they do not occur at all, while in middle-income/developing countries they begin to develop. Strong relationships are found in developed countries (Kimatu, 2016). For this reason, the application of the model must take into account the specificities of the countries in which it is applied (Arman & Al-Qudsi, 2024; Cai, 2015) and the institutional structures found in them (Erzurumlu *et al.*, 2022).

The Triple Helix model originated in, and was developed, on the example of developed economies (Fidanoski *et al.*, 2022). There are more dimensions of the helix concept than three ones. It can be quadruple, quintuple, …, n-tube helix. Higher order helices raise at least a number of important scientific difficulties, including conceptual and practical issues (Park & Stek, 2022). Leydesdorff and Smith (2022) offered a solution to recognize higher-order helices but still it is more like conceptual work than empirical concept suitable for use. Besides, desegregation n-tube helix down to the three dimensions keeps still the concept of the Triple Helix but just with a different sort of actors. Consequently, there is much less analysis on how the model works in developing countries (Casadella & Uzunidis, 2017). Nevertheless, research shows its applicability to developing economies (Tiossi & Rodrigues, 2023; Etzkowitz & Dzisah, 2008; Sianipar & Widaretna, 2012; Carvalho *et al.*, 2012), and studies readily undertake comparisons between developed and developing economies (Flechas *et al.*, 2023; Ojubanire *et al.*, 2023; Jovanovic *et al.*, 2022; Choi *et al.*, 2015).

The issues raised in Triple Helix analyses often do not cover the functioning of the industry as a whole. In both developed and developing countries, studies often refer to specific industries, e.g. the semiconductor industry (Coussi *et al.*, 2019) apparel industry (Majumdar *et al.*, 2023), Blue Economy (Kontovas *et al.*, 2022), Sectoral Innovation System (Dzikowski, 2022), patentability (Ferdinands *et al.* 2023), groups of companies, e.g. start-ups (Flechas *et al.*, 2023; Pique *et al.*, 2018), or to study only certain helix elements (Liche & Strelcová, 2023; Figueiredo *et al.*, 2023; Almeida *et al.*, 2021; Sianipar & Widaretna, 2012). These studies are valuable because they focus on elements that have great potential for development in the countries analysed, but do not cover the functioning of the innovation system as a whole.

Implementation of the Triple Helix model varies depending on the conditions specific to each economy. Research on the evolution of the Triple Helix is relevant to stimulate the business innovation of enterprises. Adequately, identifying trends related to innovation activities at a systemic level will allow support tools to be better adapted to the needs of entrepreneurs. This is because different innovation policy tools are used at different levels of development in countries, and their importance evolves over time (Kopczynska & Ferreira, 2021). However, there is a lack of rich empirical studies on the evolution of the Triple Helix, as many refer to static approaches or undertake considerations based on theory analysis (Vetsikas & Stamboulis, 2023; Lew & Park, 2021) in bibliometrics (Schocair *et al.*, 2022; Choi *et al.*, 2015; Mêgnigbêto, 2018; Skoric, 2014). The other thing of the considerations is the economic context of the evolution processes, a broken chain and creative destruction mostly. The Covid-19 pandemic, financial and economic crises are some of them.

This raises the question of implementing the Triple Helix model in innovation systems in industry as a whole and how they change over the years. This is of particular interest in the case of developing countries, where the linkages in Triple Helix systems are not as strong. The following research question is therefore revealing: How is the implementation of the Triple Helix model evolving in innovation systems? As a result of this evolution over the years, has there been a strengthening of the industry-science or industry-government nexus in the functioning of the Triple Helix over the years, i.e. are developing countries thus moving towards the development paradigm characteristic of developed countries, or are the links within the helix too weak? How has this evolution been affected by the Covid-19 pandemic crises and the global financial crisis?

The authors of this paper will answer these questions on the example of the regional innovation system of one of the regions in the catching-up country, namely Lower Silesia in Poland. The analysis is based on micro-data collected by the authors of the study in industrial enterprises in a 15 year-time period in three cycles: after Poland's accession to the European Union, after the global financial crisis and shortly after the outbreak of the Covid-19 pandemic. The collected research material covers all elements of the model, that is, interactions between enterprises, the public administration and the scientific institutes. Therefore, the purpose of this paper is to identify the evolution in time (the deviation scale and quality) of the regional innovation system and the Triple Helix in the one of Central Europe's regions (Lower Silesia in Poland) including the impact of crisis situation in the form of the global financial crisis and the Covid-19 pandemic on the innovation technology there.

So far, the authors have not found such a complex and long term approach based on the raw data collected. It makes our study unique from the science perspective. For example, raw data were used to describe national innovation system in two EU countries: Spain (Hernández-Trasobares & Murillo-Luna, 2020) and Poland (Świadek *et al.*, 2022), but there was a lack of a long term impact on the system's evolution with world crises context at all. Besides those papers are based on static data.

Our analysis is interesting to fill in the gap for the international reader of innovation systems. It is the next step to developing the current state of knowledge all around the world. The analysis carried out will enrich the knowledge on the evolution taking place in regional innovation systems in catching-up countries in the context of the Triple Helix model. The study is based on unique data and presents the functioning of the system from the point of view of enterprises. Its consideration of all elements of the helix and the industry as a whole complements the analyses cited earlier.

The analyses were organised as follows. First, a review of the literature related to the evolution of innovation systems in the context of the Triple Helix and economic crises is presented. Next, the research methodology was described. Analyses were carried out based on logistic regression. Third, the results of the study were presented and discussed with other studies. Finally, conclusions were formulated with practical implications of the analyses conducted.

Literature review

The concept of innovation systems emphasises the role of actors involved in the implementation of new technology. It is assumed that the main actors in innovation processes are firms and the institutional environment (Filippetti & Archibugi, 2011). The strength of the linkages between actors in innovation processes influences the innovativeness of the system as a whole and is therefore relevant for knowledge and technology transfer (Pereira & Franco, 2023; Runiewicz-Wardyn, 2022; Eggink, 2013). In this context, the Triple Helix model has been developed over the past 30 years. It is based on the assumption that the main actors in innovation systems are three groups of actors: companies, public administrations and scientific institutes (Leydesdorff & Etzkowitz, 2001). There are various interactions between these actors that contribute to stimulating an innovation activity in the economy. These interactions vary across countries in which they are identified (Kopczynska & Ferreira, 2021; Kimatu, 2016) and can be seen as a tool to stimulate innovation (Yadav & Majumdar, 2024; Ravic *et al.*, 2023) and to identify the evolving relationships between the actors of the helix (Galvao *et al.*, 2019). All elements of the helix play vital, albeit changing, roles in the different phases of the company development (Steiber & Alange, 2013).

The evolution of innovation systems in different countries depends on alternative factors. In developed countries, science institutions are increasingly involved in innovation processes. For startups located in Silicon Valley, universities are especially significant (Pique *et al.*, 2018). They support the knowledge transfer processes through the increased activity of technology transfer offices and the increase of the interaction between universities and investors (business angels, venture capital funds and corporate investors) (Pique *et al.*, 2021). In South Korea, there has been a shift in the focus of the system from industry-government relations to industry-university relations. Significantly, the first triple relations appear there between industry, universities and government (Pique *et al.*, 2018). The Japanese experience shows that within the spiral, university-industry relations are the strongest. Previously, as in Korea, government-industry relations played an important role. The removal of legal restrictions on university-industry collaboration has played a~~n~~ crucial role in this regard (Yoda & Kuwashima, 2020). In addition, the evolution is blurring the traditional boundaries between companies and universities (Pan & Guo, 2022).

Statistical analyses comparing Triple Helix relationships between developed and developing countries indicate that developed countries have a higher share of synergies between different types of helixes than developing ones (Mêgnigbêto, 2018; Choi *et al.*, 2015). This is true not only for industry-university and industry-government collaborations (Ferdinands *et al.*, 2023), but also inside the industrial sector. These linkages are particularly important for strengthening the startup ecosystem, as the actor of the Triple Helix separately does not positively influence its quality (Flechas *et al.*, 2022). In developing countries, the government plays a significant role in this process, creating institutional mechanisms (Samo & Ul Huda, 2019; Chang *et al.*, 2021) and financial ones (O'Dwyer *et al.*, 2023; de Lima *et al.*, 2022).

In developing countries, building an advanced innovation system based on the Triple Helix model is not fully possible, because is hampered by the immaturity or absence of crucial institutional elements necessary for the Triple Helix to be operational (Tiossi & Rodrigues, 2023). This results in the development of individual partnerships that do not affect the system as a whole (van Dijk, 2023; Yegorov, 2018). Without favourable conditions that relate to the institutional context, such as culture, economy or regulatory framework, the effectiveness of the company-university relationship (despite the high productivity of research dissemination) will be insufficient (Feola *et al.*, 2021). The Russian experience suggests that the transition to a paradigm based on university-enterprise partnerships may be hampered by weak science-enterprise interactions (Oplakanskaia *et al.*, 2019). In China, the functioning of enterprise-science collaboration is highly dependent on the innovation capacity of the system (Zhao & Wu, 2017; Wang *et al.*, 2007). It follows that knowledge absorption capacity, which is positively correlated with knowledge transfer capacity, plays an important role in the evolution of innovation systems. Shortening the system evolution cycle can therefore be done in two ways: (1) by promoting knowledge absorption capacity (Zhao *et al.*, 2019; Ranjbar *et al.*, 2022) and (2) by stimulating knowledge sharing through knowledge transfer from university institutions. In this arrangement, the driving force of the system is the knowledge generated by R&D, but the developmental force is the knowledge transfer induced by the government (Pan & Guo, 2022). The government can interact in this context by stimulating the establishment of technology parks and incubators and also using incentives (Ribeiro & Nagano, 2023). This is a problem in developing economies because, on the one hand, universities are able to create new knowledge, but there are problems in transferring it to entrepreneurs (Liche & Střelcová, 2023). In Jordan, it has been shown that universities are more likely to deliver skilled human resources to the industry than the new knowledge or innovation (Mohammed, 2010). The problem of aligning knowledge to industry needs is also found in China. On the one hand, it has been proven that the absorptive capacity of industry, especially in a private sector, has exceeded the knowledge transfer capability of universities (Ye & Wang, 2020). On the other hand, the example of Thailand shows that this process can be hindered by the companies themselves. This is due to limited network experience and weak social capital among system actors, especially small and medium enterprises (Nakwa & Zawdie, 2016).

The links within the Triple Helix are weaker in developing countries (Tiossi & Rodrigues, 2023). Despite this, there should be an evolution in developing countries that shows a strengthening of the system through the development of interactions within the relationships between enterprises, science domain and government. However, for such an evolution to take place, the linkages within the system must be strong and stable to resist shocks occurring in the market. In the last decade, the European economy has been exposed to several crises: the international financial crisis and the Covid-19 pandemic, and now the Russian invasion on Ukraine. Research shows that innovation systems in developed countries cope better with economic crises than catching-up countries (James *et al.*, 2023; Nguyen & Duong, 2019; Toshevska-Trpchevska *et al.*, 2019). Factors influencing resilience to crises in a European setting include the competence and quality of human resources, specialisation in the high-tech sector along with the development of the financial system (Lundvall, 2023; Umiński *et al.*, 2023; Filippetti & Archibugi, 2011), capacity to learn (Butkus *et al.*, 2023). The better developed they are, the better a country copes with the crisis. In Norway, the crisis in the oil and gas industry triggered companies to engage even more strongly in innovation and geographically expand their knowledge networks (Rypestol *et al.*, 2022). The situation was similar in an ICT cluster in southern Sweden (Martin & Trippl, 2017). Unfortunately, Central and Eastern Europe countries declined the level of innovation during the crisis (Friz & Gunther, 2021), and innovation firms declined their labour productivity (Toshevska-Trpchevska *et al.*, 2019). Nevertheless, despite the decline in innovation, the association with Schumpeterian creative destruction was noticeable (Friz & Gunther, 2021).

Poland is among the developing countries in Central and Eastern Europe and one of its regions at the NUTS 2 level is the Lower Silesian Voivodeship. The Lower Silesian region is characterised by a higher than average level of innovation in Poland (Statistics Poland, 2023) with a very strong high technology position of the central agglomeration (Wrocław). The primary smart specializations of the region are: pharmaceuticals, internet and communication technology, spatial mobility (electric cars), machine and equipment production. In this context, Lower Silesia can be regarded as representing a region in a catching-up country that is above the average for such countries. Setting this information with the studies cited above, open questions remain about the evolution of the Lower Silesian regional innovation system and its resilience to shocks in the form of economic crises. Will the region's above-average level of innovation and public support focused on high technology (smart specialisation) make it resilient to crises (a development trajectory characteristic of developed countries), or will it have the characteristics of catching-up countries, with the system proving too unstable to be little affected by crises? The study's authors lean toward the second claim, therefore, the main hypothesis is as follows:

H0: *The regional innovation system of Lower Silesia is not sufficiently developed to be able to defend itself against external crises.*

The specific hypotheses relate to the individual elements of the Triple Helix:

H1: *Innovation activity of firms is deflected by external market shocks related to the financial crisis and Covid-19 pandemic.*

H2: *Innovation cooperation with science is deflected by external market shocks related to the financial crisis and Covid-19 pandemic.*

H3: *Innovation cooperation with business support organizations is deflected by external market shocks related to the financial crisis and Covid-19 pandemic.*

Once these hypotheses have been verified, it should be clear how the innovation system responds to external crises and whether it is resilient enough to come through them with clean or almost clean hands? It will let us adapt the current innovation policy to be more flexible, time changing (dynamic vs static) and finally resilient to external crises in contrast to the project of the smart specialization of the EU regions. The lack of the other similar research does not allow us to know at this stage about policy implications but some conclusions will be formulated after our empirical analyses.

Research methods

Surveys in the Lower Silesian Voivodship were carried out three times in the different time periods: 2004–2006, 2010–2012, 2019–2021. In the first two cases, the data of the enterprises to which the survey forms were addressed came from the Teleadreson database. This is a collection of active industrial enterprises. The collection efficiency of the surveys was 11%. The last survey used the full address database of enterprises purchased from the Statistics Poland. The efficiency was 6%. This last case is a representative survey with a random sampling error of 5%. In total, more than 1,600 companies from Lower Silesia completed the questionnaire.

Surveys conducted in the Lower Silesian Voivodship are not the only ones carried out by employees of the Department of Innovation and Entrepreneurship at the University of Zielona Góra. Analyses of national and regional innovation systems have been carried out here for the last 15 years. Surveys have been successively and systematically collected from industrial enterprises from the next after another regions in Poland. So far, more than 20,000 enterprises have been surveyed and the third round of the survey is currently on the way. Furthermore, the survey form is subject to evolutionary improvement based on global research trends (OECD & Eurostat, 2005). At the same time, it remains in line with international standards for innovation surveys in OECD countries (OECD & Eurostat, 2005). This makes it possible to compare the three survey periods without significant divergence. The possibility of their comparability with other research conducted worldwide remains significant.

Logistic regression (logit) with a stepwise regression forward was used in the statistical modelling of innovation processes (Stanisz, 2016). The reason for using this method is the binary form of the dependent variables. Classical linear regression is limited to use due to the possibility of negative results, which are illogical. Modelling of this type is often used in medical science, where the problem boils down to whether the patient is healthy or sick (Stanisz, 2016). In economics, they can be referred to as decision-making models. An entrepreneur decides to carry out a certain type of innovation activity under the influence of the internal and external conditions present. Generally speaking, logistic regression is a mathematical model that can be used to describe the influence of many variables X1, X2, …, Xk on the dichotomous variable Y. When all independent variables are qualitative, the logistic regression model is synonymous with the log-linear model (Świadek & Gorączkowska, 2020).

The regression coefficients[1] are usually estimated using maximum likelihood estimation (Gourieroux & Monfort, 1981). It uses the assumption of the form of a logistic distribution (Gruszczyński, 2009). MLE consists in determining the vector of parameters in such a way as to maximize the probability of the occurrence of values that previously appeared in the sample (Welfe, 2008). In the most general categories, MLE maximizes the credibility function or its square (Stanisz, 2016).

In the logit model, the probability is related to the odds. Probability is understood as a situation in which the number of successes is determined in relation to the number of attempts. On the other hand, the odds are expressed by the probability that a given event will occur (success) to the probability that a given phenomenon will not occur (failure) (Danieluk, 2010).

The one of the issues to use a logistic regression is "unobserved heterogeneity" across compared points in time (see more Mood, 2010; 2017). In parallel, additional calculations of the same models were performed for linear regression (the stepwise linear regression) to check whether the same results would be obtained in two different regressions (logistic or linear distribution). According to the results, the same independent variables in each model were obtained using the stepwise linear regression forward. They are all significant and the signs are the same. The analyses and conclusion in the paper are based on statistical significance and the signs and less on values. This proved that unobserved heterogeneity does not significantly affect the results using logistic regression.

The following additional statistics were used to determine the goodness of fit of the model: Wald χ 2, R^2 Cox-Snell, R^2 Nagelkerke, AUC value,

[1] This section and the next one are description of logistic model according to the literature review. It is just theoretical background to explain the method used. The same part of the description was previously published by authors in the different paper (Świadek & Gorączkowska, 2020, p. 817) where the same method was used.

p-value and Hosmer-Lemeshow test (Wald χ^2, p-value). It is worth noting that for models with a dichotomous dependent variable, the pseudo R^2 used does not reach high values, which is logical. A value of 0.2 is considered to be a good fit (McFadden, 1979).

To ascertain the utility of the model, a case classification matrix was used. It determines the success of predicting the occurrence of an event or the absence of an event. The weighted average of successes of 0 and 1 is the AUC and ROC curve, which were discovered and used after the Japanese attack on Hearl Harbor in 1941 till now.

The variables adopted for the study were adjusted according to the standards of the Oslo methodology (OECD & Eurostat, 2005). The set and interpretations of dependent and independent variables, including reference ones is shown in Table 1.

A formal expression of these equations for a firm *i* is as follows:

$$TECH\_INN_t\ (EQUIP\ or\ R\&D) = \alpha_0 + \alpha_1 Equip\_inv_i + \alpha_2 R\&D\_inv_i + \alpha_3 R\&D\_inhouse_i + \alpha_4 COOP\_sup_i + \alpha_5 COOP\_cus_i + \alpha_6 COOP\_com_i + \alpha_7 COOP\_univ_i + \alpha_8 Coop\_PAN_i + \alpha_9 COOP\_dom_i + \alpha_{10} SUPP\_entreinc_i + \alpha_{11} SUPP\_businangel_i + \alpha_{12} SUPP\_traincentr_i + \alpha_{13} SOUR\_insid_i + \alpha_{14} SOUR\_maga_i + \alpha_{15} SOUR\_cus_i + \alpha_{16} SOUR\_assoc_i + \alpha_{17} BARR\_extfound_i + \alpha_{18} BARR\_markknowl_i + \alpha_{19} BARR\_cooperation_i + \alpha_{20} BARR\_monopoly_i + \alpha_{21} EFF\_mat_i + \alpha_{22} EFF\_num_i + \alpha_{23} EFF\_capa_i + \alpha_{24} EFF\_mark_i + \alpha_{25} EFF\_eco_i + \alpha_{26} EFF\_elasti_i + \alpha_{27} EFF\_qual_i + control\ variables + u_i.$$

Results

Lower Silesian Voivodship is one of the most dynamically developing industrial regions in Poland. Therefore, this region can be seen as an example of a region in Central and Eastern Europe where an evolution of the innovation system towards developed regions is taking place. It has a strong urban centre — the Wrocław agglomeration — and outside it mainly agricultural and tourist areas. In 2005, the share of total expenditure on innovative activities in the voivodship in national expenditure was 7.08%, to reach 9.91% in 2021 (bdl.stat.gov.pl).

The study in the Lower Silesian Voivodship was carried out three times. The first time focused on the years 2004–2006, when Poland joined the European Union and was on a path of the dynamic economic growth. The next survey was conducted in 2010–2012, in the final phase of the global financial crisis. The leading indicator of industrial prosperity began to rise, although the effects of the crisis were still being felt in the economy in real terms. The third period is 2019–2021, the Covid-19 pandemic time and the beginning of economic stagnation in Poland (high inflation rate, negative consumption rate). The above phenomena can be observed in Figure 1 showing the index of an industrial business climate.

The starting point for the analyses is the good economic situation and the next reference points are the two crisis periods. Presenting the results of the research in this way allows the evaluation of changes in entrepreneurs' decisions regarding their innovation activity as a result of the shocks appearing. It will also allow the identification of consequences for the evolutionary development of the regional innovation system in Lower Silesia.

In Poland, the years 2004–2006 were a period of the dynamic economic growth for some time after accession to the European Union. Despite the use of EU transitional funds until 2007, the economic situation remained high. The lack of economic or political shocks meant that the innovation system developed naturally and evolutionarily, although it initially started from a low level.

The two models built for the first period show a simple structure of factors inhibiting and dynamizing the development of the young innovation system in Lower Silesia (Table 2). New production technology as a result of R&D activities (TECH_INN_R&D) depends mainly on innovation cooperation with universities and with suppliers. Export activities play an important role, and the effects achieved through such innovations are an increase in production capacity.

In terms of market-purchased ready-to-use production technologies (TECH_INN_EQUIP), a wider range of effects are obtained than for R&D activities. They are related to higher production capabilities, more new products and improved quality. The R&D activities carried out, cooperation in the supply chain with suppliers and customers are also significant. However, these conditions apply to large companies.

The model with ready-to-use new technology (purchase of machinery and equipment) predicts the success of zeros and ones well — 68% and 79% respectively (Table 3). It means the odds that an entrepreneur who does not meet the conditions of the model, will not implement new technologies are 79%, while when they do, the chances of such implementation are 68%. The area under the ROC-curve (AUC), is 79% — the chance that the model can correctly predict the empirical decisions of an entrepreneur (Figure 2).

The second model for new production technologies as a results of R&D successfully predicts zero at 94% and one at 28% (Table 4), with AUC of 78% (Figure 3).

The second survey was conducted in Lower Silesia in 2010–2012 just after the global financial crisis. The economic situation was unstable, although a significant recession in 2008–2009 was followed by a short time improvement in 2009 and another decline in 2010–2012. This was a period of slight growth for the Polish economy.

It can be seen that the innovation system in Lower Silesia has clearly diversified. More conditions have emerged. On the one hand, this means a greater complexity of relations to new technologies there (Table 5), and on the other hand, regularities in the functioning of the system have emerged.

The conduct of R&D work was characteristic of the enterprises that used medium-low technology and with a partial share of foreign capital. Innovative entrepreneurs established cooperation with universities and PAS institutes (Polish Academy of Science institutes) with business angels. Combining R&D activities with passive technology transfer (purchase of machinery and equipment) is also significant. Entrepreneurs, as a result of unfavourable market circumstances, decided to implement new technologies reducing material and energy intensity, while entering new markets and improving product quality.

The purchase of ready-to-use technological innovations took place in the case of using the services of technological incubators. Innovative cooperation with PAS institutes is also significant. Small and medium-sized companies gained in importance because they were more willing to invest in new technologies compared to large companies.

In these firms, where revenues were falling, the purchase of production technology was reduced. It is important that R&D activity accelerates the passive technology transfer. If the R&D exists, companies are more likely to buy ready-to-use technologies on the market. Material suppliers are still crucial, although such cooperation is losing momentum.

Enterprises buy ready-to-use technologies to reduce material and energy consumption, increase production capacity and diversify products. Still, despite limitations in access to external sources of innovation financing, entrepreneurs are able to overcome these difficulties and decide to make further investments in innovation.

The theoretical model successfully predicts zeros at 94% and ones at 27% (Table 6). The area under the ROC-curve is 76% (Figure 4). The high AUC value is due to the small number of companies that were innovative.

The model of changes in production technology that are carried out together with R&D predicts the success of zeros and ones to a similar degree as the earlier model. It correctly estimates the absence of technological innovation at 98% and the occurrence of technological innovation at 28%. The AUC value is 81% (Table 7 and Figure 5). As before, the high value of AUC is due to the large difference between the number of enterprises that have not introduced new technologies compared to those which did it.

The final period, 2019–2021, is a series of ongoing events. This is related to the Covid-19 pandemic and its effects on the global economy. The long-term consequences of these events are difficult to predict, but the study carried out for the years indicated allows first conclusions to be drawn about the economic losses caused by the pandemic at the very least. At the same time, it is important to remember that entrepreneurs anticipate events and make investment decisions taking into account what will happen in the future.

The Covid-19 pandemic crisis affected medium-sized companies the most — they were excluded from the model this time (Table 8). At the same time, small enterprises started to invest in new technologies supported by R&D activities. Large enterprises have again returned to the model and this applies both to the purchase of ready-to-use technologies and those supported by R&D activities. In the same respect, business incubators play a significant role.

Stagnating revenues are resulting in a decline in interest in new production technologies linked to investment decisions. This effect is similar in scale to that observed after the financial crisis. A progressive relationship between the purchase of new machinery and R&D activity naturally emerges. Entrepreneurs are more likely to implement new production technologies if they are engaged in activities combining these two activities (the growing competence effect).

Despite the increased importance of cooperation with customers, they were not a source of knowledge about new solutions for the companies. Internal sources of innovation were also in decline. Instead, branch magazines were the main factor supporting investment decisions in companies.

This may be due to the limited personal contact of company employees with others during the pandemic (lockdown). A significant barrier limiting the implementation of novelties was the lack of external funding sources. In terms of effects, the increase in product range, production flexibility and capacity had a positive impact on the functioning of the system.

The latest model of technological change influenced by the purchase of machinery and equipment predicts the success of ones twice more as the previous two models (56%) (Table 9). The prediction of zeros is still at a high level (92%). Thus, the theoretical model reflects the empirical data well (AUC=83%) (Figure 6).

The situation is similar for the R&D-pushed technological innovation model. The AUC is 86% (Figure 7). The success rate of zeros (non-appearance of investment) is 97% and of ones is 54% (Table 10). This means that there is a high probability that if the entrepreneur does not fulfil the conditions of the model, he is not interested in innovation. On the other hand, if he fulfils them, he will implement such technologies with 54% probability.

Discussion

During the first research period, the stimulation of the implementation of new technologies through R&D activities was positively influenced by cooperation with universities and suppliers. In this setting, the importance of universities in R&D activities has become apparent, which is significant in both developed and developing countries (Aldabbas *et al.*, 2020). The appearance of this variable in the model is very important because having superior universities and industries is necessary for building a successful Triple Helix model of the economy (Kim & Lee, 2016).

New production technologies are mainly introduced in exporting entities. The presence of the export in the model is not surprising (Manjunatha, 2021), but it is worth noting that the implementation of new technologies is positively correlated with export activity, firm size and foreign capital share (Cieślik *et al.*, 2019). In the case of Lower Silesian, only export activity appeared among the indicated elements, which shows that the regularities in the system were only emerging in the first research period. Analyses by Vaona and Pianta (2008) showed that large companies combine the purchase of new machinery with expansion into new markets. In the case of

Lower Silesia, this effect was not directly demonstrated, but export activity can be considered to partially confirm it.

In terms of market-purchased ready-to-use production technologies, R&D plays a vital role. On the one hand, this is a positive phenomenon, because it shows that new knowledge is generated with the implementation of new technical equipment. On the other hand, it was found that the research potential of such investments can be afforded by large firms, which have more financial capacity to implement novelties and are more likely to implement process innovations than product ones (Fang *et al.*, 2021). Such a settlement can be justified through the research of Hirsch-Kreinsen *et al.* (2006), who showed that it is only when an advanced level of economic development is reached out, innovations beyond R&D appear in low- and medium-advanced technology.

During the first research period, it is interesting to note that entrepreneurs, despite the presence of a barrier in the form of limited availability of external funding or lack of information about new markets, are more inclined to purchase new technologies anyway. This is due to the pressure of the market, its dynamic development and the ability of an entrepreneur to cope with the negative circumstance.

It can be seen that the regional innovation system in Lower Silesia in the first research period was young, dynamic and market condition supports its development. It was not complex, and innovation cooperation in the supply chain or with universities (although at a low level in the second case) significantly accelerated technological development. Entrepreneurs coped with negative external circumstances.

During the second research period, the innovation system in Lower Silesia clearly diversified, which resulted in the development of regularities in its functioning. Those created through R&D activities appeared in entities applying medium-low technology. Companies using this type of manufacturing technique are more likely to seek external technological knowledge (Wu & Wang, 2017), which is evident in the model by establishing cooperation with universities and PAS institutes or with business angels.

In the case of investment in ready-to-use technological innovations the effects of Poland's accession to the EU are visible — the burden of innovation is shifting to medium and small enterprises. This indicates a transition to the next stage of system maturity, as smaller firms are able to implement innovations continuously (even over a long period of time) (Stock *et al.*, 2002). Furthermore, in high-technology companies, the chances of purchasing new equipment decrease. This indicates that in Lower Silesia, as a result of economic development, the innovation system may have been based on low- and medium-low technology entities, as proven by Hirsch-Kreinsen *et al.* (2006) in their study.

Studies conducted in Europe in countries with a higher development level than Poland indicate that process innovations are implemented in small and medium-sized enterprises to increase elasticity (Vaona & Pianta, 2008). This shows that the evolution of the system in the region was on a trajectory towards developed countries, as there was an increase in capacity and product mix during the period under review.

The innovation system in Lower Silesia has become more diverse, which seems natural given the unfavourable economic conditions. Suppliers and R&D institutes were still significant. Passive technology transfer could be mutually stimulated and actively created (synergy effect). The main results were the reduction of material and energy costs. This applied to both innovation activity. External financial sources, although further limited, did not discourage entrepreneurs from new investments, although it could be noted that their number is slowly decreasing.

The last research period was related to the Covid-19 pandemic. The effect of the pandemic is evident in the group of medium-sized companies. Although evolutionarily they should have strengthened their position, the consequences of the shock are too strong for them. Small enterprises have evolutionarily shifted from new technologies supported by the purchase of new machinery towards R&D-based technologies. This is in line with the analysis of Archibugi *et al.* (2013), which showed that in the post-crisis period small firms are more willing to implement new solutions.

Despite this, it is a period with the large firms returning, which are three to four times more likely to introduce innovations than others. It is apparent that they have been least affected by the new economic conditions. Such a trend should not happen, as it sets the regional system back in time for some 20 years (the flashback effect). At the same time, the presence of small companies in the model with the exclusion of medium-sized ones, stands in opposition to research conducted in Europe, where it has been shown that during the financial and economic crisis, companies' commitment to innovation increases with their size (Toshevska-Trpchevska *et al.*, 2019). In addition, the Covid-19 pandemic prompted entrepreneurs to create business innovations to counteract its effects (Alameeri *et al.*, 2021). However, this was not the case for Polish medium-sized enterprises.

Stagnating revenues decrease the interest of new technologies purchased on the market. This effect is similar to that observed after the financial crisis in the previous research period.

Innovation collaboration is the evidence of a partly progressive evolution of the system. An increase in the importance of customers was observed here. This is how it should look from an evolutionary perspective, i.e. a decline in the importance of suppliers and a shift of influence towards customers. This is because collaboration with customers enables the creation of solutions with a greater degree of novelty, i.e. radical innovation instead of incremental innovation (Sanchez-Gonzalez & Herrera, 2015; Lettl *et al.*, 2006). At the same time, the strengthening of collaboration with scientific institutes is not evident. The interaction has changed and the quality and quantity of interactions have declined, demonstrating the negative impact of crisis conditions on the innovation system in Lower Silesia. Nevertheless, research in China has shown that collaboration with customers is a more effective mechanism for stimulating innovation than collaboration with science institutes for financially troubled entrepreneurs (Ma *et al.*, 2017). This is the present situation, where the lack of external funding sources significantly limits innovation activity.

Business incubators are the most significant in stimulating innovation in this region. The importance of incubators can be explained in terms of creative destruction. European studies have shown that, in times of crisis, innovation is characterised by young firms that adapt dynamically to market changes (Archibugi *et al.*, 2013), and those are the main collaborators with incubators.

In the last research period only one barrier significantly limits technological innovation, i.e. the lack of external funding sources. At the same time, it is worth noting that this factor was also present in previous research periods, but was not strong enough to limit the innovativeness of enterprises. Now it is unfortunately the main restriction issue (the sinking effect).

The effects of innovation activities increased in product mix, production elasticity and production capacity. The first of these is a symptom of the evolution of the innovation system in Lower Silesia. In spite of external difficulties, it is constantly up to date, increasingly strong, and the range is also being developed on the basis of ongoing R&D activities. This time, entrepreneurs have chosen to improve production elasticity rather than reduce costs. This new approach is the evidence of technological advancement. But is this enough in times of crisis? It is difficult to answer this question. Companies continue to increase production capacity in the hope of a future upturn. It is worth noting that this is occurring in each study period, varying in range and impact.

In recent studies, the innovation system in Lower Silesia has maintained its high dynamics, despite the global Covid-19 pandemic. However, the focus has shifted towards large enterprises. There is an increasing synergy between passive technology transfer and active technology creation. Innovation cooperation has shifted towards customers and suppliers have become irrelevant. Business incubators strongly stimulate technological change, but based on R&D activities. During the current crisis, entrepreneurs have chosen to improve production elasticity rather than reduce costs, waiting for the better times. There is unfortunately a lack of external funds to continue the technological change.

Evolutionary analysis of the regional innovation system and policy implications

Three surveys conducted in Lower Silesia have provided varying conclusions about the changes taking place in the regional innovation system in the catching-up country. They were divided into three groups: evolutionary development, no relation to evolution, and regression in development.

According to the evolutionary trajectory, two areas of economic activity are developing: innovation cooperation in the supply chain and the interaction of active creation and passive technology transfer. The first of these has been called „learning by cooperation". Entrepreneurs in Lower Silesia have moved from innovation cooperation with suppliers toward that with customers. This is a natural evolutionary trajectory observed in the literature. The second effect is the "growing competence effect." The awareness of innovation grows as an organization matures, insofar as processes of technological change are taking place — from the weak relationship between R&D and the purchase of machinery and equipment, through its bidirectionality and growing dependence, to maintaining these directions and increasing its strength, despite unfavourable external circumstances.

The second group of conclusions concerns the lack of links between the phenomena studied and the evolutionary trajectory. This applies to two important elements of the Triple Helix, namely innovation cooperation with R&D units and business support organizations. Although there are strong single relationships, the organizations involved change from period to period. The lack of stability and regularity for development, which has given rise to the term "isolation effect." It means strong changes at different points in the system, but individual and unsustainable. Such instability is characteristic of developing economies (de Oliveira *et al.*, 2020). This indicates that the potential from strengthening the system with cooperation with scientific institutions has not yet shifted to the characteristics of a knowledge-based economy (Yoon, 2015), and this means that although cooperation with institutions from the scientific domain occurs, it does not have spectacular effects on innovation (Jaklic *et al.*, 2014). The isolation effect also applies to sources of information about new technologies. There is no noticeable continuity of influence, but rather a passive observation of emerging external market shocks. The same is true of the innovation effect, although here entrepreneurs try to react and adapt to crises (the adaptation effect).

The third and final group of conclusions concerns taking a step backward in the evolution of the innovation system. This concerns the size of companies and one of the barriers to innovation. In the first case, a return to the dominant role of large companies in the region (the flashback effect) can be observed, when it is the medium and small ones that should have an increasingly strong position. This has been proven in studies conducted in the developed economies of Northern Europe (Toshevska-Trpchevska *et al.*, 2019). This can further strain system performance by limiting knowledge sharing processes, as it is small and medium-sized companies that place more weight on information received from external agents, while large companies place more weight on internal information (Luengo-Valderrey, 2018). The second element of this arrangement is the limitations in obtaining external financing for technological change. The development of an innovation system should solve this issue over time. In RIS in Lower Silesia, this is not happening, and the problem is still growing, which will clearly have consequences in the future. Entrepreneurs pointed out this limitation from the beginning, but they handled with it quite well. Later they coped worse, until this factor began to reduce the region's innovation performance in real terms (the sinking effect). Without systemic solutions in times of crisis or a favourable market turnaround, it will strongly slow down RIS in Lower Silesia, as the lack of a developed financial environment hinders innovation performance (Kapetaniou *et al*., 2018).

In the light of the above conclusions, the main hypothesis (H0) has been partially confirmed — the regional innovation system of Lower Silesia is not developed enough for its natural evolution to allow it to fully withstand the shocks of external crises. There are elements in the system that perform their functions. The core of the system, i.e. the enterprises and the relations between them, are strong and resistant to shocks. This results in the rejection of hypothesis H1. The functioning of the other elements of the Triple Helix is disrupted, resulting in the acceptance of hypotheses H2 and H3. Hence, a stunted development of the system in some aspects is observed.

There are some crucial solutions recommended to regional government according to the innovation policy in Lower Silesia. Most of them could be implemented by two ways to the system grants in the region with the high efficiency of the money spent. The first way is to create new financing lines for a pointed solutions and the second one is to add new functions (a weight) to the existing programs, which let it choose more fitting projects to the regional innovation trajectory — an evolutionary approach. The primary fund source for the next years would be: National Reconstruction Program and Cohesion Fund.

The local government should support parallel: chain delivery projects (evolutionary from delivery line to customer one), R&D and the new equipment projects (strong internal interaction between those two function of innovativeness) and push more funds to medium and small enterprise. Adding them to the regional priorities should achieve another more horizontal implication — strengthen the external financing for innovation project at last, which is the main obstacle right now. The purpose of innovation projects in the region is another issue here. The current development level in Lower Silesia–will allow the local government to decide what direction and effect for the future should be taken — eco-innovation, production elasticity or capacity or maybe number of innovation products. Doing it to all directions is more like diversification than specialization — avoiding the smart way to reach long term goals. The last implication is connected with universities and support organizations. Evolutionary innovation development requires stable acting and supporting the economy — rethinking of the meaning and purpose for both of them. The science at this stage is a large question mark in the region — collaboration with universities has stopped. It requires more specific data to offer anything new there. Continuity for support organization is more easy to program especially for the local funds. Strengthen them with more funds (credit loans and guarantee fund) should keep them to be more active in a long time at the regional level.

Conclusions

The research provided valuable information on the evolution of the regional innovation system in a catching-up country using the example of the Lower Silesia Voivodeship in Poland. The study was conducted during three periods: (1) dynamic development, (2) after the global financial crisis, and (3) after the Covid-19 pandemic. It shows the evolution of the regional innovation system in combination with disruptions from external shocks (second and third research periods).

The analyses take into account the Triple Helix model, which indicates that linkages between enterprises, science institutes and public administration play an important role in innovation systems. Linkages between enterprises are stable in the region and evolving. This applies to changes in cooperation with suppliers and customers (learning by cooperation) and the combination in enterprises of active creation of technology with its passive transfer (the growing competence effect). It means the slow change has been made and innovation maturity of enterprises in Lower Silesia is growing. Science institutes and business support institutions, as two another parts of the Triple Helix, are failing. There is a lack of continuity here. Their influence on the system is strong, but spotty. These two areas do not fit into the evolutionary trajectory and have been named as the "isolation effect." In contrast, companies themselves react and adapt to changing external market conditions (the adaptation effect).

In two areas, the regress of the innovation system has been noted. Although small and medium-sized companies are expected to pull up technological change over time, in Lower Silesia this role is being taken back by large companies (the flashback effect). The second area of backsliding in the system is the limited ability to raise external funds to finance innovation. With the time ticking and the presence of shocks, this factor has evolved from a non-obstacle to a real threat (the sinking effect).

This study makes an important contribution to the knowledge on the evolution of innovation systems in the context of the Triple Helix model. First of all, it is based on micro data collected by the authors, which constitutes a unique approach to the issue at hand. The 15-year research period made it possible to capture the realisation of the Triple Helix model in the period of prosperity after Poland's accession to the European Union and in the period of two economic crises: the global financial crisis and the Covid-19 pandemic. The analysis of these data in a long-term perspective made it possible to identify changes taking place in catching-up countries in the regional innovation system, taking into account the Triple Helix on the example of Poland. This allowed the identification of implications for innovation policy, which can be taken into account when building tools to support innovation in developing countries.

The analyses performed have their limitations. The region was described in three different time periods including crisis. It is not possible to tell separately which changes that took place are the effect of crises or the evolution. Both variables count here. It is only known what the regional innovation system looks like in three different time~~s~~ periods. More accurate would it be to check the continuity changes with full raw data, although another restrictions appear in such a situation. Another limitation for this research is the lack of a business support organization in the first time period (years 2004–2006) but two others include this variable. The matrix of success 0 and 1 cannot be validated here because too few fulfilled questionnaire were collected. About 200–250 would it be enough to make a more advanced prediction and validation of models.

Future research directions also emerge from the analysis. The study was conducted at a high level of generality — it looked at the behaviour of the system. Since it is difficult to find evolutionary regularities in the area of cooperation with scientific institutions or business support organizations, it is worth taking a closer look at the role they play in RIS in Lower Silesia. The identification of problems and gaps related to their functioning would allow for a more collegial formulation of tools for regional innovation policy.

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Annex

Table 1. Definition of the variables used in equations

Variables	Description
Dependent Variable	
TECH_INN_R&D	Nominal variable; 0: lack of innovation activity; 1: new technology due to R&D
TECH_INN_EQUIP	Nominal variable; 0: lack of innovation activity; 1: new technology due to equipment
Independent Variable	
Enterprises Attributes	
Equip_*inv*	Dummy variable; 1: new equipment and machinery investment; 0: otherwise
R&D_*inv*	Dummy variable; 1: R&D investment; 0: otherwise
R&D_*inhouse*	Dummy variable; 1: in house R&D investment; 0: otherwise
Sectoral and Science	
COOP_*sup*	Dummy variable; 1: inn. cooperation with supplier; 0: otherwise
COOP_*cus*	Dummy variable; 1: inn. cooperation with customer; 0: otherwise
COOP_*com*	Dummy variable; 1: inn. cooperation with competitor; 0: otherwise
COOP_*univ*	Dummy variable; 1: inn. cooperation within university; 0: otherwise
COOP_*PAS*	Dummy variable; 1: inn. cooperation within Polish Science Academy; 0: otherwise
COOP_*dom*	Dummy variable; 1: inn. cooperation within domestic R&D; 0: otherwise
Support System	
SUPP_*techinc*	Dummy variable; 1: cooperation with technology incubator; 0: otherwise
SUPP_*business*	Dummy variable; 1: cooperation with business incubator; 0: otherwise
SUPP_*businangel*	Dummy variable; 1: cooperation with business angel; 0: otherwise
SUPP_*traincentr*	Dummy variable; 1: cooperation with training and consulting centre; 0: otherwise
Source of the New Knowledge	
SOUR_*insid*	Dummy variable; 1: Source: inside the firm; 0: otherwise
SOUR_*maga*	Dummy variable; 1: Source: magazine and publication; 0: otherwise
SOUR_*cus*	Dummy variable; 1: Source: customer; 0: otherwise
SOUR_*assoc*	Dummy variable; 1: Source: scientific and technology association; 0: otherwise
Barier for Innovation	
BARR_*extfound*	Dummy variable; 1: Barrier: lack of external funding; 0: otherwise
BARR_*markknowl*	Dummy variable; 1: Barrier: lack of knowledge about the market need; 0: otherwise
BARR_*cooperation*	Dummy variable; 1: Barrier: cooperation issue; 0: otherwise
BARR_monopoly	Dummy variable; 1: Barrier: sort of monopoly market structure; 0: otherwise
Effect of innovation	
EFF_*mat*	Dummy variable; 1: reduction in materials and energy consumption; 0: otherwise
EFF_*num*	Dummy variable; 1: increasing the number of different products; 0: otherwise
EFF_*capa*	Dummy variable; 1: increasing production capacity; 0: otherwise
EFF_*mark*	Dummy variable; 1: entering a new market; 0: otherwise
EFF_*eco*	Dummy variable; 1: reducing harmful impact on the environment; 0: otherwise
EFF_*elasti*	Dummy variable; 1: strengthen production elasticity; 0: otherwise
EFF_*qual*	Dummy variable; 1: improvement in the quality of products; 0: otherwise

Table 1. Continued

Variables	Description
Control Variables	
SmallF	Dummy variable; 1: small firm; 0: otherwise
MediumF	Dummy variable; 1: medium firm; 0: otherwise
LargeF	Dummy variable; 1: large firm; 0: otherwise
Foreign_cap	Dummy variable; 1: foreign capital owner; 0: otherwise
Export	Dummy variable; 1: international sale range; 0: otherwise
DomMarket	Dummy variable; 1: domestic sale range; 0: otherwise
RegSale	Dummy variable; 1: regional sale range; 0: otherwise
Rev_drop	Dummy variable; 1: revenue – drop down; 0: otherwise
Rev_stab	Dummy variable; 1: revenue – stable; 0: otherwise
MLT_firm	Dummy variable; 1: medium low technology firm; 0: otherwise
MHT_firm	Dummy variable; 1: medium high technology firm; 0: otherwise
HT_firm	Dummy variable; 1: high technology firm; 0: otherwise
Age	Age of company (a natural logarithm)

Table 2. Results of the estimation of models depicting market-purchased ready-to-use production technologies and the creation of new production technologies as a result of R&D activities in Lower Silesian (years 2004–2006)

Variable	TECH_INN_EQUIP	TECH_INN_R&D
Age	0.8*	-
LargeF	2.24*	-
Foreign_cap	-	3.41***
R&D_*inv*	1.81***	-
COOP_*sup*	1.73**	3.03***
COOP_*cus*	1.64*	-
COOP_*univ*	-	5.28***
SOUR_*assoc*	0.27**	-
EFF_*num*	2.24***	-
EFF_*qual*	1.99***	-
EFF_*capa*	3.59***	2.93***
BARR_*extfound*	1.59**	-
BARR_*markknowl*	2.61**	-
Sample	492	492
Wald $\chi 2$	131.36	99.60
R^2 Cox–Snell	0.23	0.18
R^2 Nagelkerke	0.31	0.27
AUC	0.79	0.78
p-value	0.00	0.00
Hosmer–Lemeshow test		
Wald $\chi 2$	20.54	9.73
p-value	0.008	0.08

Note: (***) – statistical significance at 1%, (**) – statistical significance at 5%, (*) – statistical significance at 10%.

Source: Questionnaire research with our own calculation with Statistica 13.3 software.

Table 3. Matrix of case classification — the new technology related to equipment in Lower Silesia (years 2004–2006)

Real Belonging of Objects	Classification of Objects Based on the Logit Model		
	Predicted: 0	Predicted: 1	Correct (%)
Observed: 0	211	55	79.32
Observed: 1	72	154	68.14

Source: Our own calculation with Statistica 13.3 software.

Table 4. Matrix of case classification — the new technology related to R&D in Lower Silesia (years 2004–2006)

Real Belonging of Objects	Classification of Objects Based on the Logit Model		
	Predicted: 0	Predicted: 1	Correct (%)
Observed: 0	352	22	94.12
Observed: 1	84	34	28.81

Source: Our own calculation with Statistica 13.3 software.

Table 5. Results of the estimation of models depicting market-purchased ready-to-use production technologies and the creation of new production technologies as a result of R&D activities in Lower Silesia (years 2010–2012)

Variable	TECH_INN_EQUIP	TECH_INN_R&D
MLT_firm	-	1.78**
HT_firm	0.31**	-
SmallF	1.58**	-
MediumF	2.67***	-
Foreign_cap	-	3.14***
Rev_drop	0.54***	-
Rev_stab	-	0.57**
DomMarket	1.51**	-
R&D_*inv*	2.05***	-
Equip_*inv*	-	3.08***
COOP_*sup*	1.44*	-
COOP_*PAS*	4.29**	4.09**
COOP_*univ*	-	4.31***
SUPP_techinc	9.60***	-
SUPP_businangel	-	4.06*
SUPP_*traincentr*	-	1.60*
EFF_*num*	1.76***	-
EFF_*mark*	-	1.54*
EFF_*qual*	-	1.98**
EFF_*capa*	1.70**	-
EFF_*mat*	2.25**	3.04***
EFF_eco	-	2.17**
BARR_*extfound*	1.46*	-

Table 5. Continued

Variable	TECH_INN_EQUIP	TECH_INN_R&D
BARR_ *cooperation*	-	0.23***
BARR_*monopoly*	-	2.01*
Sample	761	761
Wald $\chi 2$	126.46	149.72
R^2 Cox–Snell	0.15	0.18
R^2 Nagelkerke	0.22	0.31
AUC	0.76	0.81
p-value	0.00	0.00
Hosmer–Lemeshow test		
Wald $\chi 2$	13.68	16.26
p-value	0.09	0.04

Note: (***) – statistical significance at 1%, (**) – statistical significance at 5%, (*) – statistical significance at 10%.

Source: Questionnaire research with our own calculation with Statistica 13.3 software.

Table 6. Matrix of case classification — the new technology related to equipment in Lower Silesia (years 2010–2012)

Real Belonging of Objects	Classification of Objects Based on the Logit Model		
	Predicted: 0	Predicted: 1	Correct (%)
Observed: 0	526	36	93.59
Observed: 1	145	54	27.14

Source: Our own calculation with Statistica 13.3 software.

Table 7. Matrix of case classification — the new technology related to R&D in Lower Silesia (years 2010–2012)

Real Belonging of Objects	Classification of Objects Based on the Logit Model		
	Predicted: 0	Predicted: 1	Correct (%)
Observed: 0	625	15	97.66
Observed: 1	87	34	28.10

Source: Our own calculation with Statistica 13.3 software.

Table 8. Results of the estimation of models depicting market-purchased ready-to-use production technologies and the creation of new production technologies as a result of R&D activities in Lower Silesia (years 2019–2021)

Variable	TECH_INN_EQUIP	TECH_INN_R&D
SmallF	-	1.85*
LargeF	2.87 **	3.96***
Foreign_cap	0.32*	-
Rev_stab	0.50**	-
RegSale	-	0.37**
R&D_*inhouse*	5.46***	-
Equip_*inv*	-	5.27***
COOP_*com*	-	0.15**
COOP_*cus*	2.62***	3.23***
COOP_*dom*	-	3.00*
SUPP_*business*	7.34	21.45**
SOUR_*inside*	0.49**	-
SOUR_*cus*	0.49**	-
SOUR_*mag*	2.61***	-
EFF_*num*	2.07***	4.40***
EFF_*elast*	-	2.30**
EFF_*capa*	2.77***	-
BARR_*extfound*	0.47**	-
Sample	396	396
Wald $\chi 2$	129.20	126.11
R^2 Cox–Snell	0.28	0.27
R^2 Nagelkerke	0.40	0.43
AUC	0.83	0.86
p-value	0.00	0.00
Hosmer–Lemeshow test		
Wald $\chi 2$	13.38	19.77
p-value	0.09	0.00

Note: (***) – statistical significance at 1%, (**) – statistical significance at 5%, (*) – statistical significance at 10%.

Source: Questionnaire research with our own calculation with Statistica 13.3 software.

Table 9. Matrix of case classification — the new technology related to equipment in Lower Silesia (years 2019–2021)

Real Belonging of Objects	Classification of Objects Based on the Logit Model		
	Predicted: 0	Predicted: 1	Correct (%)
Observed: 0	255	22	92.06
Observed: 1	51	66	56.41

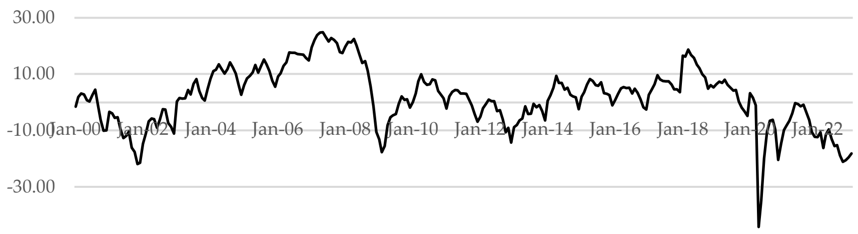
Source: Our own calculation with Statistica 13.3 software.

Table 10. Matrix of case classification — the new technology related to R&D in Lower Silesia (years 2019–2021)

Real Belonging of Objects	Classification of Objects Based on the Logit Model		
	Predicted: 0	**Predicted: 1**	**Correct (%)**
Observed: 0	308	8	97.47
Observed: 1	36	42	53.85

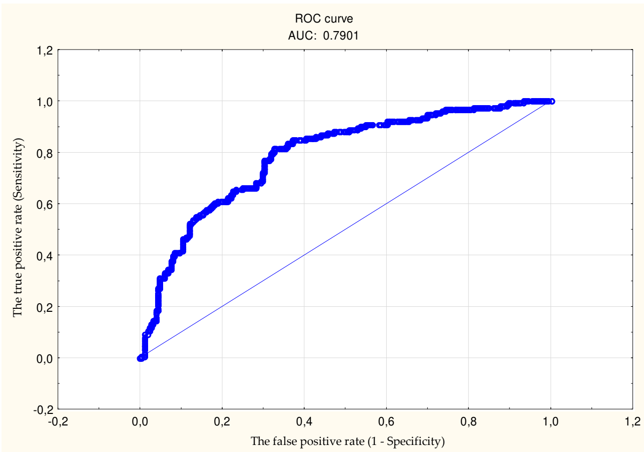
Source: Our own calculation with Statistica 13.3 software

Figure 1. Business cycle index for the Polish manufacturing industry in years 2000–2022



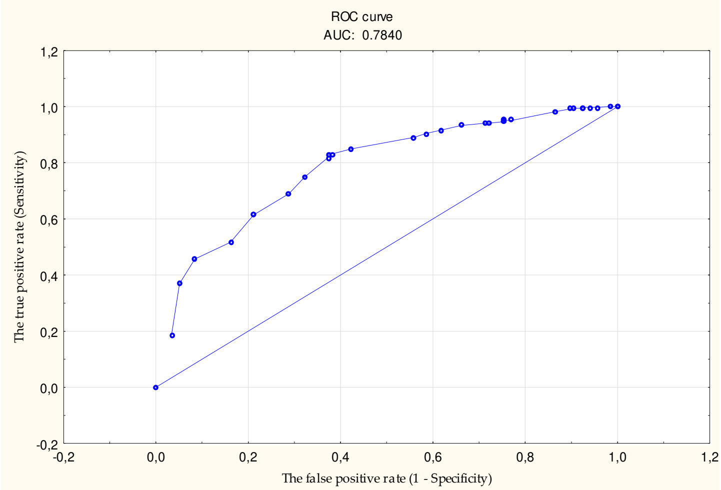
Source: Statistics Poland. Macroeconomic Data Bank, https://bdm.stat.gov.pl, 22.03.2023

Figure 2. Receiving Operation Curve (ROC) for a new technology related to equipment change in Lower Silesia (years 2004–2006)



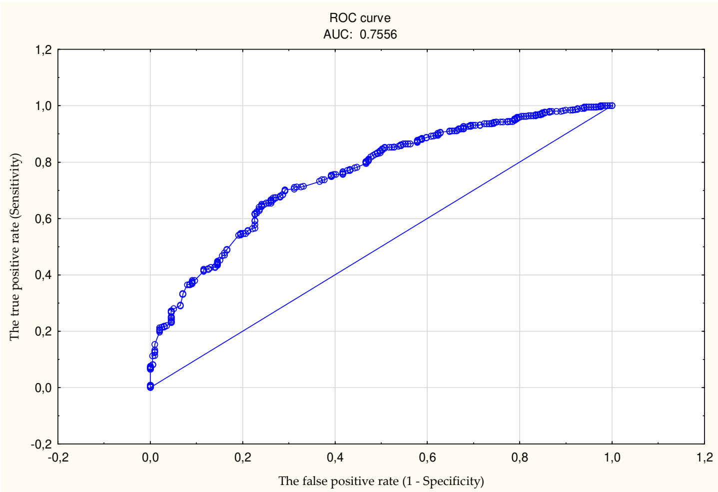
Source: Our own calculation with Statistica 13.3 software.

Figure 3. Receiving Operation Curve (ROC) for a new technology related to R&D in Lower Silesia (years 2004–2006)



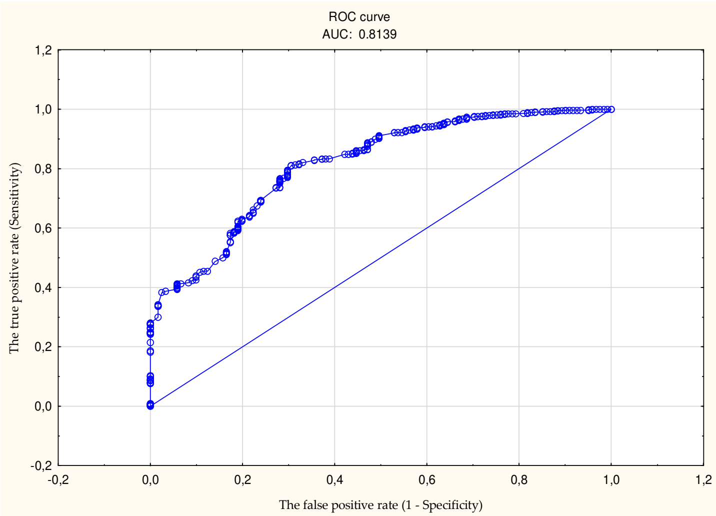
Source: Our own calculation with Statistica 13.3 software.

Figure 4. Receiving Operation Curve (ROC) for a new technology related to equipment change in Lower Silesia (years 2010–2012)



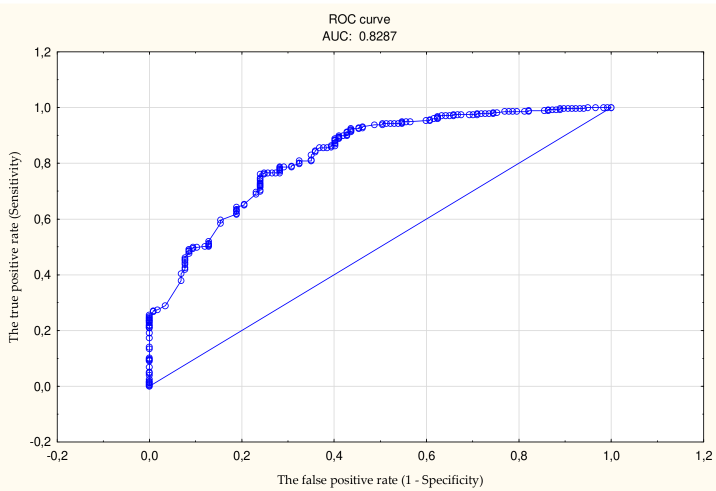
Source: Our own calculation with Statistica 13.3 software.

Figure 5. Receiving Operation Curve (ROC) for a new technology related to R&D in Lower Silesia (years 2010–2012)



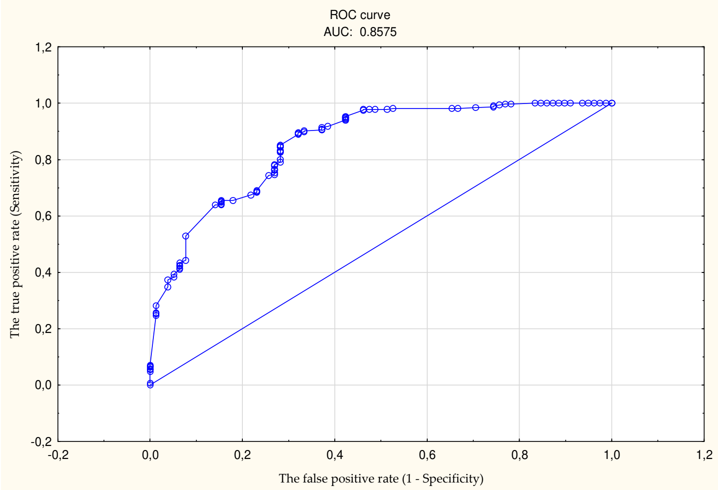
Source: Our own calculation with Statistica 13.3 software.

Figure 6. Receiving Operation Curve (ROC) for a new technology related to equipment change in Lower Silesia (years 2019–2021)



Source: Our own calculation with Statistica 13.3 software.

Figure 7. Receiving Operation Curve (ROC) for a new technology related to R&D in Lower Silesia (years 2019–2021)



Source: Our own calculation with Statistica 13.3 software.