Aigerim Anvarbek Kyzy*

IMPACT OF TECHNOLOGICAL PROGRESS ON ECONOMIC GROWTH IN DEVELOPED COUNTRIES. ACCOUNTING FOR MODEL UNCERTAINTY AND REVERSE CAUSALITY

DOI: 10.26399/meip.1(68).2020.03/a.a.kyzy

Introduction

Modern economics has been shaped by the evolution of many theories that have been proven through various studies of many great minds. One of such great minds, Adam Smith, marked the beginning of the contemporary theory of economic growth. Robert Solow[1] and Trevor Swan[2], who independently introduced neoclassical growth models, were pioneers in this area. Physical capital accumulation was the key mechanism of both models. Assuming the existence of an additional production factor, such as knowledge that is embedded in technological progress and human capital, Solow-Swan models present the most straightforward way of interpreting the growth of per capita output. They assume technological progress as an exogenous factor. In the 1980s endogenous growth theories began their formalisation. Such theories emerged as a response to the criticism of previously mentioned exogenous

* Aigerim Anvarbek Kyzy – Masters Student in Lazarski University, e-mail: aigerimanvar@gmail.com

1 R. Solow, *A Contribution to the Theory of Economic Growth*, “The Quarterly Journal of Economics”, Vol. 70, No. 1, 1956, pp. 65–94.

2 T. Swan, *Economic growth and capital accumulation*, “Economic Record”, Vol. 32, Issue 2, 1956.

growth theories. Romer[3] made the first attempts at endogenising technological progress. In endogenous growth models, the microeconomic basis is used to construct macroeconomic models by looking at the determinants of savings and technological development. In other words, in such models, economic growth results from endogenous mechanisms. The key impact of endogenous growth models is that economic policies such as trade openness, free competition and innovation advancement might have a positive effect on economic growth. Joseph Schumpeter referred to innovation as the "leading engine for economic growth"[4]. According to a generally accepted definition of innovation, it is the introduction of new ways to do things, including new organisational structures as well as new products and processes. Innovation can contribute to an increase in productivity, as the application of technology could lead to more effective use of productive resources. Those countries and firms that innovate demonstrate higher productivity of labour than those that do not. Many authors claim that growth emerges evenly neither between different sectors nor in the same sector. However, it arises in combination with new technologies. Olivier Blanchard noted that the role of technological progress is of utmost importance for long-term economic growth[5]. Such a point of view is commonly shared, but there is no determined way of taking such factors into consideration while constructing a model. Technological progress is generally presented as a result of research and development (R&D) activities as well as intellectual property. R&D involves activities made by the company that will contribute to product enhancement or innovative production methods. It leads to the increase in productivity of firms and, accordingly, to the growth of the economy. Using R&D activities, governments and corporations design new products and services or improve the existing ones. In other words, technological development emerges from deliberate human activity aimed at new technological alternatives that boost manufacturing effectiveness. When new products and services are created and developed, it is intellectual property's turn represented by patent applications. The value of intellectual property in stimulating economic growth is demonstrated by empirical evidence. Innovation and technological progress should be encouraged because nowadays, they have become

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[3] P.M. Romer, *Increasing Returns and Long-Run Growth*, "Journal of Political Economy", Vol. 94, No. 5, 1986, pp. 1002–1037.

[4] J.A. Schumpeter, *Economic theory and entrepreneurial history*, Change and the entrepreneur: postulates and the patterns for entrepreneurial history, Research Center in Entrepreneurial History, Harvard University Press, Cambridge, Massachusetts 1949.

[5] O. Blanchard, *Macroeconomics*, 7th edition, Pearson, Boston 2017.

a powerful source of economic growth. However, accurately quantifying innovation and its outcomes is not an easy task because the outcomes of innovation can take the form of many distinct intangibles. Accordingly, it is essential to rely on indirect determinants of innovation, such as expenditure on R&D, R&D personnel and patent applications. These three things are the most commonly recognized factors of the level of innovativeness according to the literature on technological innovation. Some countries were initially backward and managed to defy the trend at different times by narrowing the productivity and income gap between themselves and the frontier market countries. Some examples are Finland, South Korea, Singapore, Japan and Israel. These countries that successfully caught up on economic growth and became developed countries are in top rankings of the world's most innovative economies, according to WIPO[6]. Economic growth is explained by a huge number of different theories, which can be compatible with each other, and such a situation can lead to model uncertainty. As a result of the model uncertainty emergence, various combinations of growth theories indicate valid specifications for the growth model. Many researchers adopted a Bayesian Model Averaging (BMA) in order to avoid model uncertainty. Though, most BMA methods have been designed for specific samples of countries assuming exogenous determinants of development. Consequently, another issue, such as the endogeneity of growth determinants arises. Such a dual problem can be solved by the combination of BMA methods and appropriate likelihood function for panel data models with weakly exogenous regressors and fixed effects[7]. This econometric methodology is used in this work, applied to a panel of developed countries over the period 1973–2017. This paper aims to demonstrate the significance of measures of technological development on economic growth and to find out whether expenditure on R&D has the strongest effect on economic growth in developed countries. Accordingly, there are hypotheses that: firstly, technological progress has a positive impact on the growth of the economy, and secondly, expenditure on R&D as a determinant of technological development has the strongest impact on economic growth. Empirical research is an essential part of this work. Based on the availability of data, an analysis of 19 developed countries in 1982–2017 was performed. Growth regressions using panel BMA under

6 World Intelectual Property Organization, *World Intellectual Property Indicators 2016*, https://www.wipo.int/edocs/pubdocs/en/wipo_pub_941_2016.pdf, accessed 10.02.2020.

7 E. Moral-Benito, *Growth Empirics in Panel Data Under Model Uncertainty and Weak Exogeneity*, "Journal of Applied Econometrics", Vol. 31, No. 3, 2016, pp. 584–602.

weak exogeneity is conducted in order to discover the statistical correlation of economic growth and determinants of technological development.

The first part of this article presents the evolution of the theory of economic growth and the role of technological innovation during that process. The second part of this paper provides the interpretation of technological innovation, including the specifics of the innovation process, identification of determinants of technological development and the appropriability of research results. The third part provides the analysis of the role of market structure in stimulating technological innovation. The fourth part contains various empirical studies, which were conducted in order to find the statistical correlation between technological innovation and economic growth both at a firm and country levels in developed, developing and least developed countries. The fifth part presents the empirical part of this work, including data description, econometric analysis and the description of the results obtained.

1.Theoretical background

1.1. Economic growth theory

In every country, one of the main objectives of all programmes is to achieve a high standard of living, which is a determinant of happiness and well-being of citizens. The primary factor of the standard of life is sustained by economic growth. As claimed by Snowdon and Vane,

> "there is no more important issue challenging the research efforts of economists than to understand the causes of economic growth"[8].

Hence, economists investigate factors that determine the long-run growth of an economy, such as human resources, natural resources, capital formation, technological development, and social and political factors.

1.1.1. Solow growth model

Robert Solow developed a model that explains long-run economic growth using the key physical inputs in the production process, such as labour and capital, together with technological progress, which was assumed to increase

[8] B. Snowdon, H.R. Vane, *Modern Macroeconomics: Its Origins, Development, and Current State*, Northampton, Massachusetts 2005.

productivity. This model is known as “Solow growth model”, and the aggregate production function is used, showing the relation between the level of output and the levels of various inputs such as capital, labour and technological progress as an exogenous variable over time. According to the model, there was only one commodity, that is overall output, and the economy was closed. The production function used by Solow:

$$Y = A_t F(K, L) \tag{1}$$

Where Y denotes output, K and L represent capital and labour, while the term A_t implies technological change and is supposed to depend merely on time, demonstrating that by the time more will be produced with a given quantity of both capital and labour due to technological progress. In the production function mentioned above the technological change, A_t, is shown outside production function. The reason is that Solow took technological change as an exogenous variable; in other words, it is derived externally. The technological change, the source of long-term economic growth in the model, was not explained by Solow, but was merely assumed[9]. The neoclassical growth model concludes that the economic growth by the capital accumulation leads to only temporary growth, because of diminishing returns, as the rate of population growth, and the readiness of people to save limit the output rise, without technological progress. Hence, according to Snowdon and Vane to keep sustainable and steady long-term growth of output, the model incorporated the influence of technological development. Nevertheless, the model did not exclude a contribution of savings and investment to capital formation but predicted that savings and investment would affect the short-term economic growth rate, rather than the long-term one. Solow performed a significant calculation to show the sources of economic growth over a certain period by examining the United States economic data from 1909 to 1949. Using his theoretical structure, he extracted a portion of economic growth, which was due to more wealth accumulated per person from the advanced technology. In the modern study of economics, these were the first calculations of national growth. Outcomes of calculations showed that technological progress accounted for seven-eighths of the growth of the U.S. economy, while the capital stock increase accounted for only one-eighth of

[9] J. McArthur, J.D. Sachs, *Growth Competitiveness Index: Measuring Technological Advancement and the Stages of Development*, Global Competitiveness Report 2001–2002, Oxford University Press for the World Economic Forum, New York 2002.

the growth per capita income. Solow's theoretical suggestion of his model in which technological progress was the main driver of economic growth, in the long run, was supported by his empirical evaluations.

Solow's works contained an important message that technological innovation must be understood in order to understand long-term economic growth. However, his growth models present a technical challenge because the process of technological change is not interpreted. Solow's followers focused on savings and investment as the primary feature of economic growth instead of studying the sources of long-term technological change. The Solow model was criticized by Snowdon, because technological progress cannot be incorporated as a public good, as all countries have a different level of development, in other words, the availability of technology is different in, for instance, developing and developed countries. The production function in a growth model was showing mixed results for varying levels of capital per worker ratios.

The Solow model is the first model that introduced convergence. It predicts that economies converge to their steady state equilibrium in the long run[10]. The model implies that the differences in productivity of workers depend on the country's position. Hence, poorer countries shall grow faster and eventually catch-up with more prosperous countries. Moreover, as countries with a higher ratio of capital per worker have a lower rate of return, capital is assumed to flow from richer countries to poorer ones until rates of return of two countries counterbalance and lead to convergence. Though, access to more productive technology could accelerate the rate of convergence. However, Paul Romer indicated that such a hypothesis that states that economies with low income per capita tend to grow faster than economies with high income per capita is inconsistent with the cross-country evidence.

1.1.2. Romer growth model

Romer was the first economist to clearly express the problem of non-convergence of per capita incomes in different economies. Instead of modifying the Solow model, Romer presented a new, endogenous theory of growth without steady-state income level and with an increase in growth rates over time as well as indefinite income per capita differentials between countries. Technological change is "endogenous" in this theory; in other words, it can depend on the growth of population and accumulation of

[10] K. Beck, M. Grodzicki, *Konwergencja realna i synchronizacja cykli koniunkturalnych w Unii Europejskiej,* Wymiar strukturalny, Wydawnictwo Naukowe SCHOLAR, Warszawa 2014.

capital. Moreover, Romer's theory binds the creation and development of new ideas, which can increase productivity as well as output, with the number of workers in that area. Hence, an increase in the number of workers in the knowledge sector will lead to economic growth increase.

Furthermore, Romer mentions that the creation of knowledge has positive externalities because as knowledge is generated, it can be freely used, and everyone can benefit from that knowledge. The spillover effect becomes stronger, as ideas develop, and knowledge is created; this affects the economy generating increasing returns. Paul Romer's works are among the first ones to attempt mentioning such issues; however, his assumptions, such as increasing returns were too far from reality. The reason was that both a degree of monopoly power and externality are involved in a market solution, an inefficient outcome is generated. As a result, technological change will not be produced efficiently in unregulated markets.

Romer commented that the Solow model "takes as given the behavior of the variable that it identifies as the main driving force of growth". Solow claims that the technological progress was taken as an exogenous variable to simplify the model and because he did not know how to model it. Although, as claimed by Snowdon and Vane, the technical development was not explained within the model, in the analysis of economic growth, it was highlighted as a significant explanatory factor.

1.1.3. Production function

The most widely used neoclassical production function is the Cobb--Douglas production function as follows:

$$Y = A_t K^{\alpha} L^{1-\alpha} \alpha \varepsilon \{0,1\} \quad (2)$$

Here α and $1-\alpha$ are representing the share of capital and income in national income. Each component of this production function can be divided by labour to see the relation between output per worker and capital per labour with a given technology:

$$Y/L = A(t_0)(K/L) = A(t_0)K^{\alpha}L^{1-\alpha}/L = A(t_0) \quad (3)$$

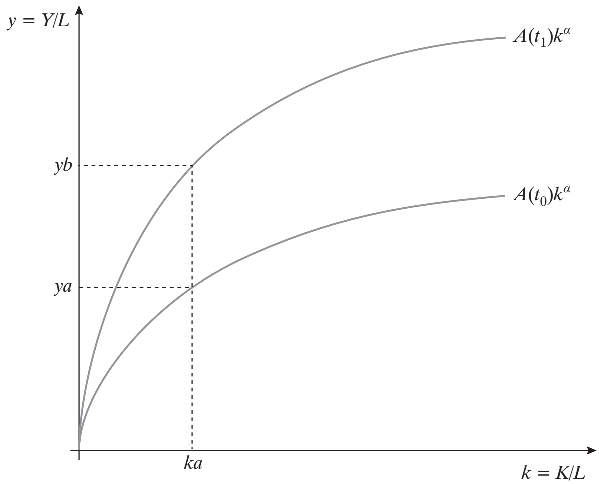
With output per worker, Y/L, denoted as y and capital-labour ratio, K/L, denoted as k it gives the following equation:

$$y = A(t_0)k^{\alpha} \quad (4)$$

According to the previus page-mentioned equation, with a given technological change, an increase in capital per labour will cause an increase in output per worker. While exogenous technological progress from period 0 to period 1 will shift the production function upwards, increasing production per labour, as shown in the graph below.

Figure 1

Technological Progress



Source: B. Snowdon, H.R. Vane, *Modern Macroeconomics...*, *op. cit.*

According to a neoclassical definition, technical progress is an autonomous phenomenon that causes the aggregate production function to shift upwards, bringing a higher level of output for each different level of capital per labour. This is demonstrated in Figure 1.

Classical economists such as David Ricardo and John Stuart Mill had a fear of ‘stationary state' of the economy. They supposed that as capital stock continuously increases, the economy will come to a steady state, meaning that beyond that point, the growth of an economy would stop. This fear was justified at the time because, in research on economic growth technological progress, that could postpone the steady state of the economy, was not considered by economists in their studies.

Technological progress is a significant factor in determining the pace of economic growth. It provides a long-term and sustainable rate of change. According to studies of many economists, it cannot only accumulate capital, but it plays a significant role in increasing long-term output. Technological progress can lead to increased productivity of labour, capital, and other resources through the discovery of new and improved methods of goods production. It increases total factor productivity (TFP) that is combined productivity of all inputs. The primary outcome of technological progress is that more goods can be produced with a given amount of resources or the given number of products can be produced with fewer resources used. Technology is the leading force of efficient allocation of capital and labour in the economy. Higher output can be the result of a technological boom in different types of industries[11].

2. Technological innovation

Technological innovation is a major driving force of economic growth and human advancement; however, in technology policy discussions today, this input is often lost or undervalued. The key feature of productivity growth is to do more with less, and as an increasing number of products and services are produced with the same or less manufacturing input than was needed in the past, productivity growth increases citizens' living standards in the long run. Moreover, productivity growth and economic growth are inseparable, while productivity growth also has a strong connection with the process of the creation of new knowledge[12]. Consequently, the process of knowledge production is mostly the focus of research on the determinants of economic growth. Romer launched a genuine growth industry with his idea that knowledge is not consistent with the standard assumptions of decreasing returns, but rather shows increasing returns. Briefly, knowledge is a public good that can be used by producers without diminishing the accessibility to others. In other words, this means that it is often non-excludable, meaning that once knowledge exists, it is freely available to everybody to use, and non-rivalrous, meaning that one person's ability to use knowledge does not hinder another person's ability to use it. Thus, the fact that those who invest nothing in knowledge discovery can easily get a "free ride" on other people's inventiveness can demotivate innovators when they cannot capture all the benefits of their inventions. A key reason for patent protection to secure inventors is the non-exclusive nature of technology. Indeed, innovation should also, to a certain extent, be excluded. Otherwise, companies would have little incentive to invest in innovations.

11 O. Blanchard, *Macroeconomics*, *op. cit.*

12 B. Égert, *Regulation, Institutions, and Productivity: New Macroeconomic Evidence from OECD Countries*, "American Economic Review Papers & Proceedings", No. 5, 2016, p. 106.

2.1. Specifics of innovation process and technological development

Innovation is one of the most widespread terms in today's world; however, what it means precisely can be vague. One determination is that innovation is an implemented novation that provides a qualitative increase in the efficiency of processes or products demanded by the market. It is the outcome of human intellectual activity, imagination, creative process, discoveries, inventions and rationalization. In other words, innovation is

> "the development and widespread adoption of new kinds of products, production processes, services, and business and organizational models"[13].

The concept of "innovation" was developed at the beginning of the 20th century in the scientific works of the Austrian and American economist Joseph Schumpeter as a result of the analysis of "innovative combinations" and changes in the development of economic systems. Schumpeter was one of the first scientists who introduced this term into scientific use in economics. According to Schumpeter,

> "innovation can be defined as a series of interactions starting from an idea of innovation ending with its implementation and popularization, the aim of which is a change in a product, technology, and society"[14].

Innovation is not only the introduction of a new product as a final result but all preceding activities, such as an idea, research and development, design, production, marketing, and popularization. Moreover, innovations can be referred to as the process of learning and accumulating knowledge. Such factors as technological progress, expectations of goods and services, customers and competition on markets significantly influence innovation development.

According to Porter[15], innovativeness and competitiveness are closely connected, because the wealth of the nation is elaborated by generations rather than inherited as natural resources, labour force potential or the value of a currency. Porter claims the economic development of a specific

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13 R.D. Atkinson, S.J. Ezell, *Innovation Economics: The Race for Global Advantage*, Yale University Press, New Haven 2012, p. 8.

14 J.A. Schumpeter, *Economic theory...*, *op. cit.*

15 M.E. Porter, *The Competitive Advantage of Nations*, "Harvard Business Review", 1990, pp. 73–91.

country depends on the implementation of innovations. In other words, the ability of societies to create and accumulate knowledge to introduce innovations influences the country's competitiveness. In Porter's opinion, high innovativeness level of a country directly affects the high living standards of its citizens[16]. Economic growth is a measure of the general well-being of the citizens of a particular country. A country's gross domestic product (GDP) and its annual rate of increase are used as a unit of measurement. Such economists as Schumpeter, Solow, Romer, Acemoglu[17], Aghion and Howitt[18], and others have studied factors contributing to economic growth. They have shown that economic growth cannot be explained only by the increase in factors of production, such as capital and labour. "Technical progress" referred to by Solow claims that GDP per capita cannot grow in the long run without an assumption that productivity also grows. Innovation-based models have been established to explain the growth of the economy. Romer introduced one model, according to which innovation leads to productivity growth, because of the creation of new varieties of products, not necessarily improved ones while Aghion and Howitt presented another model that is based on "quality improving innovations that render old products obsolete". Technological progress can be defined as a technical change, that is any technology invented, adopted and improved that improves quality of life and advances the well-being of societies. Technological progress is claimed to be the fundamental force of the long-term increase of a country's welfare, demonstrated in the work of Solow and Swan in the 1950s. According to them, the contribution of factors of production, such as capital and labour, is temporary. According to the Solow-Swan standard model, labour productivity grows either through factor accumulation, that is an addition of more units of capital per worker, or through technological progress. David Ricardo's law of diminishing returns to capital holds that incremental increase in capital amount, while the number of workers stays unchanged, leads to declining increases in output per worker. In such a case, investment becomes less attractive. So, technology progress rather than capital deepening can sustain the growth of the production per worker over the long-term offsetting diminishing returns on capital, as demonstrated in the Solow-Swan model.

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16 M.E. Porter, *The Competitive...*, *op. cit.*

17 D. Acemoglu, *Introduction to Modern Economic Growth*, Department of Economics, Massachusetts Institute of Technology, Cambridge 2009.

18 P. Aghion, P. Howitt, *The Economics of Growth*, The MIT Press, Cambridge 2009.

2.2. Features of the innovation process

As innovation is science-based, higher education is of great importance as a fundamental feature of a country's innovation strategy[19]. There is no higher education anywhere in the globe without significant government investment. Investing in science is crucial for technological growth, which leads to economic growth. For instance, the United States, the country with one of the biggest economies worldwide, is heavily investing in basic science through the federal budget. According to Sachs and McArthur, the government budget of the United States for science is nearly 90 billion USD per year or approximately 1% of GDP. Furthermore, as Adam Smith emphasized the division of labour; innovation relies on market-based incentives, especially on the extent to which the market itself is involved. Paul Romer and others emphasized the importance of the market scope for the promotion of innovation. Development of a new idea requires considerable R&D investment, and subsequent sales must recover this fixed cost of innovation. When the potential market for innovation is large, recovering R&D costs is obviously easier. However, high R&D expenses are not justified in a small market. That is one reason why being an open economy is important. An export-oriented economy has the entire world as a potential market, while a closed economy has a limited domestic market having no incentives for innovation and failing to get new ideas from outside. Besides, the innovation process has a basically mixed public and private good nature. A core feature of knowledge is what economists call "non-rivalrous", which implies that the first individual is unable to lose the idea if he discovers a new idea and shares it with others. Ideas are the kind of commodity the use of which by one individual does not imply that it is less accessible for others. Everyone can participate in advancing knowledge without depriving others of the knowledge. Accordingly, the extensive diffusion of ideas benefits society. In order to achieve this, knowledge-based economies strive to distribute fundamental scientific knowledge, new mathematical theorems and the like freely and widely.

The U.S. has a rather efficient patent system, although, now it is a stressed one. Once an inventor files a patent, in exchange for the monopoly privileges of the patent, he or she must reveal in detail what the invention entails. This

[19] D.J. Sachs, J.W. McArthur, *Technological Advancement and Long-Term Economic Growth in Asia*, Technology and the New Economy, [in:] Ch. En Bai, Ch.-W. Yuen (eds.) (emphasis in original), MIT Press, Cambridge 2002, p. 160.

is incredibly crucial when making the knowledge accessible to the public. Also, the system is efficient in processing a vast number of patents, far more than 150,000 annually. After the patent is granted, the judicial system has significant competence to protect intellectual property. Nevertheless, the system is under tremendous stress connected with the suitable patenting scope, the definition of new patent limits and the sheer quantity of new patent applications to be processed.

Moreover, the temporary monopoly rights given to an invention by a patent also encourage discoverers. Patents provide the inventor with financial benefits for a given period but restrict other people's capacity to use the knowledge in society. Patents are restricted to specific new technologies and are granted for a limited period, so that knowledge can subsequently be freely used across society. The cost of permanent monopoly rights would be too high in slowing the spread of new ideas. In the meantime, governments are supporting fundamental scientific discovery by directly subsidizing main research at universities, public research laboratories, and even private firms qualifying for public grants.

2.3. Determinants of technological development

As the rate of technological growth determines the rate of economic growth, it is crucial to know its determinants; in other words, it is essential to understand what affects the technical process. Olivier Blanchard argues that significant discoveries are guided and operated by scientific research and chance rather than any economic forces. Hence, in modern economies, the technological process is generated by a trivial method of research and development practice. Private firms and governments allocate considerable resources to applied research and development, and gradual accumulation of production experience results in economically valuable ideas. R&D is a significant source of technical change as it results in new goods, new processes and new knowledge. R&D activities fundamentally affect the innovation process, and innovation is an essential factor that influences productivity, productivity growth, and competitiveness.

In developed countries with a strong economy, such as the United States, the United Kingdom or Japan, the expenditure on research and development varies between two and three per cent of GDP. Most of the U.S. researchers in the R&D area are working for firms, as every firm wants to increase its chances to discover or develop a new product that will increase its profit.

Spending on R&D is different from investing in machines in the sense that many other firms can use an idea. Hence, this idea must be somehow protected. Accordingly, not only the creation of an idea but also the extent to which a firm benefits from that idea, called appropriability, is essential.

Cavdar and Aydin claimed in their work that fiscal and monetary policies could create only a short-term increase in GDP, while technological progress can lead to the long-term and sustainable growth. Scientific innovation resources have a significant impact on the economic development of a country. Consequently, to maintain their competitiveness, countries must acquire and efficiently use technologies in the production process. These technologies are further developed by means of undertaking the research and development (R&D) activities by corporations or government and by improving services or products or developing new ones. In general, companies prefer technology transfer, because R&D is considered an expensive, risky and time-consuming activity. According to Cavdar, such companies suppose they can accomplish their "technological capacity, knowledge generation, diffusion and application"[20] at a moderate cost, more efficiently, and with less risk. However, technology transfer is not enough to sustain the company's competitiveness, which can be gained only by reaching a sufficient level of investments in technology and innovation. A statement regarding a positive impact of innovation on economic growth is widely recognised. Gurbiel states that in today's world economy innovation is one of the critical drivers of economic growth. Consequently,

> "an appropriate economic policy should concentrate on strengthening these processes throughout the country and easing the flow of information and technology between the main players – innovators, companies, state agencies, and financial institutions"[21].

Furthermore, Cavdar and Aydin noted the importance of the role science and technology (S&T) played in stimulating economic growth, supporting this statement by the variety of the works of literature identifying this fact. S&T indicators were presented in two distinguished groups: input ones as resources and output ones as a performance. The input indicators are divided into financial and human resources. A financial contribution is indicated

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[20] C. Cavdar, S. Aydin, *Understanding the Factors Behind Current Account Deficit Problem: A Panel Logit Approach on 16 OECD Member Countries*, "Procedia Economics and Finance", 2015.

[21] R. Gurbiel, *Impact of Innovation and Technology Transfer on Economic Growth: The Central and Eastern Europe Experience*, 2002.

by R&D spending as a percentage of GDP, which in general is used for evaluating and comparing technological progress in different countries. And the number of science and technology graduates and the number of researchers employed in R&D indicate human resources. On the other hand, there are output indicators classified by economic, technological and scientific indicators. An indicator of an economy is a share of high-tech exports in total exports of a country. Patents and patent applications measure technological development while research publications indicate a scientific technology output.

The role of innovation is expressed by the level of spending on R&D across different countries around the world. Even though R&D expenditure is frequently used as a determinant of innovation, generally, it is perceived as an imperfect determinant of innovation. The research can be fertile in case the expenditure on R&D leads to the creation of many new products. In such a case, firms will spend even more on R&D, increasing the rate of technological progress. This fertility of research is a result of fruitful interaction between basic research and applied research and development. These two types of investigations highly depend on one another as basic research cannot lead to technological progress on its own, while applied research and development ultimately depend on the basic one. The process of successful technology adaptation to a county's conditions and distribution across companies and sectors is necessary for productive transformation. Indeed, some of the nations with the most significant success in accelerating economic growth, such as Finland, Israel, and South Korea, are world leaders in R&D[22]. Many authors tried to find out what the relation between IP and the speed of technological growth is, in other words, whether the protection of inventions from their usage without permission accelerates or slows down technological growth. IP is the primary element for the development of a product and a crucial determinant of investment decisions. The most broadly used measures of innovation output, patents, are one form of IP. An organisation or a country that protects IP encourages R&D investments stimulating technological innovation, which is a critical element of competitive maintenance. Kaplan and Norton[23] believe that IP plays a fundamental role in business performance and economic growth in

[22] D. Prieto, F.R. Zolessi, *Functional Diversification of the Four MARCKS Family Members in Zebrafish Neural Development*, "Journal of experimental zoology", Part B, Molecular and developmental evolution, No. 1, 2017, pp. 119–138.

[23] R.S. Kaplan, D.P. Norton, *Strategy Maps: Converting Intangible Assets into Tangible Outcomes*, Harvard Business School Press, Boston 2004.

knowledge-based economies. Investment in R&D has generally been viewed as one of the primary methods for securing technological progress and, thus, innovation and economic development. Moreover, it improves the chance of attaining a greater technology level in companies and areas, enabling them to implement new and superior goods and processes, leading to higher earnings and growth rates.

The pioneers of the Endogenous Growth Model, Romer and Lichtenberg, indicated that the connection between investment in technology and spending on R&D contributes to increased productivity and, thus, growth[24]. Many studies attempt to clarify the relationship between investment in R&D and growth. In his article, Hall demonstrated that expenditure on R&D is positively correlated with the productivity and profitability of businesses, and producing a comparatively high private rate of return[25]. Furthermore, by using the Generalized Moment Method (GMM) and panel data from a study of 23 countries between 1992 and 2004, Sadraoui and Zina[26] examined the dynamic relationship between R&D activities and economic development. Results proposed a positive and strong relationship between R&D activities and economic development for all analysed nations. Ulku[27] explored the impact of innovation on per capita outputs both in developing and developed countries. She examined data on patents and research and development for 20 OECD countries and 10 non-OECD countries from 1981 to 1997. According to the outcomes, there is a positive correlation between per capita GDP and innovation in both OECD and non-OECD nations, whereas the impact of R&D stocks on innovation is only significant in large market OECD nations. Zachariadis indicated that R&D activities lead to patenting, patenting to technological progress, and technological development to economic growth[28]. He used annual patent statistics, spending on R&D, gross production, and an increase in productivity. His empirical research findings showed that

[24] More about the subject in K. Beck, *Determinants of Intra-Industry Trade: An Investigation with BMA for the European Union*, [in:] CBU International Conference. Innovation in Science and Education, 2018, DOI: 10.12955/cbup.v6.1131.

[25] B.H. Hall, J. Mairess, *Empirical Studies of Innovation in the Knowledge-Driven Economy*, National Bureau of Economic Research, Cambridge, Massachusetts 2006.

[26] T. Sadraoui, N.B. Zina, *Dynamic panel data analysis for R&D cooperation and growth*, "International Journal of Foresight and Innovation Policy", Vol. 5, No. 4, 2009, pp. 218–233.

[27] H. Ulku, *R&D, Innovation, and Economic Growth: An Empirical Analysis*, International Monetary Fund, 2004.

[28] M. Zachariadis, *R&D, innovation, and technological progress: a test of the Schumpeterian framework without scale effects*, Department of Economics, Oklahoma State University, Stillwater 2003.

spending on R&D, patenting, and productivity have a positive correlation. Another significant proxy for measuring innovation is patent data. Schmookler[29] carried out a thorough examination of the use of patent data and discovered that patent data are data corresponding to significant inventions. It would be adequate to consider patent statistics simply as an indicator of the number of inventions in various areas and periods produced for the private economy. Nevertheless, there are some other studies not showing a significant relationship between patent data and GDP. Employees of R&D department constitute another essential determinant of technological innovation. Researchers are the key component of the R&D processes. Griffith et al.[30] define researchers as specialists involved in the designing and development of new knowledge, products, processes, methods and systems. Romer discovers a positive correlation between the number of R&D professionals and the growth rate of productivity in a sample of most developed economies. Furthermore, some other research by Pianta[31] demonstrated that innovation has a positive effect on production and employment. This positive effect is due to the potential of new equipment, new products, lower prices, higher revenues and investment, greater productivity, impacts on revenue and general demand development. The author also accentuates that, among developed countries, the ones having the highest rates of investment and innovation showed higher growth of production and employment. According to previous studies, expenditure on R&D, the number of patents and the number of scientists and engineers in R&D departments are the measuring tools for the intensity of innovation. Especially in knowledge-based economies, IP plays a fundamental role in the decisions to invest in innovation.

2.4. Appropriability of research results

Another determinant of R&D and technological progress level is the degree of appropriability of research results. Appropriability refers to various means that an economic agent can use to profit from his inventions or innovations, temporarily having some monopoly power over the knowledge that he

[29] J. Schmookler, *Invention and Economic Growth*, 1st ed., Harvard University Press, Cambridge, Massachusetts 1966.

[30] R. Griffith, S. Redding, J. Reenen, *Mapping the Two Faces of R&D: Productivity Growth in a Panel of OECD Industries*, “The Review of Economics and Statistics”, 86 (4), 2004, pp. 883–895.

[31] R.C. Pianta, *Enhancing relationships between teachers and children*, American Psychological Association, Washington 1998.

creates[32]. There are appropriability mechanisms, such as intellectual property rights (IPRs), including patents, copyright, trademarks, industrial design, utility models and plant breeders' rights. For innovators, "those firms which are first to commercialize a new product or process in the market"[33], the legal protection given to the new product is very important; the firm cannot obtain significant returns without such protection. Competitor or imitator firms can have more profit than the innovator firm by producing the same product. Many sciences and engineering-based companies mistakenly believe that developing new products that meet customer needs will lead to a big success; however, this success will be for a product rather than for the innovator. This situation demonstrates that being first to market is not a source of strategic advantage. Intellectual property rights grant inventors a temporary monopoly on the use of their ideas; hence, they attempt to balance between the way to reward successful research with the social benefits and the widespread adoption of good intentions. Blanchard claimed that patents are the optimal way to protect a new product, as they give an innovator firm the right to prevent others from the production of that product for some time. In practice, according to Teece, patents do not work as they are supposed to work in theory, because they rarely provide perfect appropriability to innovations, except some chemical products and mechanical inventions. Process innovations have fragile protection because the legal requirements to maintain their validity or prove their infringement are high. Moreover, such protection helps to stimulate firms to spend on R&D.

R&D plays a significant role in technological progress; however, for some countries, it is not that important. Researchers emphasize two methods of growth: growth by innovation and growth by imitation. Developed countries, which are at the forefront of technology, must innovate to sustain growth. While developing countries, which have reduced technology availability, must imitate instead of innovating in order to grow. In other words, such countries import and adapt existing technologies rather than produce new ones. This fact justifies weak patent protection in less technologically advanced countries. The inadequate patent protection has one very beneficial advantage: domestic firms can use and adapt foreign technology without being penalized, i.e. paying high royalties to inventors of the technology.

The invention of new processes and products requires significant science and engineering competencies; however, the invention is not enough to

32 D.J. Teece, *Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy*, School of Business Administration, University of California, Berkeley 1986, pp. 285–305.

33 *Ibidem*.

benefit from innovation, this is only the first step towards the commercial success. The next step is the protection of returns to innovation, that is a big challenge. A firm's ability to appropriate returns determines its performance and future survival. The fact that to obtain profit from inventions innovators should realize the role of the appropriability and the nature of the additional assets required to commercialize their inventions is widely accepted nowadays. Ceccagnoli and Rothaermel[34] mention several high-profile examples in which innovators lost to imitators, because of their inability to appropriate returns for their innovations. The issue is that if firms cannot capture the development of new products, they will not engage in R&D; therefore, technological progress will be slow. Hence, the protection of both innovation and its return should be considered before the product is commercialized to stimulate technological development. Generally, a patent is used as a protection of an invention for a specified period. Otherwise, it is useless to invest in R&D and any innovation because the inventor will not be able to benefit. Patents are issued in exchange for a public disclosure after a given period; hence, an invention will make its impact on overall technological progress.

Cavdar and Aydin assert that patents are significant instruments for the protection of the innovation process, that stimulates technological innovation, which functions as a critical tool in gaining competitive advantage. Hence, strengthening patent laws is significant and substantial for the transformation of organizations from imitators to innovators. Most companies use patents as tools to protect innovations against imitators and to receive returns, because innovation and technology development is a very costly process.

2.5. Role of market structure

Optimal market conditions are essential to have an effective and sustainable innovation. Baumol[35] provides support for oligopoly as an optimal market structure for innovation. The reason is that in oligopolistic markets, competition affects incentives to innovate, while in monopolistic market firms have less incentive to innovate as they already have profit before the

[34] M. Ceccagnoli, F.T. Rothaermel, *Appropriating the Returns from Innovation, Technological Innovation: Generating Economic Results Advances in the Study of Entrepreneurship*, "Innovation and Economic Growth", Vol. 18, No. 3, 2008, pp. 11–34.

[35] W.J. Baumol, *Contestable Markets: An Uprising in the Theory of Industry Structure*, "American Economic Review", Vol. 72, No. 1, 1982, pp. 1–15.

innovation[36]. Baumol conducted an unusual and bold research effort that led to the development of the theory of contestable markets. According to the theory, there are markets served by a small number of firms and still characterized as competitive as potential short-term entrants exist because there are free entry and exit. Hence, the idea of the theory is that the price and output determination is dependent on the threat of competition rather than on the type of market structure. As long as entry barriers protect a monopoly, and thus there is no fear of competition, it will make an extraordinary profit. However, when there are no barriers to entry and exit, other firms can quickly enter the market increasing competition, causing price falls and making the market contestable. Accordingly, as claimed by Amavilah, the theory of contestable markets demonstrates that

> "potential competition leads to more efficient outcomes in imperfectly competitive settings than it was previously thought"[37].

Furthermore, the theory highlights the importance of equal accessibility of technology to firms, as that can determine the average cost of the product. As long as all companies in a market can behave competitively, despite the type of structure, it is better for them to invest in the development of new technologies to keep their competitiveness. Schumpeter advanced a controversial argument that monopoly is more conducive to innovation than highly competitive markets. There is extensive literature investigating the effects of market structure on innovative activity, but it has proven difficult to identify robust empirical results. The absence of a monotone relationship and the endogeneity of market structure are two of the most critical problems. According to Gilbert[38], several theoretical studies have demonstrated that the competition-innovation relationship is monotonic only under restrictive conditions. The reason is behind the opposing effect of the 'efficiency' and 'replacement' effects. Due to the efficiency effect, a monopolist is afraid of losing his privileged position because a new entrant can produce a close substitute for the monopolist's product. In such a case, the monopolist has a stronger incentive to invest in innovation and R&D, to remain a monopolist.

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36 K.J. Arrow, *Economic Welfare and the Allocation of Resources for Invention*, Princeton University Press, Princeton 1962, pp. 609–626.

37 V.H. Amavilah, *Knowledge = Technology + Human Capital and the Lucas and Romer Production Functions*, Munich 2014, pp. 3–17.

38 R.J. Gilbert, *Competition and Innovation*, "Journal of Industrial Organization Education", Vol. 1, No. 1, 2006.

On the other hand, due to replacement effect, a monopolist has lower innovation incentives as it is already making a profit before the innovation and other firms are recouping its costs. In this case for the monopoly, the innovation replaces an existing profit by a larger one. The former leads to lower innovation incentives in more competitive situations where aggregate industry profits are more moderate. The latter leads to lower innovation incentives for a monopolist that has existing profits at stake. Kenneth Arrow appears to oppose the Schumpeterian hypothesis by comparing the additional profit to be gained from undergoing some process innovation in perfect competition and monopoly markets. He shows the increase in profit for a monopolist mathematically when reducing marginal cost should be lesser than for a perfectly competitive producer – where we assume that marginal cost is equal to the average cost in such markets. It is because the perfectly competitive firm can capture the whole market, given that there are similar goods in the industry, if we assume either absolute intellectual property rights or the possibility of secrecy. A monopolist already earns some supernormal profit and 'replaces' this profit with a small improvement. For this reason, a monopolist may have less incentive to innovate and increase its profits than a perfectly competitive firm who can move to achieve positive earnings from an original position of zero profit.

Duguet et al. argue that

> "the probability of engaging in R&D for a firm increase with its size, its market shares and diversification, and with the demand pull and technology push indicators"[39].

In other words, bigger firms have more incentive to invest in research and create innovations. Hence, innovations are most likely to occur in rapidly growing sectors of the economy.

2.6. Empirical studies

To understand the role of technological innovations in economic growth, it is necessary to look at empirical studies. Hence, some most outstanding studies and research are presented on the next pages.

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[39] E. Duguet, B. Crepon, J. Mairesse, *Research, Innovation, and Productivity: An Econometric Analysis at the Firm Level*, National Bureau of Economic Research, Washington 1998.

China is one of the successful examples of economic development. As Zhang et al.[40] point out, one of the most important reasons why China's achievements could be so great in terms of economic growth is scientific progress and innovation. In today's harsh competitive environment, countries have to benefit from scientific innovation resources more than ever before. As Zhang et al. state, there is a significant relationship between scientific innovation and economic growth[41]. In China and several other Asian countries like Korea, Taiwan and Singapore, aggressive technology acquisition and efficient use of these technologies in production processes played a significant role in the economic development of these countries. The above-mentioned states further developed these acquired technologies to increase their international competitiveness by improving their research and development capabilities. Consequently, as scientific innovation contributes more to economic growth, governments give more importance to technological investments. Ulku, in her research[42], has investigated the relationship between R&D, innovation, and economic growth for 20 OECD countries and 10 non-OECD countries. The analysis uses various panel data techniques, such as fixed effects and GMM, and uses patent and R&D data for the period 1981–1997. The study tested two hypotheses, and the first one is that R&D investment increases the level of innovation, and the latter has constant returns. The second hypothesis is that innovation leads to permanent growth of the level of GDP per capita. Obtained results show that innovation and GDP per capita have a strong positive relationship in both the OECD and non-OECD countries. However, only the OECD countries with a large market can increase the level of innovation by investing R&D, while those OECD countries that do not have such a market size and an effective R&D sector use technology spillovers to promote their innovations. The study was giving support to endogenous growth theories and maintaining a positive relationship between R&D and innovation, as well as between innovation and GDP per capita; however, it does not provide any evidence for constant returns to innovation, indicating that R&D models are not fully endogenous and are not able to explain sustainable growth. Nevertheless, the author claims that R&D models can explain long-term growth when there are constant returns to such factors as capital, innovation and knowledge stock. Moreover, although the lack of constant returns to innovation, R&D based models cannot be rejected, as

40 J. Zhang, L. Wang, S. Wang, *Financial Development and Economic Growth: Evidence from China*, "Journal of Comparative Economics", Vol. 40, No. 3, 2012.

41 J. Zhang, L. Wang, S. Wang, *Financial...*, *op. cit.*

42 H. Ulku, *R&D, Innovation, and Economic Growth...*, *op. cit.*

patent and R&D data are not a complete measure of innovation. Ciobanu et al.[43] conducted a study regarding the Central and Eastern European countries. They examined the circular dependency between economic growth and the level of innovation. The analysis was conducted in 15 countries for the period from 1996 to 2010 by using a panel data regression model. To emphasize the relation between innovation and economic growth, the authors have used two models with two different dependent variables, such as the number of patent applications and economic growth. Their findings indicated that the level of development of an economy, reflected in the allocation of resources for research and development is the leading cause of innovation. The results pointed out that Central and Eastern European economies recorded fast economic growth, but it was not based on the innovation process. The authors claim that innovation is still in a catch-up process connected to the growth rate. Bujari and Martinez[44], in their study, analysed the impact of technological innovation on economic growth in Latin America. They used the data of twelve representative countries for the period from 1996 till 2008 to imply a dynamic panel data model with GMM system estimation. Their findings showed that the processes of technological innovation have a positive impact on economic growth in Latin America, and those countries could achieve economic growth by developing technological innovation. The primary outcome of the study was that investment in R&D, patents and high-tech product exports could lead to the rise of TFP and increase the GDP per capita in Latin American countries. Zachariadis, in his research, indicated that R&D investment and TFP growth have a positive relationship[45]. He performed a direct test of endogenous growth theory that was based on the Schumpeterian endogenous growth framework without scale effect. The data on 20 U.S. manufacturing sector industries for the period 1963–1988 are employed. The author showed that R&D intensity increases the rate of patenting, which in turn leads to technological progress, while the latter is relevant to raise the growth rate of output per worker. Another finding is that aggregate research intensity to industry level innovation success leads to technological spillover. Cakir and Elgin in their research, analyse to what extent the total factor productivity can be used as a proxy for

43 R. Ciobanu, R. Petrariu, R. Bumbac, *Innovation: a path to competitiveness and economic growth. The case of CEE countries*, "Theoretical and Applied Economics", Vol. 20, No. 5, 2013.

44 A. Bujari, F.V. Martinez, *Technological Innovation and Economic Growth in Latin America*, "Revista Mexicana de Econom'ıa y Finanzas", Vol. 11, No. 2, 2016, pp. 77–89.

45 M. Zachariadis, *R&D, innovation, and technological progress: a test..., op. cit.*

technological progress[46]. TFP is decomposed to three components, such as technological progress, scale effect, and change in technical efficiency. Authors empirically examine the relationship between the growth in the technological component of TFP and several S&T indicators. They investigate whether such indicators are significantly related to the increase in technological progress part of TFP by conducting a panel data analysis. They used data from 160 countries from 1960 through 2009. Results of the research indicate that:

> "the technological progress component of the TFP series properly reflects actual technological progress"[47].

Moreover, among several scientific and technological indicators, the number of scientific articles, patent applications and trademark applications are positively correlated with the technological progress component of the TFP. Porter and Stern[48] conducted one of the first studies that utilized aggregate level patent data to examine the determinants and the effects of innovation. They contributed to the empirical understanding of economic growth by estimating parameters of "ideas" production function and the magnitude of the intertemporal and international spillovers in ideas. They examine the time-series pattern of international patenting to evaluate the determinants of the flow of ideas directly. They used a panel dataset of patents to derive ideas production from the overall relationship between the ideas sector and productivity growth. Consequently, they distinguish the properties of the ideas production function from the sensitivity of TFP growth to ideas production. Another goal was that, by exploiting the accumulation of patents over time, they explicitly estimated the strength of the spillover from ideas-to-ideas. In other words, they assess the strength of the linkage between patenting in the past and current ideas sector productivity. One more goal was that by evaluating patenting patterns using a panel dataset of the OECD countries, they contribute to emerging literature on the differences between domestic and international knowledge spillovers. Explicitly, they differentiated the shape of the national ideas production function from the more general world ideas production function. The authors found a positive relationship between innovation and human capital in the R&D sectors and knowledge

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46 S. Cakir, C. Elgin, *Technological Progress and Scientific Indicators: A Panel Data Analysis*, Bogazici University, Istanbul 2015.

47 S. Cakir, C. Elgin, *Technological Progress...*, *op. cit.*, p. 5.

48 M.E. Porter, S. Stern, *Measuring the "Ideas" Production Function: Evidence from International Patent Output*, National Bureau of Economic Research, Cambridge, Massachusetts 2000.

stock. Moreover, they found that innovation and TFP growth have a significant but weak correlation. One unexpected result was that there is a strong positive relation between ideas productivity and the national ideas stock and strong negative relationships with foreign knowledge stock.

The literature using patents as an innovation determinant consistently found the positive long-term role of innovation in stimulating economic growth, although there are different views and findings for the short-term purpose. Schmookler highlighted that, in spite of the negative relationship between these variables, their relationship ought to be positive in the long run. Indeed, Devinney[49] demonstrated the positive short-term correlation between patents and economic growth implicitly by analysing associations between changes in these variables. Moreover, the positive effects of innovation on GDP in both short-term and long-term, have been discovered in more recent research by Yang[50] by analysing Taiwanese patent data and using a similar model.

3. Data description

The data set was sourced from different databases, such as the Penn World Table version 9.1, the World Bank, the OECD and the United Nations Educational, Scientific and Cultural Organization (UNESCO). Data is available for 10 indicators of economic activity. GDP per capita, employment level, human capital, capital stock, investment, government expenditure, and trade openness are variables of interest. The control variables, such as patent application, R&D expenditure, and R&D personnel are determinants of technological development, which are employed to show the impact of technological innovation on economic growth.

GDP per capita – dependent variable

GDP is the most common method of measuring the economic performance of a country. GDP corrected for Purchasing Power Parity (PPP) in millions 2011 USD is used in my dataset.

GDP per capita is a better indicator of a nation's standard of living as it adjusts to population. The original per capita GDP is taken as a proxy for the initial conditions of the country.

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[49] T.M. Devinney, *Characterising International Patent Behaviour*, Australian Graduate School of Management, Sydney 1994, pp. 94–124.

[50] C.H. Yang, *The Effects of Strengthening Intellectual Property Right in NIEs: Evidence from Taiwan's 1994 Patent Reform*, Tamkang University, New Taipei City 2004.

Variables of interest

The variables that are examined in order to demonstrate the impact of technological progress in economic growth, which are patent applications, expenditure on R&D and R&D personnel in our case. This set of technological progress measures was chosen based on such principal reasons as data availability and preceding literature.

The key independent variable is total patent applications, by both residents and non-residents, by priority years in numbers, obtained from the World Bank database.

Another independent variable is represented by R&D expenditure as a percentage of GDP, obtained from the OECD Main Statistics and Technology Indicators database. This indicator is being used to proxy for technological innovation. Also, for this variable, it is critical to consider its lagging effects. The rates of return to R&D are challenging things to estimate. Formerly, because of a data availability problem, R&D had generally been ignored. Empirical literature recognises the importance of the level and dynamics of public spending on R&D behind innovation and economic expansion in any economic system[51]. Total R&D personnel in full-time equivalent (FTE) is obtained from the UNESCO Institute for Statistics. R&D in FTE is the amount of time spent on R&D work during one year per full-time job (approx. 35 hours per week), allowing for 4-6 weeks of holidays. R&D work done outside regular working hours is considered in calculating R&D in full-time equivalents, provided it is rewarded.

Control cariables

These variables are always included in growth regressions, because they have been recognised to influence economic growth on both empirical and theoretical grounds.

Another important variable in this analysis is an investment stock. There are several methods of measuring investment. In this paper, the proxy for investment is a share of gross capital formation at current PPPs.

Gross fixed capital formation is defined as the acquisition and creation of assets by producers for their use, minus disposals of produced fixed assets[52]. The data for an investment stock are acquired from the Penn World Table dataset.

The human capital index is based on average years of schooling and assumed a rate of return to education. The data on education are obtained

51 Organisation for Economic Co-operation and Development (OECD), *The knowledge-based economy*, Technical Paper No. 102, OCDE/GD (96), Paris 1996.

52 Organisation for Economic Co-operation and Development (OECD), *op. cit.*

from the Barro-Lee[53]. The data available refer to the period from 1970 to 2017. It is often argued that secondary and tertiary education can have a positive effect on economic growth. However, education levels also seem to influence each other. Consequently, the best way to look at human capital, in general, is to look at the average number of educational years. The data on human capital are obtained from the Penn World Table dataset.

The employment level is indicated by the number of employees in millions. According to the Penn World Table (PWT), all persons aged 15 and over who performed work during the reference week, even for only one hour a week, or who did not work but had a business or a job but were temporarily absent, are considered as employed. The data for the employment level are obtained from the PWT dataset.

Capital stock at current PPPs reports capital stock levels in terms of the prices in that period. It is based on the investment and costs of structures and equipment. The data for the capital stock are obtained from the Penn World Table dataset.

Although there are several methods of measuring Foreign Direct Investment (FDI), in this analysis, the inflow of FDI as a percentage of GDP is used. Generally, multinational companies prefer to allocate to countries with the favourable business environment. In other words, they require specific preconditions, such as political stability, economic security and a certain level of human capital. Consequently, the inflow of FDI should be used rather than outflow FDI. The data for FDI are acquired from the World Bank database. The country average was taken for this analysis.

In this paper, trade openness is calculated by summing up imports and exports of goods and services as a percentage of GDP. The sum of imports and exports shows the total trade flows of goods and services into and out of a country. The larger the value of the sum of imports and exports as a percentage of GDP, the more open the country is. The data for trade openness are obtained from the Penn World Table dataset.

The data on government expenditure are acquired from the Penn World Table database yearly from 1970 until 2017. The data demonstrate general government final consumption expenditure as a percentage of GDP. This measure is used to show how much, if at all, the government expenditure influences economic growth.

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53 R. Barro, J.W. Lee, *A New Data Set of Educational Attainment in the World*, “Journal of Development Economics”, Vol. 104, 2013, pp. 184–198.

Table 1 summarises the definition of all variables in the model used. The table also includes the source of the variables considered.

Table 1

Variable definitions and sources

	Variable	Source	Definition
1	GDP per capita	World Bank	Expenditure-side real GDP, at chained Purchasing Power Parities (in mil. 2011 USD), for a particular year divided by average population for the same year
2	Human Capital	Penn World Table 9.1	Index of human capital per person, based on years of schooling and returns to education
3	Capital	Penn World Table 9.1	Capital stock at Current Purchasing Power Parities (in mil. 2011 USD)
4	Employment	Penn World Table 9.1	Number of persons employed (in millions)
5	Government spending	Penn World Table 9.1	Share of government consumption at Current Purchasing Power Parities
6	Investment	Penn World Table 9.1	Share of formation of gross capital at Current Purchasing Power Parities
7	Trade openness	Penn World Table 9.1	The outward and inward orientation of a given country's economy, calculated as a sum of the shares of merchandise exports and imports at current PPPs
8	Expenditure on R&D	OECD	Total intramural expenditure on R&D as a percentage of GDP
9	R&D personnel	UNESCO	Total R&D personnel in full-time equivalent
10	Patent application	World Bank	Total patent applications in numbers

Source: Own study.

The sample consists of 19 countries from different regions. The countries used in the analysis are: Australia (1), Austria (2), Belgium (3), Canada (4), Denmark (5), Finland (6), France (7), Germany (8), Iceland (9), Ireland (10), Italy (11), Japan (12), Netherlands (13), Norway (14), Portugal (15), Spain (16), Sweden (17), United Kingdom (18), United States (19).

Developed countries are going to be considered because of the size of the market and the availability of the data. In contrast to studies concentrated on the development of specific countries, in this study, a wider range of countries is analysed. Moreover, more and up-to-date information on technological indicators is examined, and recently released data have been collected.

4. Methodology

The evolution of economic growth theory and determinants of technological development have been described in previous chapters. This study aims to determine whether the determinants of technological development have a positive impact on economic growth. Moreover, this study seeks to identify specifically which of those determinants, such as expenditure on R&D, R&D personnel and patent applications, have the strongest relationship with economic growth.

In this part, practical implications of Enrique Moral-Benito's econometric methodology of growth empirics in panel data under model uncertainty and weak exogeneity will be described. Step by step the model will be reviewed since it would be used in the empirical analysis.

Firstly, the reasons to use this specific model will be discussed. Brock et al.[54] claim that in the study of growth data, one crucial aspect is attention to the limits while concluding the data. These limits are the general weakness of the available data and model uncertainty. The limited number of countries available constrains the prospect for reliable generalisation in empirical growth research. Such a constraint leads to imprecise parameter estimates and prevent researchers from applying more sophisticated methods.

> "A natural response to this constraint is to use the within-country variation to multiply the number of observations"[55].

The optimal solution for the limited number of countries is the usage of different episodes within the same country. Supposing that important variables change over time, this seems to be the most promising way to bypass most of the problems faced by growth researchers. Furthermore, as time passes, more and more data become available, and this way of avoiding some

[54] W. Brock, S. Durlauf, *Growth Empirics and Reality*, "World Bank Economic Review", Vol. 15, No. 2, 2001, pp. 229–272.

[55] *Ibid.*

limits can only improve. Moreover, Brock and Durlauf argue that growth theories are open-ended, which means that several different theories are consistent with one another. It leads to model uncertainty because the variety of approaches brings about problems in identifying the most effective policies to promote growth. In other words, growth theories do not provide sufficient guidance for choosing the right empirical model.

Bayesian Model Averaging is employed by researchers to deal with model uncertainty. Most studies were conducted with BMA approaches developed for single cross-sections of countries assuming exogenous growth determinants. Therefore, another challenge to empirical growth research is the endogeneity of growth determinants. In principle, some of these issues can be addressed in a data panel context that allows for country-specific fixed effects to be included in the empirical model and feedback from economic growth to the regressors.

Moral-Benito[56] combines BMA methods with an appropriate likelihood function for panel data models with fixed effects that allow regressors to obtain feedback from economic growth to address the dual challenges of model uncertainty and endogenous regressors. He extended the approach in his previous work by allowing weakly exogenous regressors. Specifically, he combined likelihood, based on the same identifying assumptions as generalised panel method of moments estimators, with BMA techniques that use the unit information prior on the parameter space[57]. Given the evidence obtained in Moral-Benito's work, the hypothesis of no conditional convergence cannot be rejected. The reason is that the convergence velocity point estimate is relatively low, and its subsequent variance makes this estimate statistically indistinguishable from zero. This discovery throws doubt on what was often considered the central prediction of the neoclassical growth model. On the contrary, it provides evidence for endogenous growth models, which do not predict conditional convergence. Another finding was that all nine growth theories considered in Moral-Benito's study were ineffective to predict long-term economic growth robustly. The uncertainty about the estimate seems sufficient to prevent any of the candidates from being designated as a robust determinant of economic growth. The fragility of growth regressions is sufficiently high to doubt the validity of the approach to identify the sources of long-term economic growth.

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[56] E. Moral-Benito, *Growth Empirics in Panel Data...*, *op. cit.*

[57] E. Moral-Benito, *Model averaging in economics: an overview*, "Journal of Economic Surveys", Vol. 29, No. 1, 2013, DOI: 10.1111/joes.12044.

4.1. Econometrics methodology

The empirical determinants of economic growth are evaluated in the literature as:

$$\gamma_i = clny_{i0} + \beta_{xi} + \epsilon_{\mathrm{i}} \tag{5}$$

where $\gamma_i = t^{-1}(lny_{it} - lny_{i0})$ indicate the growth rate of GDP per worker between 0 and t. x_i is a vector of variables that determine the long run income level. This estimating equation can be obtained from a generic one-sector growth model, such as the Solow-Swan model.

4.1.1. Growth empirics and panel data

Regressions of cross-country growth are commonly estimated from small-T panels with the help of global aggregate series datasets of Heston et al.[58] The dataset covers 40 years, from 1960 to 2000, but the data are broken down at intervals of 5 or 10 years to focus on long-term economic growth. A panel variant of the basic regression of empirical growth is generally considered in the equation:

$$lny_{it} = alny_{it-1} + x_{it}\beta + \eta_i + \varsigma_i + v_{it} \quad (i = 1, ..., N;\ t = 1, ..., T) \tag{6}$$

where $\alpha = (1 + c)$, η_i is a country-specific fixed effect allowing heterogeneity across countries to be considered, while ς_i is a period-specific shock common to all countries.

The use of panel data in empirics of economic growth can be preferable to cross-sectional data because of two main reasons. From one point of view, the prospects for reliable generalisations are restricted by the limited number of countries available in cross-country growth regressions; thus, using differences in a country for multiplying the number of observations is a natural response. From another point of view, the use of panel data methods allows the solution of the inconsistency of empirical estimates resulting from the presence of omitted country-specific effects, which lead to misinterpretation of the underlying dynamic structure, if correlated with other regressors.

58 A. Heston, R. Summers, B. Aten, *Penn World Table*, Center for International Comparisons of Production, Income and Prices, University of Pennsylvania 2006, 2009, 2011.

Weak exogeneity in the panel setting implies that current regressor values do not correlate with the future performance of economic growth shocks. Nevertheless, previous shocks to the dependent variable can be correlated with current regressors to allow feedback from GDP on growth factors. For example, the idea that economic growth affects population growth rate and the level of democracy can be endorsed by strong empirical support. According to Moral-Benito, this feedback effect refers to most of the growth determinants commonly considered. Appropriately, weak exogeneity, also known in the panel data terminology as predetermination, is a natural assumption in the growth context to address reverse causality concerns, which can be executed as follows:

$$E(v_{it}/y_i^{t-1}, x_i^t, \eta_i = 0(i = 1, ..., N; t = 1, ..., T) \qquad (7)$$

where $y_i^{t-1} = (y_{i0}, ..., y_{it-1})'$ and $x_i^t = (x_{i0}, ..., x_{it})'$. It is also possible to correlate right-hand variables with country-specific effects η_i, but not with the current shock.

Moment conditions implied by the assumption of weak exogeneity are commonly used within the perspective of a method-of-moments, and in this category, the best examples of these are GMM estimators of first differences. As the number of countries is limited, there is not a very large cross-sectional dimension in the growth datasets. It may be weak first differences equation instruments with persistent series such as GDP. The use of the system-GMM estimator was proposed to solve this weak-instrument problem[59]. Though, this estimator requires the further assumption of mean variables stationarity, which may not be acceptable, for instance, in datasets starting at the end of a war. Also, the lack of formal statistical justification for combining them with Bayesian methods such as BMA is a potential disadvantage of these estimators. Moral-Benito developed a likelihood function based explicitly on the identifying exogeneity assumption for panel data models with fixed effects and weakly exogenous regressors as an alternative to the GMM techniques mentioned above[60]. Using this likelihood-based approach, feedback from economic growth to regressors, in other words, reverse causality, may be

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59 More about estimation of systems of simultaneous equations can be found in K. Beck, *Model dwóch gospodarek a wyniki badań nad synchronizacją cykli koniunkturalnych. Weryfikacja teoretyczna i empiryczna*, „Myśl Ekonomiczna i Polityczna", 3(46), 2014, pp. 17–47.

60 E. Moral-Benito, *Likelihood-based estimation of dynamic panels with predetermined regressors*, "Journal of Business and Economic Statistics", 31(4), 2013, pp. 451–472.

provided. Based on the large samples of 'fixed T, large N' the resulting maximum likelihood estimator is asymptotically analogous to the first-differentiated GMM estimators, but in terms of finite-sample performance, it outperforms its GMM counterpart. The fact that such a likelihood function is available enables the BMA to be combined with this type of dynamic panel data models with feedback.

4.1.2. Likelihood function for panel data models with weak exogenous regressors

The likelihood function for panel models with weakly exogenous regressors was deduced by developing the model's implications for the 1st and 2nd moments of the observed variables in equation (1) and establishing a likelihood based on a multivariate regression model with dispersion matrix restrictions. To this end, the fundamental equation (1) is enhanced by additional reduced-form equations capturing the process of unrestricted feedback as follows:

$$x_{it} = \gamma_{t0} y_{i0} + \ldots + \gamma_{t,t-1} y_{i,t-1} + \wedge_{t1} x_{i1} + \ldots + \wedge_{t,t-1} x_{i,t-1} + c_t \eta_i + \vartheta_{it} \quad (8)$$

where c_t is an order parameter vector of $k \times 1$ and, for $h < t$, γ_{th} is the $k \times 1$ vector $\gamma_{th} = (\gamma^1_{th}, \ldots, \gamma^k_{th})$ with $h = 0, \ldots, T-1$. While $\wedge_{th}$ is an order parameter matrix of $k \times 1$ and ϑ_{it} is a predication errors vector of $k \times 1$.

4.1.3. Bayesian Model Averaging

Moreover, due to the lack of clear theoretical guidance on the selection of regressors to include in the vector x_{it}, model uncertainty in growth empirics emerges. This leads to the creation of potentially numerous empirical models, each provided by a different regressor combination. If the research has K possible independent variables, there can be 2^K different models. Accordingly, this results in the uncertainty of researchers regarding the specification of the empirical growth model.

BMA struggles with the problem by estimating models for all possible combinations of variables and building an overall weighted average. With proper likelihood function, BMA is a natural alternative to avoiding model uncertainty. BMA has three primary steps, such as choosing prior distributions, determining the likelihood function, and computing the full posterior distribution.

The model weights for this averaging are derived from the posterior model probabilities that arise from Bayes' theorem. Posterior distribution of coefficient β, that summarizes the uncertain quantities we know in Bayesian analysis, is given in the following manner:

$$P(\beta| y) = \sum_{j=1}^{2^K} P(\beta| Mj,y)\times P(Mj| y) \tag{9}$$

where data is represented by y, the number of models are denoted by $j(j = 1, 2, ..., m)$, number of potential regressors are showed by K, the conditional distribution of coefficient β for a given Mj model is indicated by $P(\beta \vee Mj,y)$, and the posterior probability of the model is denoted by $P(Mj \vee y)$.

The posterior model probability (PMP), employing Bayesian theorem can be represented as follows[61]:

$$PMP_j = \frac{L(y\vee M_j)\times P(M_j)}{\sum_{j=1}^{2^K} L(y\vee M_j)\times P(M_j)} \tag{10}$$

where PMP_j is proportional to $L(y \vee M_j)$ – the model specific marginal likelihood that is average measurements of model compliance with data. While $P(M_j)$ is a model specific prior probability, which is used as a catalyst for uncertainty in Bayes' theorem.

While applying Bayesian approaches, it is essential to determine the model specific prior distribution. The binomial model prior presented by Sala-i-Martin et al.[62] is:

$$P(M_j) \propto \left(\frac{EMS}{K}\right)^{k_j} \times \left(1 - \frac{EMS}{K}\right)^{K\text{-}k_j} \tag{11}$$

where EMS indicates the expected model size and k_j is the number of covariates in a given model. The above-mentioned prior can be converted into a uniform model prior, which means that priors on all models are all equal – $P(M_j) \propto 1$, when $EMS = \frac{K}{2}$. Any other possible combination of priors previously considered

61 M. Błażejowski, J. Gazda, J. Kwiatkowski, *Bayesian Model Averaging in the Studies on Economic Growth in the EU Regions – Application of the Gretl BMA package*, "Economics & Sociology", 9(4), 2016, pp. 168–175.

62 X. Sala-i-Martin, G. Doppelhofer, R. Miller, *Determinants of Long-term Growth: a Bayesian Averaging of Classical Estimates (BACE) approach*, "American Economic Review" No. 94, 2004, pp. 813–835.

in the BMA literature in terms of cross-validated predictive performance is outperformed by the unit information prior combined with the uniform model prior[63]. The largest set of growth determinants is identified by the already mentioned combinations of priors. Beta-binomial model prior is another example of prior model probability[64]:

$$P(M_j) \propto \Gamma(1 + k_j) \times \Gamma\left(\frac{K - EMS}{EMS} + K - k_j\right) \tag{12}$$

The probability of a model of each size is the same when the beta-binomial distribution has expected model size K/2. So, for both binomial and beta-binomial prior with $EMS = K/2$, the prior probability of variable inclusion in the model is 0.5.

The use of the posterior probabilities of the models as a weight makes it possible to calculate the unconditional posterior mean and standard deviation of the coefficient βi. In BMA, 'posterior' implies after taking into consideration the relevant evidence concerning the specific case under analysis. The conditional probability that is established after the relevant evidence or a posteriori data, acquired through an experience, is taken into consideration is the posterior probability of a random event. The posterior mean is the Bayes' assessment of the unknown parameter. The following formula refers to the posterior mean of the coefficient β_i that is not dependent of the space of the model[65]:

$$PM = \sum_{j=1}^{2^K} PMP_j \times \hat{\beta}_{ij} \tag{13}$$

where $\hat{\beta}_{ij} = E(\beta i | y, M_j)$ denotes the value of the coefficient β_i estimated with ordinary least squares (OLS) for the model M_j. The posterior standard deviation (PSD) is calculated as follows (see next page):

63 T. Eicher, C. Papageorgiou, A. Raftery, *Default Priors and Predictive Performance in Bayesian Model Averaging, with Application to Growth Determinants*, "Journal of Applied Econometrics", 26(1), 2009, pp. 30–55.

64 E. Ley, M. Steel, *On the Effect of Prior Assumptions in Bayesian Model Averaging with Applications to Growth Regressions*, "Journal of Applied Econometrics", 24(4), 2009, pp. 651–674.

65 M. Prochniak, B. Witkowski, *The application of Bayesian Model Averaging in assessing the impact of the regulatory framework on economic growth*, "Baltic Journal of Economics", 14(1–2), 2014, pp. 159–180.

$$PSD = \sqrt{\sum_{j=1}^{2^K} PMP_j \times V(\beta_j \vee y, M_j) + \sum_{j=1}^{2^K} PMP_j \times \left[\hat{\beta}_{ij} - E(\beta_i \vee y, M_j)\right]^2} \quad (14)$$

where $V(\beta_j \vee y, M_j)$ denotes the conditional variance of the parameter for the model M_j.

The most important statistic for BMA, posterior inclusion probability (PIP), for the regressor x_i equals:

$$PIP = \sum_{j=1}^{2^K} 1(x_i = 1 \vee y, M_j) \times PMP_j \quad (15)$$

where $\varphi i = 1$ indicates that the variable x_i is included in the model.

Additionally, a researcher can be interested in the sign of the estimated parameter, provided it is included in the model. The posterior probability of positive sign of the coefficient in the model [*P*] is calculated in the following way[66]:

$$P \sum_{j=1}^{2^K} P(M_j \vee y) \times CDF(t_{ij} \vee M_j), if sign[E(\beta_i \vee y)] = 1$$
$$1 - \sum_{j=1}^{2^K} P(M_j \vee y) \times CDF(t_{ij} \vee M_j), if sign[E(\beta_i \vee y)] = -1$$

where CDF signifies cumulative distribution function, while $t_{ij} \equiv \left(\hat{\beta} | \, i/\hat{SD}_i \vee M_j\right)$.

5. Results

In Table 2 one can find the results of applying Bayesian Model Averaging, employing Moral-Benito's panel BMA under weak exogeneity, which works particularly well if we specify the unit information prior (UIP) on the parameter space. The UIP prior is a particular case of the so-called 'g-prior'[67]

[66] K. Beck, *Bayesian Model Averaging and Jointness Measures: Theoretical Framework and Application to the Gravity Model of Trade*, "Statistics in Transition" new series, 18(3), 2017, pp. 393–412, DOI: 10.21307/stattrans-2016-077; K. Beck, *Determinants of Intra-Industry Trade: An Investigation with BMA for the European Union*, [in:] "CBU International Conference. Innovation in Science and Education", 2018, DOI: 10.12955/cbup.v6.1131; K. Beck, *Determinanty synchronizacji cykli koniunkturalnych: analiza z wykorzystaniem BMA i miar łączności*, Część 2, Wyniki estymacji, „Myśl Ekonomiczna i Polityczna", 1(60), 2018, pp. 19–52, DOI: 10.26399/meip.1(60).2018.01/k.beck.

[67] A. Zellner, *On Assessing Prior Distributions and Bayesian Regression Analysis with g-prior Distributions*, [in:] P. Goel, A. Zellner (eds.), *Bayesian Inference and Decision*

under the choice $g = n$, where n refers to the number of observations in the sample. Additionally, regarding the model prior distributions, the uniform prior was applied, meaning that all models are equally probable a priori. Eicher et al. recommended this combination of priors. The prior probability of including a given regressor is 0.5. As 9 regressors were used, the space of the model consists of $2^K = 2^9 = 512$ elements, and the inference itself was carried out on the basis of all models. The results of applying BMA are presented in Table 2.

Table 2

Growth regressions using panel BMA under weak exogeneity

	Variables	PIP (I)	PM (II)	PSD (III)	P (+) (IV)
1	Human capital	0.9974	13404.8600	3794.6620	1.0000
2	Capital stock	0.9347	0.0011	0.0004	0.9999
3	Employment	0.8942	-336.2044	164.8580	0.0014
4	Government Spending	0.8749	-105906.6000	55772.5500	0.0000
5	Expenditure on R&D	0.6549	2620.9270	2419.6990	0.9969
6	Investment	0.5237	-24914.7100	30558.5400	0.0000
7	Trade openness	0.5045	1776.3390	2369.8570	1.0000
8	R&D personnel	0.4414	-0.0071	0.0111	0.0011
9	Patent applications	0.2970	0.0038	0.0130	0.7964

Source: Own study.

The sample covers 19 countries over the period from 1973 to 2017, divided into 5-year sub-periods. All regressors have been standardised. The first column presents the posterior inclusion probability. The second and third columns report the BMA posterior mean and standard error, respectively. The fourth column demonstrates the coefficient sign that indicated whether the variable has either positive or negative relations with the dependent variable.

The results indicate that 7 variables out of 9 were qualified as robust determinants of economic growth: human capital, capital, employment,

Techniques: Essays in Honor of Bruno de Finetti, North-Holland/Elsevier: Amsterdam 1986, pp. 233–243.

government spending, expenditure on R&D, investment, and trade openness. The remaining two, such as R&D personnel and patent applications, display lower posterior than the prior probability of inclusion, which is 0.5. A stable sign of the coefficient among all the analysed models also characterises all the variables that were qualified as robust, and it is in accordance with expectations of the theory, with the exception of employment and investment, which are characterised by negative posterior mean. These variables have a negative impact on economic growth. Expenditure on R&D turned out to be the robust determinant of economic growth models, including this variable taking 65.4% share in posterior probability mass.

The above table demonstrates the names and corresponding statistics of variables. The second column that is a Post Mean shows the coefficients averaged over all models, including the models wherein the variable was not included. The covariate human capital has a comparatively high coefficient and seems to be the most important. In the first column, which represents PIP, the importance of the variables in explaining the data is given. PIP is the sum of PMPs for all models wherein a covariate was included. We see that with 99.7%, virtually all of posterior model mass rests on models that include human capital.

In contrast, R&D personnel variable has an intermediate PIP of 44.1%, while the covariate patent applications do not seem to matter much. Consequently, their unconditional coefficients, a weighted average over all models, are quite low, since in the outcome coefficients equal to zero in the majority of models. Human capital is certainly positive, while employment is most likely negative, according to the posterior mean. Moreover, the fourth column P (+), the posterior probability of a positive expected value coefficient conditional on the inclusion, demonstrates the coefficient sign. Here, we see that in all models found containing these variables, the (expected values of) coefficients for human capital and employment were positive. In contrast, the corresponding number for government spending is zero, i.e. virtually all models that include government spending have the negative coefficient sign. Further forming opinions about the importance of our variables, it might be more interesting to look at their standardised coefficients.

Considering a balanced panel for 19 developed countries, BMA is combined with dynamic panel data models under weak exogeneity of the regressors and correlated country-specific effects. The sample period is 1973–2017 at 5-year intervals so that the number of time series observations is T = 9. Table 2 presents some moments of the coefficients' BMA posterior distributions. Posterior distribution moments reported in the table are marginalised over all the models considered, i.e. they are not conditional on inclusion. The interest in conditional or unconditional moments depends on the prior held by the researcher regarding the inclusion of a particular variable. If the researcher is confident that a given variable belongs to the model, the conditional moments provide the estimates of interest. However, if this is not the case, unconditional versions are more appropriate.

Columns (I) and (II) in Table 2 present the mean and standard deviation (SD) of the coefficients' BMA posterior distributions. While the exact distribution of the ratio of BMA posterior mean to posterior SD is not known, several interpretations of this ratio are available in literature. Raftery[68] suggested that for a variable to be considered effective, the ratio of mean/SD (in absolute value) must exceed 1, which from a frequentist viewpoint implies that the regressor improves the power of the regression. Masanjala and Papageorgiou[69] are more stringent and consider a threshold value of the mean/SD ratio of 1.3, which approximately corresponds to a 90% confidence interval in frequentist approaches. Finally, Sala-i-Martin et al. set this threshold at 2 since they argue that having a mean/SD ratio of 2 in absolute value indicates an approximate 95% Bayesian coverage region that excludes zero. According to the estimates in columns (I) and (II) in Table 2, five variables (human capital, capital, employment, government spending, expenditure on R&D) present a ratio of mean/SD larger than 1 in absolute value. Among them, the human capital coefficient has a ratio larger than 3.5 in absolute value, the capital coefficient has a ratio larger than 2.7, the employment coefficient has a ratio larger than 2, and the government spending coefficient ratio larger than 1.8.

Column (I) in Table 2 reports the BMA posterior inclusion probability (PIP) of each regressor. This probability is an indicator of the weighted average goodness-of-fit of models containing a particular variable relative to models not containing that variable. The PIP of a given regressor is calculated as the sum of the posterior model probabilities for all of the models, including that particular variable. According to Raftery, evidence for a regressor with a PIP from 50% to 75% is called weak, from 75% to 95% positive, from 95% to 99% strong and > 99% very strong. The PIPs presented in Table 2 indicate that robust evidence is obtained for the human capital coefficient. However,

68 A. Raftery, *Bayesian model selection in social research*, "Sociological Methodology", Vol. 25, 1995, pp. 111–163.

69 W. Masanjala, C. Papageorgiou, *Rough and Lonely Road to Prosperity: a Reexamination of the Sources of Growth in Africa using Bayesian Model Averaging*, "Journal of Applied Econometrics", Vol. 23, 2008, pp. 671–682.

strong evidence is not obtained for any of the regressors considered. Positive evidence is found in favour of the capital, employment and government spending variables. The evidence in support of the remaining regressors is only weak, according to the Raftery scale. Finally, note that PIP is not reported for the convergence coefficient because initial GDP (i.e. the lagged dependent variable) is included in all models under consideration, resulting in a PIP equal to one by definition. I do so because the theory offers strong guidance in favour of the inclusion of initial GDP in growth regressions. Furthermore, the likelihood function considered in this paper would be fundamentally different for models without a lagged dependent variable, so that comparability across models would not be ensured.

Finally, as an alternative measure of our posterior confidence in the sign of the coefficient, we include in column (IV) the so-called sign certainty probability, which is the posterior probability that the coefficient is on the same side of zero as its posterior mean (i.e. the probability that the coefficient is either positive or negative). For instance, for capital, we can interpret this object as the resulting p-value when testing the null $H_0{:}\beta_K > 0$ against the alternative $H_0{:}\beta_K \leq 0$, where β_K is the capital posterior coefficient. Analogous to common 5% significance tests in classical terms, Sala-i-Martin et al. consider the 97.5% threshold for this type of sign certainty probabilities.

To sum up, R&D expenditure is a robust determinant of economic growth, but R&D personnel and patent applications are not robust, as they have lower posterior than the prior inclusion probability, which is 0.5. Models, including expenditure on R&D variable, take 65.4% share in posterior probability mass, while models including R&D personnel and patent application variables take 44.14% and 29.7% share in posterior probability mass. In posterior inclusion probability (PIP), the importance of the variables in explaining the data is given.

Posterior Mean indicates the coefficients averaged over all models, including the models wherein the variable was not included. R&D expenditure has a positive and comparatively high coefficient and seems to be significant. Patent applications variable has a positive but relatively low coefficient while R&D personnel variable has a negative coefficient.

The corresponding number for R&D personnel is almost zero (0.0011), i.e. virtually all models that include R&D personnel have the negative coefficient sign. Expenditure on R&D has a corresponding number 0.9969, which means that it has a positive coefficient sign. Patent applications has 0.7964, meaning that it has a positive sign as well. Two out of three variables have coefficient signs predicted by the theory. Consequently, two determinants of technological development, out of three used in this work, have a positive relationship with GDP per capita.

Based on the results obtained, determinants of technological innovation, such as expenditure on R&D and patent applications, have a positive relation with economic growth presented by GDP per capita. Accordingly, as the determinants increase, by increasing technological innovation likewise, there is an increase in GDP per capita that leads to economic growth. Thus, the determinants of technological innovation have a positive impact on economic growth. Moreover, R&D expenditure is one of the robust variables, so the model containing R&D expenditure is the one that is closest to the true model. As predicted by the hypothesis, the strongest effect on economic growth among the determinants of technological development is made by R&D expenditure.

Conclusions

Today, at the time of notable technological change, researchers are compelled to think about the relations between technology and economic development. Investigating this relationship will be helpful in finding new ways and methods of increasing economic growth. Indeed, the literature on economic growth, technological progress and relations between them is extremely rich. Many authors claim that technological innovation is almost undoubtedly the main driver of long-term economic growth. Moreover, over the previous fifty years, a key finding has been that technological progress is crucial to long-term economic growth. This work contains many studies, which have been supporting such a statement both on a theoretical basis and in the empirical analysis.

In the thesis, two main tasks are identified. The first one is to describe the important role of technological innovation in the process of economic growth. The second one is to discuss the determinants of technological development and other factors of economic growth and conduct empirical analysis based on them. To reach the first goal, the evolution of growth theory is provided with a detailed description of technological innovation's role. To reach the second goal, interpretation of factors of economic growth, especially determinants of technological development, taken due to the common usage in the related literature and data availability, is provided. Moreover, Moral-Benito's "panel growth regressions in the presence of model uncertainty and reverse causality concerns" is considered and econometric framework is applied. This econometric methodology combines BMA with a suitable likelihood function for dynamic panel models with weakly exogenous regressors and fixed effects.

This paper attempts to prove that technological progress has a positive impact on economic growth and that expenditures on R&D variable has the strongest effect on economic growth among other measures of technological development. Firstly, it demonstrates the evolution of economic growth models. Starting with Robert Solow and his model of economic growth that showed the importance of technological progress while analysing changes in the level of output – and proceeding with another major contributor of growth theory, Paul Romer, who developed the new growth theory that analyses the technological innovation as a core element of development rather than an external aspect. Secondly, it characterizes technological innovation by providing a general overview, definitions, specifics, features and references to different works where the concept is elaborated. Moreover, measures of technological development, such as spending on R&D, R&D personnel and patent applications, are examined and analysed. Some other factors, such as appropriability of research results and the role of market structures, are taken into consideration as well.

The model uncertainty and endogeneity of the long-term economic growth determinants are two of the primary problems in growth econometrics. Model uncertainty occurs due to the compatibility of many growth models. Concerns about endogeneity occur in the form of excluded variables and reverse causality between economic growth and regressors. BMA methods have been the best-known solution to model uncertainty. In this study, BMA is combined with an appropriate likelihood function for panel data models with country-specific effects and weakly exogenous regressors. Because of this, in a unified econometric framework with adequate statistical foundations, model uncertainty is handled as well as omitted variables and reverse causality issues.

The most relevant results obtained from the analysis of the determinants of technological development are presented in the empirical part of this study. Human capital, capital stock, employment, government spending, expenditure on R&D, investment, trade openness, R&D personnel and patent applications represent independent variables. Except for R&D personnel and patent applications, which display posterior probability lower than 0.5, the rest of the variables are qualified as robust determinants. Models, including expenditure on R&D variable, take 65.4% share in posterior probability mass, showing the significance of this variable in explaining the data. And models, including R&D personnel and patent application variables, take only 44.14% and 29.7% share in posterior probability mass.

The coefficients averaged over all models, including the models where the variable was not included, are presented in posterior means. Expenditure on R&D has a positive and comparatively high coefficient. Patent applications variable has a positive but relatively low coefficient, while R&D personnel variable has a negative coefficient.

In accordance with the theory expectations, two measures of technological development have a positive sign of the coefficient. Accordingly, virtually, point estimates in all models that include expenditure on R&D and patent applications have a positive coefficient sign. Therefore, these measures of technological development have a positive relationship with GDP per capita.

Based on the outcomes, technological progress determinants such as spending on R&D and patent applications have a positive relationship with per capita GDP. As the determinant increases, there is an increase in GDP per capita. Accordingly, an increase in technological innovation contributes to economic growth. In this way, the determinants of technological innovation have a positive impact on economic growth. Furthermore, the model containing expenditure on R&D is the one that is closest to the true model as it is one of the robust variables. As predicted in the hypothesis, expenditure on R&D has the greatest impact on economic growth among the determinants of technological development.

The results have shown us the statistical correlation between the level of the determinants of technological development and the level of GDP per capita. Encouraging R&D activities such as investment in R&D and implementation of effective IP policies to stimulate innovation will cause rapid growth of the economy and increase standards of living. Although two out of three determinants of technological development are not robust and have a weak effect on the growth of the economy, their impact is still positive.

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Impact of technological progress on economic growth in developed countries. Accounting for model uncertainty and reverse causality

Abstract

The aim of this paper is to analyse the relationship between the determinants of technological innovation and economic growth. Moreover, it is aimed at examining whether expenditures on R&D variable has a stronger impact on economic growth, comparing to other determinants of technological development. The primary reason to choose the topic is that we are living in a century of notable technological change and investigating the relationship between technology progress and economic development is the way to find new methods of accelerating economic growth. The literature on this topic is extremely rich and many authors claim that the main driver of long-term economic growth is technological innovation. Furthermore, over the previous fifty years, a key financial finding has been that technological progress is crucial to long-term economic growth. This paper uses panel data for 19 developed countries over the period of 45 years (1973–2017) to examine the effect of such variables as expenditures on R&D, panel applications and R&D personnel on GDP per capita. The paper uses panel Bayesian Model Averaging under weak exogeneity. The results obtained show that all three indicators of technological innovation have a positive impact on per capita GDP and that expenditures on R&D have the strongest effect on economic growth.

Key words: innovation, technology, economic growth, R&D, patent

Wpływ postępu technologicznego na wzrost gospodarczy rozwiniętych gospodarek. Uwzględnienie niepewności co do postaci modelu oraz sprzężeń zwrotnych

Streszczenie

Celem niniejszego opracowania jest analiza relacji między czynnikami warunkującymi technologiczną innowację a wzrostem gospodarczym. Ponadto, ma ono na celu zbadać, czy zmienna dotycząca wydatków na badania i rozwój (B+R) ma silniejszy wpływ na wzrost gospodarczy niż inne wyznaczniki rozwoju technologicznego. Podstawowym powodem wyboru tego tematu jest fakt, że żyjemy w dobie wyjątkowych zmian technologicznych i badanie związku między postępem technologicznym a rozwojem gospodarczym jest sposobem na znalezienie nowych metod przyspieszenia wzrostu gospodarczego. Literatura na ten temat jest wyjątkowo bogata i wielu autorów uważa, że głównym motorem długofalowego wzrostu gospodarczego jest innowacja technologiczna. Co więcej, przez ostatnie 50 lat, główne ustalenia finansowe wskazywały, że postęp technologiczny jest kluczowy dla długofalowego wzrostu gospodarczego. Niniejsze opracowanie wykorzystuje dane panelowe dla 19 krajów rozwiniętych dotyczące 45 lat (1973–2017) w celu zbadania wpływu takich zmiennych jak wydatki na B+R, aplikacje panelowe oraz personel działów B+R na PKB na mieszkańca. Opracowanie wykorzystuje panelowe bayesowskie uśrednianie modeli [Bayesian Model Averaging] w warunkach słabej egzogeniczności. Uzyskane wyniki pokazują, że wszystkie trzy wskaźniki innowacji technologicznej wywierają pozytywny wpływ na PKB na głowę mieszkańca oraz że wydatki B+R mają najsilniejszy wpływ na wzrost gospodarczy.

Słowa kluczowe: innowacja, technologia, wzrost gospodarczy, badania i rozwój, patent

Влияние технологического развития на экономический рост развитых государств. Учёт неопределённости в вопросе о модели и обратной связи

Резюме

Целью настоящего исследования является анализ взаимодействия между факторами, влияющими на технологические инновации, и экономическим ростом. Кроме того, оно направлено на поиски ответа на вопрос о том, оказывает ли переменная расходов в рамках НИОКР (Научно-исследовательские и опытно-конструкторские работы) большее влияние на экономический рост, чем остальные детерминанты технологического развития. Основной причиной обращения к данной теме является тот факт, что человечество сейчас переживает эпоху исключительных технологических инноваций, в связи с чем выявление взаимосвязи между техническим прогрессом и экономическим развитием может служить основанием для поисков новых методов ускорения экономического роста. Литература по этому вопросу чрезвычайно обширна, и многие авторы считают, что основной детерминантой долгосрочного экономического роста являются технологические инновации. Более того, за последние 50 лет базисные финансовые расчёты показывали, что технический прогресс является ключевым фактором долгосрочного экономического роста. В настоящем исследовании использованы панельные данные по 19 развитым странам за 45 лет (1973–2017 годы) для изучения воздействия таких переменных, как расходы на НИОКР, панельные приложения, а также персонал, занимающийся исследованиями и разработками в области ВВП на душу населения. В исследовании используется панель усреднения байесовской модели [Bayesian Model Averaging] в условиях низкой экзогенности. Полученные результаты показывают, что все три показателя технологических инноваций положительно влияют на ВВП на душу населения, и расходы на НИОКР оказывают наибольшее влияние на экономический рост.

Ключевые слова: инновация, технология, экономический рост, исследования и развитие, патент

Cytuj jako:

Kyzy A.A., *Impact of technological progress on economic growth in developed countries. Accounting for model uncertainty and reverse causality*, „Myśl Ekonomiczna i Polityczna” 2020 nr 1(68), s. 56–105. DOI: 10.26399/meip.1(68).2020.03/a.a.kyzy

Cite as:

Kyzy, A.A. (2020) ‘Wpływ postępu technologicznego na wzrost gospodarczy rozwiniętych gospodarek. Uwzględnienie niepewności co do postaci modelu oraz sprzężeń zwrotnych’. [‘Impact of technological progress on economic growth in developed countries. Accounting for model uncertainty and reverse causality’]. *Myśl Ekonomiczna i Polityczna* 1(68), 56–105. DOI: 10.26399/meip.1(68).2020.03/a.a.kyzy