Wiadomości Statystyczne. The Polish Statistician, 2024, *69*(12), 16–37 https://doi.org/10.59139/ws.2024.12.2
Studia interdyscyplinarne. Wyzwania badawcze / Interdisciplinary studies. Research challenges
Zgłoszony/submitted: 3.02.2024, poprawiony/revised: 8.10.2024, zaakceptowany/accepted: 15.11.2024

Assessment of the impact of metrology on the economy in Poland by means of the Solow model

Barbara Batóg,[a] Mariusz Doszyń,[b] Paweł Majda,[c] Mirosław Pajor,[d] Dominik Rozkrut,[e] Monika Rozkrut,[f] Małgorzata Tarczyńska-Łuniewska[g]

Abstract. The impact of metrology on the economy is typically determined on the basis of econometric models that are the modifications of the Cobb-Douglas function and which take into account total factor productivity (TFP). Such models make it possible to examine the cointegration of metrological variables and basic macroeconomic variables. However, this approach could not be used to determine the impact of metrology on the economy in Poland due to too few observations, and thus short time series of the macroeconomic data. The aim of the study presented in this article is to assess the impact of metrology on the economy in Poland by means of the Solow growth model. This model allows a simulation-based approach to analyse the effects of metrology by perturbing TFP. To the authors' best knowledge, this type of approach has not yet been used to examine the impact of metrology on the economy.

The study demonstrates that a 1-percent increase in the net stock of standards correlates with a 0.35-percent rise in labour productivity, measured as production per employee. These findings align with similar analyses conducted in other countries, contributing to the understanding of metrology's economic significance.

Keywords: metrology, impact assessment, Solow model, total factor productivity, TFP
JEL: E01, O30

[a] Uniwersytet Szczeciński, Instytut Ekonomii i Finansów, Polska / University of Szczecin, Institute of Economics and Finance, Poland. ORCID: https://orcid.org/0000-0001-9236-7405. Autor korespondencyjny / Corresponding author, e-mail: barbara.batog@usz.edu.pl.

[b] Uniwersytet Szczeciński, Instytut Ekonomii i Finansów, Polska / University of Szczecin, Institute of Economics and Finance, Poland. ORCID: https://orcid.org/0000-0002-3710-1177. E-mail: mariusz.doszyn@usz.edu.pl.

[c] Zachodniopomorski Uniwersytet Technologiczny w Szczecinie, Wydział Inżynierii Mechanicznej i Mechatroniki, Polska / West Pomeranian University of Technology in Szczecin, Faculty of Mechanical Engineering and Mechatronics, Poland. ORCID: https://orcid.org/0000-0001-6238-655X. E-mail: pawel.majda@zut.edu.pl.

[d] Zachodniopomorski Uniwersytet Technologiczny w Szczecinie, Wydział Inżynierii Mechanicznej i Mechatroniki, Polska / West Pomeranian University of Technology in Szczecin, Faculty of Mechanical Engineering and Mechatronics, Poland. ORCID: https://orcid.org/0000-0002-7701-385X. E-mail: miroslaw.pajor@zut.edu.pl.

[e] Uniwersytet Szczeciński, Instytut Ekonomii i Finansów; Główny Urząd Statystyczny, Polska / University of Szczecin, Institute of Economics and Finance; Statistics Poland, Poland. ORCID: https://orcid.org/0000-0002-0949-8605. E-mail: dominik.rozkrut@usz.edu.pl.

[f] Uniwersytet Szczeciński, Instytut Ekonomii i Finansów, Polska / University of Szczecin, Institute of Economics and Finance, Poland. ORCID: https://orcid.org/0000-0002-9701-6388. E-mail: monika.rozkrut@usz.edu.pl.

[g] Uniwersytet Szczeciński, Instytut Ekonomii i Finansów, Polska / University of Szczecin, Institute of Economics and Finance, Poland. ORCID: https://orcid.org/0000-0002-7338-1989.
E-mail: malgorzata.tarczynska-luniewska@usz.edu.pl.

Ocena wpływu metrologii na gospodarkę w Polsce za pomocą modelu Solowa

Streszczenie. Wpływ metrologii na gospodarkę tradycyjnie ocenia się za pomocą modeli ekonometrycznych będących modyfikacjami funkcji Cobba-Douglasa, w których uwzględnia się całkowitą produktywność czynników (ang. *total factor productivity* – TFP). Takie modele pozwalają na badanie kointegracji zmiennych metrologicznych z podstawowymi zmiennymi makroekonomicznymi. Jednak w przypadku Polski, ze względu na ograniczenia wynikające z niewystarczającej liczby obserwacji, a więc krótkich szeregów czasowych zmiennych metrologicznych, nie mogły one zostać wykorzystane. Celem badania omawianego w artykule jest ocena wpływu metrologii na gospodarkę w Polsce z wykorzystaniem modelu wzrostu Solowa. Model ten umożliwia podejście symulacyjne poprzez zakłócenia w TFP. Zgodnie z wiedzą autorów takie podejście nie było dotychczas stosowane do analizowania wpływu metrologii na gospodarkę.

Badanie wykazało, że 1-procentowy wzrost zapasów netto norm koreluje ze wzrostem wydajności pracy, mierzonej jako wielkość produkcji na pracownika, o 0,35%. Wyniki te są zgodne z podobnymi analizami przeprowadzonymi w innych krajach i przyczyniają się do lepszego zrozumienia ekonomicznego znaczenia metrologii.

Słowa kluczowe: metrologia, ocena wpływu, model Solowa, całkowita produktywność czynników, TFP

1. Introduction

Metrology is a unique and multifaceted discipline that encompasses a wide range of theoretical and practical aspects related to measurement. Its interdisciplinary nature stems from its comprehensive approach to understanding measurement processes and solutions. As Konieczko and Namieśnik (2007, p. 309) highlight, metrology encompasses all facets of knowledge related to measurements, thereby establishing its significance across various fields of study. This breadth of application underscores the importance of metrology as a foundational element in both scientific inquiry and practical implementation. Metrology plays a critical role in the economy, as noted by Semerjian and Watters (2000). Its significance extends beyond mere measurement, impacting various spheres of socio-economic life, many of which may not be overtly visible. Often, the participants of these socio-economic activities do not engage directly with the metrological processes. Precision and standardisation in measurements are essential for ensuring safety and functionality of state services and products. Metrological practices are vital to monitoring reliability across numerous domains, including health and life protection, commercial transactions, and the maintenance of product and service quality. The application of standardised markings by manufacturers serves a dual purpose: it provides protection to consumers while imposing compliance obligations on sellers and distributors. These obligations necessitate the adherence to defined regulations concerning product marking, ultimately fostering a safer and more reliable marketplace.

The implications of inadequate or inexistent measuring practices encompass significant risks to public health, infrastructure and the environment. Metrology is thus integral to a diverse array of fields, including trade and services, industrial applications, healthcare, defence and environmental conservation. Furthermore, metrology is fundamental to enhancing the competitive edge of utility services. Ensuring compliance with and safeguarding metrological standards is crucial, alongside ongoing research dedicated to the verification and development of novel measurement methodologies that keep pace with advancements in technology and application. Metrology primarily resides within the domain of research and development (R&D). A symbiotic relationship emerges between these sectors, particularly in the context of new technologies, innovations and scientific inquiry that leverage technical and technological progress (Temple & Williams, 2002). The R&D activities that derive from metrological resources foster economic development and innovation, thereby enhancing national competitiveness over time (Link & Sardar, 2023).

The pivotal role of metrology in the economic ecosystem is unequivocal; however, it remains an underexplored subject, particularly with regard to the economies for which relevant statistical data is either unavailable or insufficient for comprehensive time-series analyses. This observation is particularly pertinent to Poland, which has experienced substantial qualitative transformations over the past three decades. To address the impact of metrology comprehensively, this study utilises the Solow economic growth model (Solow, 1956), facilitating a simulated analysis of the influence of metrology on various applications. The motivation behind the choice of this particular methodological approach stems from the desire to bridge existing research gaps within the relevant literature. The aim of the study presented in the article is to assess the impact of metrology on the economy in Poland by means of the Solow growth model. The findings presented in this study contribute to the theoretical discourse in the metrology field, with a particular emphasis on identifying and discussing critical metrological variables.

2. Literature review

Numerous studies have explored the relationships between metrological and economic variables, as evidenced in the existing literature. Below we discuss selected contributions.

According to Blind et al. (2000), national studies consistently indicate that the establishment of standards has a positive influence on economic growth, primarily through the enhancement of knowledge diffusion. The contribution of such standards to the growth rate varies by country, with estimates of 0.9% for Germany, 0.8% for both France and Australia, 0.3% for the United Kingdom, and 0.2% for Canada. Furthermore, the authors employed a model where economic growth (the dependent variable) is analysed in relation to several independent variables, namely gross fixed assets (capital), employment figures (labour), patent counts, licensing expenditures, and the quantity of established standards. Notably, it was found that post-German reunification, standards contributed a stabilisation of economic growth, accounting for approximately 0.7% to 0.8% of gross domestic product.

Lambert (2010) presents a comprehensive overview of the existing literature that underscores the critical role of measurement in fostering business innovation. The study elucidates the contribution of measurement knowledge to enhancing innovation practices within various business sectors. Specifically, it identifies a positive correlation between the availability of measurement knowledge and the types and intensity of innovation firms undertake. Companies operating in industries with a substantial amount of standards tend to place a higher value on the information content derived from 'technical, industry, or service standards'. Firms that rely heavily on instrumental tools, on the other hand, typically attribute greater value to information sourced from suppliers. In this study, regression models assessing five distinct measures of innovation from the surveys were employed to estimate the marginal probabilities associated with the measurement intensity indicator. By accounting for various controlling factors influencing the likelihood of individual firms engaging in innovation, the analysis demonstrated that the measurement intensity variable significantly impacted the likelihood of a firm being categorised as an innovator. For instance, one survey indicated a positive and statistically significant impact on innovation at conventional significance levels – specifically, better than 1% – concerning product and process innovation categories.

Furthermore, a positive marginal probability linked to novel process innovation also turned out statistically significant. Notably, a hypothetical firm operating within a richer measurement environment is projected to experience an increase of approximately 0.024 in the probability of being actively engaged in innovation. The second study conducted by Frenz and Lambert examines the relationship between types of innovation and their respective impacts on productivity and growth. Their findings demonstrate that indicators of measurement knowledge contribute positively and significantly to both productivity and growth, complementing the effects of product and process innovations. This reflects the inherent nature of measurement as a general-purpose technology that is pervasive in production, distribution, and innovation processes. The measurement score variables are shown to be highly significant within the dependent variables of the productivity equation.

An analysis of the coefficient indicate an 8%-increase in labour productivity for each unit change in the measurement score.

Link (2021) investigates the correlation between a specific output of measurement science, namely the calibration tests conducted at the U.S. National Institute of Standards and Technology (NIST), and aggregate productivity levels. The findings indicate a positive relationship between these two variables. The establishment of measurement standards enhances the likelihood that a company's manufacturing process will achieve a greater success than in scenarios lacking such standards. Furthermore, the presence of these measurement standards is bound to elevate the market value of the manufacturing output generated by a company as a result of smaller information asymmetries and reduced transaction costs. An important conclusion drawn from econometric modelling is that a 10-percent increase in calibration tests conducted at NIST correlates with a 0.32-percent increase in the U.S. multifactor productivity index, a result that is statistically significant at the 1-percent or higher level.

Miotti (2009) conducted a survey among French firms, revealing that the contribution of standards to gross domestic product (GDP) growth from 1950 to 2007 was both positive and statistically significant. It averaged 0.81% annually, accounting for nearly 25% of the GDP. Notably, two-thirds (66%) of the surveyed respondents associated voluntary norms with organisational benefits, while 34% considered them a financial burden. The author used the transformation of the Cobb-Douglas production function to demonstrate that the growth in total factor productivity, which encompasses technical progress, is significantly influenced by the robustness of the standards portfolio and the accumulation of scientific and technological knowledge. The author also asserted a strong correlation between innovation, technological progress and their dissemination, indicating that the dissemination can be effectively proxied by standardisation activities.

Robertson and Swanepoel (2015) conducted an analysis based on international studies that quantified the impact of a 1-percent increase in the stock of standards on the total factor productivity. Their estimates indicated a range of effect from 0.1% to 0.17%. Additionally, the estimated impact on labour productivity for the same increase in standards varied between 0.05% and 0.36%. The impact on GDP ranged from 0.17% to 1%.

Swann (2009) emphasized the significant role of metrology and measurement in driving productivity growth. He demonstrated that this growth can be attributed to various factors, including the implementation of interchangeable parts, the application of measurement to the process control, and the enhancement of decision-making, all of which collectively contribute to reducing regulatory burdens. Furthermore, the author pointed out that metrology and measurement were essential for fostering innovation, as they not only enhanced the efficiency of research and development processes, but also facilitated the introduction of new products to discerning consumers products by innovative manufacturers. Additionally, he observed that metrology and measurement played a critical role in minimising transaction costs and mitigating market failures. He concluded that although metrological research incurred substantial fixed costs, its findings could be disseminated fairly widely at a relatively low marginal costs.

The study conducted by Stokes et al. (2011) employed econometric analysis to assess the role of standards in enhancing total factor productivity (TFP) in New Zealand over the period from 1978 to 2009. The findings indicated that an increase of 1% in the number of standards correlates with a 0.10-percent rise in TFP. It is important to note, however, that these estimates carry a degree of uncertainty, primarily due to the often-indirect and qualitative nature of the impact of standards. The research also concluded that a 1-percent increase in standards translates into a 0.054-percent improvement in labour productivity.

In the report by the Centre for Economics and Business Research (2015), an econometric model that used the Cobb-Douglas function was developed. In that model, labour productivity served as a dependent variable. The explanatory variables included (but were not limited to) the technical equipment used at work and the net stock of standards. The econometric analysis indicated that standards accounted for approximately 37.4% of the annual growth in labour productivity of the British economy over the period from 1921 to 2013, which is equivalent to roughly 28.4% of the annual growth in GDP. Notably, prior studies conducted in France and Germany concluded with similar findings.

In conclusion, the results of prior research indicate that a 1-percent enhancement in the implementation of metrological standards translates into an increase in TFP ranging from approximately 0.1% to 0.17%. Furthermore, this enhancement correlates with the rise in labour productivity by an estimated 0.05% to 0.36%, and the growth in GDP by about 0.17% to 1%.

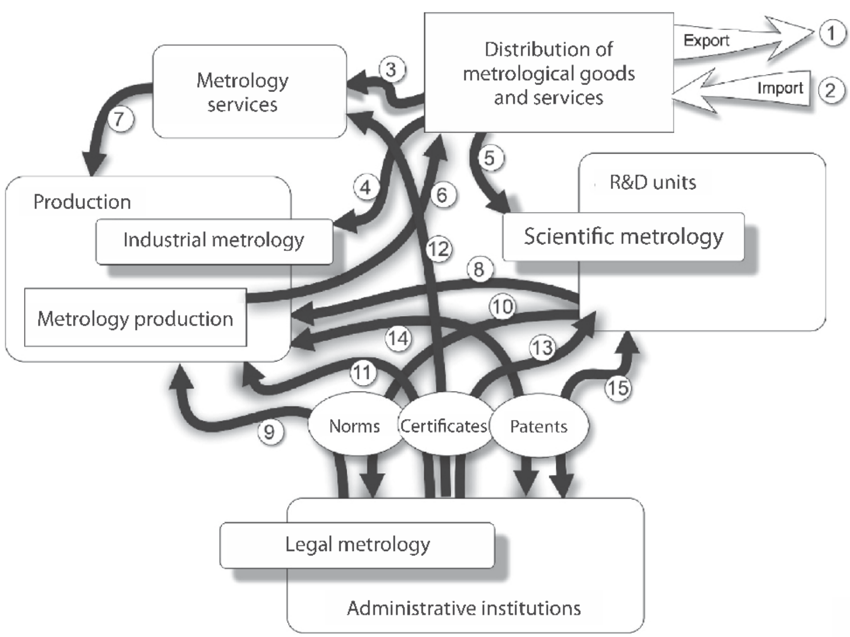
This research employs extensive time series data concerning metrological variables. Specifically, as highlighted in the report by the Centre for Economics and Business Research (2015), the key metrological variable analysed is the net number of norms (or standards). This variable is defined as the difference between the number of norms introduced in a given year and the number of norms that have been withdrawn. The time series spans from 1902 to 2014 and investigates the impact of metrological norms on the national income (adjusted for constant prices), employment and capital, excluding housing construction.

In the current body of research, Vector Error Correction Models (VECM) are constructed using the Cobb-Douglas production function, which facilitates the examination of the cointegration – indicative of a long-term equilibrium – among metrological variables and fundamental macroeconomic indicators. These models are typically estimated using annual datasets, often derived from extensive time series. However, such comprehensive data for Poland are not available at the moment.

3. Metrological variables: how to measure metrology in Poland?

Adopting a comprehensive definition of metrology enables the identification of its various components, which span multiple domains of economic activity. These domains exhibit diverse relations and interactions within the broader economic environment. A thorough analysis of these interconnections facilitates the understanding of the channels through which metrology influences the economy. Consequently, this analysis aids in isolating the critical variables necessary for a robust evaluation of the impact of metrology on economic performance. Figure 1 illustrates the interrelationships between the components of the economic environment and metrology.

Figure 1. Streams of the impact of metrology on the economic environment



Source: authors' work.

As illustrated in Figure 1, the interactions between the various components of the economic environment and metrology are highly complex. It is important to note that the figure does not show all the existing relationships, but rather highlights the principal connections. Based on Figure 1, the following parameters, identified by numbers from 1 to 15, can be defined as metrological variables:

1. the value of exports of metrological instruments;
2. the value of imports of metrological instruments;
3. the value of metrological instruments allocated to service activities;
4. the value of metrological instruments allocated to production activities;
5. the value of metrological instruments allocated to research and development (R&D) activities;
6. the value of metrological instruments manufactured by industry;
7. the value of metrological services rendered by specialised companies serving the production industry;
8. the value of the transfer of innovative technological solutions in the field of metrology from research institutions to the industry;
9. the number of standards disseminated to production activities by regulatory bodies;
10. the number of new normative solutions developed;
11. the number of metrological certificates issued for production activities;
12. the number of metrological certificates issued for service activities;
13. the number of metrological certificates issued for research and development units;
14. the number of patents acquired or submitted for protection by manufacturing entities;
15. the number of patents acquired or submitted for protection by R&D entities.

The considerations should begin with establishing which metrological means are distributed in the economic cycle and determining how many of these means a given economy has to export (1) and import (2) to indicate it is highly developed. Furthermore, these metrological means can be categorised on the basis of technological advancement. We propose a triadic division of these categories: (i) the first group encompasses simple electro-mechanical devices and measuring sensors, i.e. instruments such as pressure sensors, calipers, micrometers, and temperature sensors; (ii) the second group consists of complex measuring devices characterised by a substantial electronic infrastructure, e.g. apparatus such as recorders, oscilloscopes, and advanced electronic meters; and (iii) the third group is made up by highly sophisticated metrological systems that integrate comprehensive mechanical, electronic, and IT components (with a particular emphasis on the latter), as it significantly enhances the value proposition of these systems. This latter group includes advanced technologies such as Coordinate Measuring Machines (CMM), vision scanners, coordinate tomographs, and thermal imaging systems designed for non-destructive testing.

The extent of the proliferation of metrological instruments may serve as an indicator of the technological advancement of an economy. Entities engaged in the distribution of metrological instruments supply specialised non-production service companies (3) that provide metrological services to the industrial sector (7). The value associated with these services, alongside the number of specialised entities, reflects the metrological potential of productive economic entities functioning within a particular economy. These entities also supply the manufacturing industry directly (4). The industry, in turn, procures means for the process and embedded metrology (refer to Figure 1). It is pertinent to conducting an analysis categorised by groups of technological advancement. A critical determinant of the metrological standard of the economy is whether the industry itself manufactures metrological means for distribution (6) and the level of technological advancement associated with this production. An economy that lacks the capability to supply its own advanced metrological means indicates a low level of innovation potential. Another significant factor is the volume of metrological means supplied to R&D units (5), which can be categorised into basic research (involving a longer payback period and lower probability of return; a substantial portion of basic research does not result in immediate application to industry) and industrial research (characterised by a shorter payback period). From the metrological point of view, it is crucial to ascertain whether research and development units could engage in research aimed at the advancement of metrological technologies.

The innovative capacity of an economy is significantly influenced by the flow of new technological solutions stemming from the field of metrology, which transfers knowledge from research institutions to the industrial sector (8). In examining the effect of metrology on the economic performance, one must consider the role of administrative bodies governing the legal framework of metrology. These institutions engage with production entities, offering essential normative solutions (9) and conducting certification activities (11). In advanced economies, R&D sectors actively pursue investigations to establish new metrological standards that can be implemented within the economic framework (10), in contrast to economies that lack the ability to locally or globally implement normative solutions and thus tend to rely on imports of such solutions.

The certification efforts undertaken by administrative offices may encompass metrological service operations (12) and activities conducted by research and development entities (13). The extent of financial investment devoted to upkeeping certified research laboratories within the manufacturing sector, as well as specialised metrological services and R&D institutions, serves as an additional indicator of the technological advancement of an economy and of the significance of metrology within it. The manufacturing industry (14) and R&D sectors (15) collaborate with administrative offices in the domain of metrology, particularly concerning intellectual property protection and the assessment of the patent fidelity of emerging metrological technological solutions. A quantitative analysis of these activities and associated expenditures facilitates the evaluation of the innovative potential of an economy from a metrological standpoint.

The examination of the influence of metrology on the economy encompasses a range of relationships between a broadly-defined concept of metrology and various economic facets. The complexity of the conducted analyses is contingent on the availability of data that elucidates the streams of impact characterised by metrological variables. It is imperative to consider the potential for categorising specific sets of relationships and for simplifying research models through the exclusion of certain relationships. Drawing from the aforementioned relationships between the broadly-understood metrology and diverse aspects of economic activity, one can endeavor to conceptualise the impact of metrology on the economy as a regulatory system, analogous to industrial automation. This framework may enhance the contemplation of mechanisms for managing individual streams of impact of metrology, thereby fostering greater dynamism in economic development.

Given the complexity of the issue outlined above, this study proposes examining scientific problems through the lens of a sample metrological variable. More specifically, we investigate the influence of the 'net stock of standards' on economic development in Poland. The ensuing scientific challenges can be articulated as follows:

1. insufficient comprehensive analysis of metrology's role in Poland's economic development;
2. application of the Solow model as a methodological framework;
3. inclusion of metrological variables in econometric analyses.

Ad 1.While existing studies demonstrate a positive correlation between metrological standards and economic growth in various countries, there is a noticeable gap in the scientific literature dealing this phenomenon regarding Poland. The absence of extensive longitudinal data encompassing metrological indicators and economic fluctuations underscores the necessity for in-depth studies to evaluate how metrology influences the growth of the Polish economy.

Ad 2. This study advocates adopting the Solow growth model to analyse the relationship between metrology and economic performance. This methodological approach has not yet been employed in metrology- or economic development-related research. The relevance of the Solow model as a tool for examining this problem in Poland needs further exploration, and it does not address the essential issue of identifying effective research methodologies.

Ad 3. The study posits that an increase in the number of metrological standards could potentially influence various economic dimensions, including labour productivity, capital equipment intensity, investment levels and consumption patterns. However, the inadequacy of the available econometric data for Poland is a serious challenge to evaluating this impact. Therefore, it is crucial to formulate more sophisticated econometric models that integrate metrological variables to accurately measure their contributions to economic development.

To sum up, the scientific inquiry regarding the impact of the 'net stock of standards' on Poland's economic development struggles with the lack of comprehensive analyses and data, the necessity to use econometric models, and the need to evaluate the applicability of the Solow model to the Polish economy.

4. The Solow model and the influence of metrology

Models that assess the influence of metrology are generally grounded in the Cobb-Douglas production function, incorporating key variables such as capital (*K*), labour (*L*), TFP.

$$Y = AK^{\alpha}L^{1-\alpha}, \tag{1}$$

where

A is the total factor productivity (TFP),

α is the flexibility of production with respect to capital.

In this function, the sum of the exponents is equal to one, indicating the presence of constant returns to scale. After dividing bilaterally by the work (*L*), we obtain a function in intensive form:

$$y = Ak^{\alpha}, \tag{2}$$

where

$y = \frac{Y}{L}$ is labour productivity (production per employee),

$k = \frac{K}{L}$ is technical equipment of labour (capital per employee).

This study posits that the influence of metrology is encapsulated within parameter A, i.e. TFP. This assertion is premised on the understanding that advancements in metrology significantly enhance the efficiency of production factors, among other contributions. Furthermore, the effect of metrology on fundamental macroeconomic indicators can be evaluated through simulations employing the Solow growth model. In this context, certain hypotheses regarding the growth rates of the relevant variables will be established, reinforcing the premise that the impact of metrology resides within parameter A:

$$A = A_c m^{\gamma}, \tag{3}$$

where
A_c is TFP without metrology influence,
m is the growth factor of the metrological variable (e.g. if the number of standards increases by 10%, then $m = 1.1$),
γ is impact of the metrological variable on TFP.

Parameter A is influenced by various factors, including metrology, which is specifically represented by the exponent m^{γ}. The degree of this influence will be ascertained through the effects of changes in parameter A that arise from variations in m^{γ}. Furthermore, the impact of metrology γ can be calibrated through multiple methodologies, such as leveraging findings from ancillary studies or employing econometric estimation techniques. Assumptions regarding fluctuations in m may be established, enabling the execution of simulations. Consequently, the foundational equation of the Solow growth model can be written in the following way:

$$sAk^{\alpha} = \frac{dk}{dt} + (\lambda + \delta + g)k, \tag{4}$$

where
s is the savings rate (equal to investment rate),
λ is the population growth rate,
δ is the capital depreciation rate,
g is the technological progress.

The equation can be addressed using the Bernoulli substitution method (refer to Appendix). The outcome of the Solow model reads:

$$k_t^{1-\alpha} = \frac{sA}{\lambda + \delta + g} + \left(k_0^{1-\alpha} - \frac{sA}{\lambda + \delta + g}\right) e^{-(1-\alpha)(\lambda+\delta+g)t}, \tag{5}$$

where k_0 represents the initial value.

The equation governing the time path incorporates time index t, necessitating the introduction of indices for the other variables as well. To derive the metrological factor, we substitute equation (3) with equation (5).

$$k_t^{1-\alpha} = \frac{sA_c m^\gamma}{\lambda + \delta + g} + \left(k_0^{1-\alpha} - \frac{sA_c m^\gamma}{\lambda + \delta + g}\right) e^{-(1-\alpha)(\lambda+\delta+g)t}. \tag{6}$$

Equation (6) provides a framework for determining the temporal trajectory of the capital-labour ratio ($k = \frac{K}{L}$) as well as other key variables, including production (y), investment (i), and consumption (c) per unit of labour. To determine (6), the following parameters must be defined in advance: $s, A_c, \gamma, \lambda, \delta, g, \alpha$.

The analysed variables are calculated per one employed person. One can make assumptions about the changes in factor m and study by simulation what the impact of metrology on k and then on (efficiency) labour productivity y is. Labour productivity (y) is the sum of consumption (c) and investment (i), i.e. $y = c + i$. Investment is $i = sy$. Having determined s and y, one can evaluate consumption per capita $c = (1 - s)y$. This approach allows the simulation of the effects of metrology on fundamental macroeconomic variables, including capital, production, investment and consumption, within the framework of the Solow model.

5. An econometric assessment of the impact of metrology on basic macroeconomic variables

In the econometric literature, VECMs have been constructed using the Cobb-Douglas production function to investigate the cointegration, or long-term equilibrium, between metrological and fundamental macroeconomic variables. Typically, these models are estimated on the basis of annual datasets that encompass extended time series. However, in the case of Poland, the available time series data is considerably shorter, which has implications for the econometric methodologies employed, as the examination of cointegration necessitates long time series data. Furthermore, the available data on the current standards spans the years 2010 to 2022.[1]

To assess the influence of the quantity of standards (specifically, the net stock of standards) on GDP, the following model has been constructed:

$$y_t = A_c e^{gt} m_t^\gamma k_t^\alpha e^{u_t}, \tag{7}$$

where

y_t is GDP per employee in year t (PLN thousand/person),

A_c is the intercept,

t is the time variable,

[1] Due to data availability, the time span for model (7) is slightly different from that of the subsequent simulations based on model (9).

m_t is number of current standards per million employees,
k_t is the gross value of fixed assets per employee (PLN thousand/person),
u_t is the random error,
A_c, g, γ, α are the structural parameters of the model.

To mitigate the effects of inflation, all variables measured in PLN (y_t, k_t) were adjusted to reflect the prices of the year 2010. The GDP deflator served as the basis for these calculations. Model (7) assesses the influence of the number of standards expressed per million employees on GDP. Parameter g (incorporating the time variable) quantifies the effect of technological advancement.

The logarithmic specification of the model (7) is expressed as follows:

$$\ln y_t = \ln A_c + gt + \gamma \ln m_t + \alpha \ln k_t + u_t. \tag{8}$$

The results derived from model (8) estimation are presented in Table 1.

Table 1. Model (8) estimation results, $R^2 = 0.924, d = 0.757$

Variable	Parameter estimate	Standard error	*t*-statistic	*p*-value
$\ln A_c$	5.941	2.311	2.571	0.033
t	0.044	0.020	2.174	0.061
$\ln m_t$	0.160	0.150	1.044	0.327
$\ln k_t$	−0.440	0.536	−0.822	0.435

Source: authors' estimations.

The model does not facilitate assessing the influence of the quantity of standards on productivity per employee. Apart from the intercept, none of the parameters demonstrate a statistically significant deviation from zero at the specified significance level $\alpha = 0{,}05$. Notably, the effect of the technical equipment employed in the work process is negative, albeit statistically insignificant. Furthermore, $d < R^2$, which suggests the potential for a spurious regression.

In conclusion, the shortness of the time series concerning the current standards in Poland precludes an econometric evaluation of this variable's impact on GDP per employee.

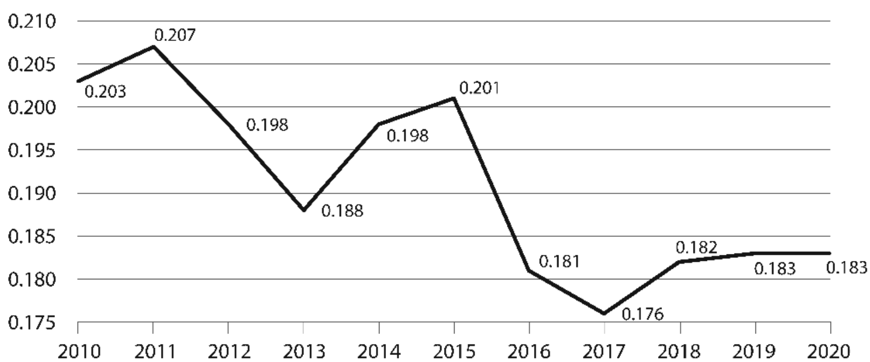
6. Simulation analysis of the impact of metrology on macroeconomic variables

The starting point for the simulation is equation (6), where the time path of technical work equipment is determined. In the first stage, the parameters occurring in the Solow model should be calibrated: $\gamma, s, \lambda, A_c, g, \alpha, \delta$.

The γ parameter indicates the impact of the number of standards on TFP. Based on previous studies presented in the literature, it was assumed that $\gamma = 0.1$.

The s parameter is the share of investment in production per employee (investment rate). Figure 2 presents the dynamics of the investment rate in Poland.

Figure 2. Investment rate in the national economy in Poland

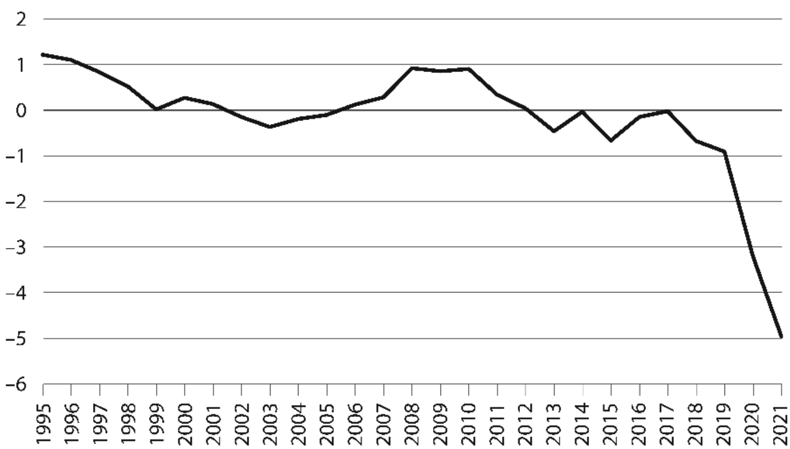


Source: authors' work based on Statistics Poland's data.

The investment rate shows a declining trend. In 2010, it was measured at 0.203, subsequently decreasing to 0.183 by 2020. For the purpose of simulations, the value of s was assumed to be 0.2.

Considering the dynamics of natural increase in Poland (see Figure 3), parameter λ was set to –0.005, indicating a decline in the population at an annual rate of 0.5%. It is noteworthy that the natural increase has been negative since 2013. The significant reduction in natural increase observed in 2021 can be attributed to the impact of the COVID-19 pandemic.

Figure 3. Natural increase per 1,000 population in Poland



Source: authors' work based on Statistics Poland's data.

Parameters A_c, g, α were estimated in accordance with the model specified by the equation

$$\ln y_t = \ln A_c + gt + \alpha \ln k_t + u_t, \tag{9}$$

where u_t denotes a random component.

Model (9) was estimated using data from 2009 to 2021, with all variables expressed in terms of 2009 prices. The findings resulting from the estimation of this model are illustrated in Table 2.

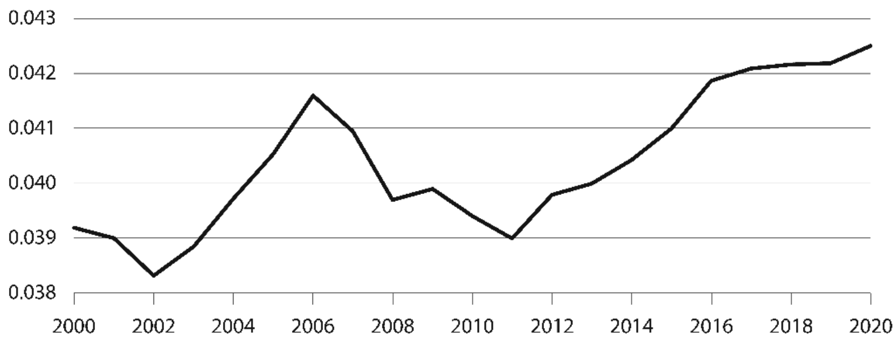
Table 2. Model (9) estimation results, $R^2 = 0.977, d = 1.364$

Variable	Parameter estimate	Standard error	*t*-statistic	*p*-value
$\ln A_c$	0.474	0.822	0.577	0.577
t	0.011	0.003	3.925	0.003
$\ln k_t$	0.725	0.146	4.960	0.001

Source: authors' estimations.

The estimation results for Model (9) demonstrate satisfactory performance. Except for the intercept, the parameters show statistical significance at the 0.05 level. The coefficient of determination is considerably high, and the $d > R^2$ condition suggests the absence of spurious regression. Consequently, the simulations are based on the following parameters: $A_c = 1.606; g = 0.011;$ $\alpha = 0.725$. The capital depreciation rate, defined as the ratio of depreciation to gross assets, is illustrated in Figure 4.

Figure 4. Capital depreciation rate in Poland



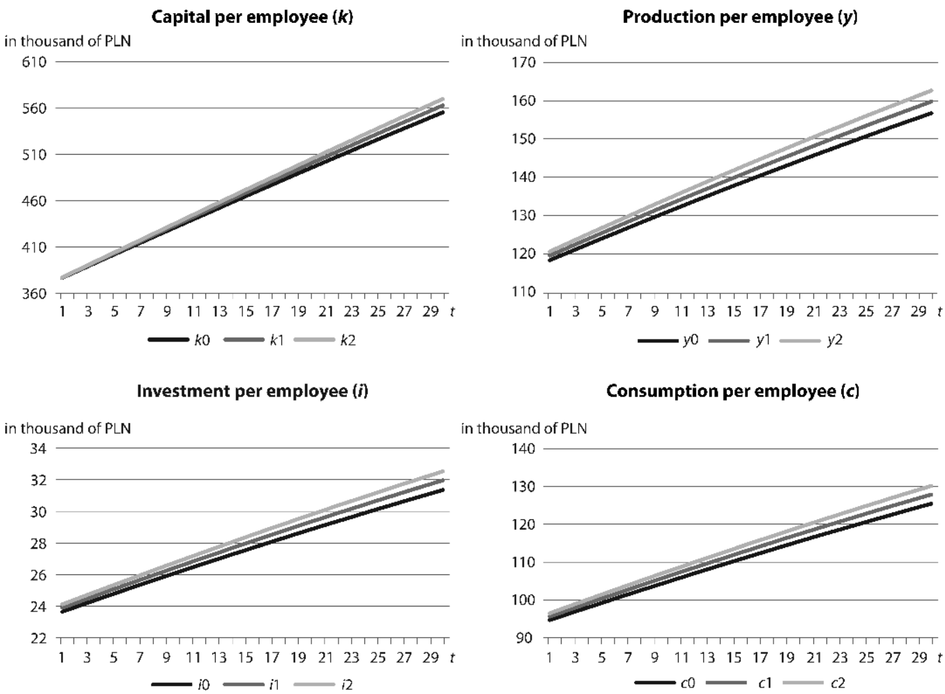
Source: authors' work based on Statistics Poland's data.

The average value of the capital depreciation rate is 0.04. Therefore, it was assumed that $\delta = 0.04$. To sum up, the following parameter values were assumed in the simulations based on the Solow model:

$\gamma = 0.1$
$s = 0.2$
$\lambda = -0.005$
$A_c = 1.606$
$g = 0.011$
$\alpha = 0.725$
$\delta = 0.04$.

In the initial phase of the analysis, capital time paths were established in accordance with the relationship delineated in equation (6). Three scenarios were postulated concerning the potential influence of metrology. In the baseline scenario, it was assumed that metrology had no effect ($m = 1$). In the subsequent scenarios, on the other hand, it was assumed that the coefficient representing changes in the number of standards was $m_1 = 1.1$ and $m_2 = 1.2$ indicating increments of 10% and 20%, respectively. The results of graphical simulations for the subsequent 30 periods are illustrated by the Figure 5.

Figure 5. Time paths for the studied macroeconomic variables depending on the impact of metrology



Note. Indices '0', '1' and '2' represent simulation scenarios. '0' is a variant that does not alter the impact of metrology, '1' indicates a 10% increase in the impact of metrology, and '2' signifies a 20% increase in the impact of metrology.
Source: authors' estimations.

The aforementioned figures demonstrate that metrology, and the quantity of standards in particular, favourably affects the studied macroeconomic variables. Now the question arises as to the degree of this influence. To ascertain metrology's comprehensive impact, one can calculate its effect on the equilibrium point within the Solow growth model.

Based on the implications of relationship (6), it can be assumed that if time approaches infinity ($t \to \infty$)

$$k_t^{1-\alpha} \to \frac{sA_c m^\gamma}{\lambda + \delta + g}, \tag{10}$$

$$k_t \to \left(\frac{sA_c m^\gamma}{\lambda + \delta + g}\right)^{1/(1-\alpha)}. \tag{11}$$

Formula (11) facilitates determining the capital intensity of labour in the state of equilibrium. For the variants under consideration, this solution yields the following results:
$m \;\; = 1: \bar{k}_t = 1172.62$
$m_1 = 1.1: \bar{k}_t = 1213.97$
$m_2 = 1.2: \bar{k}_t = 1252.99.$

Based on the aforementioned solutions, it can be concluded that a 10-percent increase in the number of standards corresponds to a long-term increase in the value of k by 3.5%, while a 20-percent increase in the number of standards results in a 6.9-percent increase in k. To sum up, we observed that a 1-percent increase in metrology, quantified by the number of standards per a million employees, leads to a 0.35-percent rise of the capital intensity of labour. Similar proportional changes are applicable to the other variables *(y, c, i)*.

7. Conclusions

This study aims to propose the Solow model of economic growth as a framework for assessing the impact of metrology on the economy. A significant part of the existing literature regarding the macroeconomic implications of metrology involves estimating econometric models that account for the cointegration of macroeconomic variables alongside metrological variables. However, the development of such models necessitates extensive time series data, which is not readily available for all economies, including Poland. The Polish economy has been functioning under market principles for merely three decades, experiencing numerous transformations during this timeframe, including qualitative changes. Consequently, the Solow model, which facilitates simulation analyses, has been employed to evaluate the impact of metrology on economic outcomes.

The parameters of the Solow model were calibrated using statistical data. Specifically, the parameter representing the effect of the metrological variable (defined as the number of current standards) on TFP was derived from analogous studies conducted in other economies. Within the framework of the Solow model, it is posited that the metrological variable influences TFP.

The simulation study elucidates the impact of the metrological variable on labour productivity (measured as production per employee), the capital intensity of labour, and investment and consumption patterns. The synthetic impact of metrology on labour productivity is quantified at 0.35%, indicating that a 1-percent increase in the net stock of standards results in a 0.35-percent enhancement in labour productivity. This effect also applies to the technical equipment of labour, investment, and consumption. Notably, this finding aligns with results established in comparative studies across other economies.

Future studies will employ alternative methodologies, including multi-equation econometric models, to validate the obtained results and assess metrology's impact on the economy.

Acknowledgements

This publication was financed from the state budget as part of the Minister of Education and Science programme called 'Polish Metrology' (Pol. Polska Metrologia). The project (no. PM/SP/0023/2021/1) is titled 'Assessment of the impact of metrology on the Polish economy'.

References

Blind, K., Jungmittag, A., & Mangelsdorf, A. (2000). *The Economic Benefits of Standardization. An update of the study carried out by DIN in 2000*. DIN German Institute for Standardization. https://www.din.de/resource/blob/89552/68849fab0eeeaafb56c5a3ffee9959c5/economic-benefits-of-standardization-en-data.pdf.

Centre for Economics and Business Research. (2015). *The Economic Contribution of Standards to the UK Economy*. https://www.bsigroup.com/LocalFiles/en-GB/standards/BSI-standards-research-report-The-Economic-Contribution-of-Standards-to-the-UK-Economy-UK-EN.pdf.

Konieczko, P., & Namieśnik, J. (Eds.). (2007). *Ocena i kontrola jakości wyników pomiarów analitycznych*. Wydawnictwo Naukowo-Techniczne.

Lambert, R. (Ed.) (2010). *Economic Impact of The National Measurement System*. National Measurement System. https://assets.publishing.service.gov.uk/media/5a7c258540f0b645ba3c6fbc/nms-economic-impact-evidence-paper-r-lambert-july-2010.pdf.

Link, A. N. (2021). *The Economics of Metrology: An Exploratory Study of the Impact of Measurement Science on U.S. Productivity, Department of Economics* (UNCG Working Paper No. 21-1).

Link, A. N., & Sardar, R. R. (2023). R&D and regional competitiveness: a study of global entrepreneurial firms. *International Entrepreneurship Management Journal*, *19*(1), 369–378. https://doi.org/10.1007/s11365-022-00825-2.

Miotti, H. (2009). *The Economic Impact of Standardization. Technological Change, Standards Growth in France*. Afnor Group. https://normalisation.afnor.org/wp-content/uploads/2016/06/Etude-ImpactEcoNorm-GB2009.pdf.

Robertson, K., & Swanepoel, J. A. (2015). *The economics of metrology* (Australian Government, Department of Industry, Innovation and Science Research Paper 6/2015). https://www.industry.gov.au/sites/default/files/June%202018/document/pdf/the_economics_of_metrology.pdf.

Semerjian, H. G., & Watters, R. L. Jr (2000). Impact of measurement and standards infrastucture on the national economy and international trade. *Measurement*, *27*(3), 179–196. https://doi.org/10.1016/S0263-2241(99)00065-2.

Solow, R. M. (1956). A Contribution to the Theory of Economic Growth. *The Quarterly Journal of Economics*, *70*(1), 65–94. https://doi.org/10.2307/1884513.

Stokes, F., Dixon, H., Generosa, A., & Nana, G. (2011). *The Economic Benefits of Standards to New Zealand*. Business and Economic Research Limited. http://academico.une.org/Documents/BERLreportontheeconomicbenefitsofSNZAug2011.pdf.

Swann, G. M. P. (2009). *The Economics of Metrology and Measurement*. Innovative Economics Limited. https://assets.publishing.service.gov.uk/media/5a7c32ece5274a25a91411ea/prof-swann-report-econ-measurement-revisited-oct-09.pdf.

Temple, P., & Williams, G. (2002). Infra-technology and economic performance: evidence from the United Kingdom measurement infrastructure. *Information Economics and Policy*, *14*(4), 435–452. https://doi.org/10.1016/S0167-6245(02)00065-3.

Appendix: Solving the Solow model

The Solow equation with the influence of metrology reads:

$$sAk^{\alpha} = \frac{dk}{dt} + (\lambda + \delta + g)k. \tag{A1}$$

This equation can be solved using the Bernoulli substitution.
We substitute

$$z = k^{1-\alpha}, \tag{A2}$$

then differentiate (A2)

$$\frac{dz}{dt} = (1-\alpha)k^{-\alpha}\,\frac{dk}{dt}. \tag{A3}$$

and divide (A3) by $(1-\alpha)$

$$\frac{1}{(1-\alpha)}\frac{dz}{dt} = k^{-\alpha}\,\frac{dk}{dt}. \tag{A4}$$

Equation (A1) is divided by k^{α}

$$sA = \frac{dk}{dt}k^{-\alpha} + (\lambda + \delta + g)k^{1-\alpha}. \tag{A5}$$

Substituting (A4) and (A2) into (A5) we receive

$$sA = \frac{1}{(1-\alpha)}\frac{dz}{dt} + (\lambda + \delta + g)z. \tag{A6}$$

From (A6) we obtain the equation

$$\frac{dz}{dt} + (1-\alpha)(\lambda + \delta + g)z = (1-\alpha)sA. \tag{A7}$$

This is a non-homogeneous differential equation. Equation (A7) is multiplied by the integrating factor $e^{(1-\alpha)(\lambda+\delta+g)t}$

$$\frac{dz}{dt}e^{(1-\alpha)(\lambda+\delta+g)t} + (1-\alpha)(\lambda + \delta + g)ze^{(1-\alpha)(\lambda+\delta+g)t} = (1-\alpha)sAe^{(1-\alpha)(\lambda+\delta+g)t}. \tag{A8}$$

The left side (A8) is a derivative of the expression $ze^{(1-\alpha)(\lambda+\delta+g)t}$, therefore

$$\frac{d}{dt}\left(ze^{(1-\alpha)(\lambda+\delta+g)t}\right) = (1-\alpha)sAe^{(1-\alpha)(\lambda+\delta+g)t}. \tag{A9}$$

We integrate (A9), where c is a constant

$$ze^{(1-\alpha)(\lambda+\delta+g)t} = \frac{sA(1-\alpha)}{(1-\alpha)(\lambda+\delta+g)}e^{(1-\alpha)(\lambda+\delta+g)t} + c. \tag{A10}$$

We divide (A10) by $e^{(1-\alpha)(\lambda+\delta+g)t}$

$$z = \frac{sA}{\lambda+\delta+g} + ce^{-(1-\alpha)(\lambda+\delta+g)t}. \tag{A11}$$

Substituting $t = 0$, we obtain the constant c

$$c = z_0 - \frac{sA}{\lambda+\delta+g}. \tag{A12}$$

Substituting (A2) and (A12) with (A11) we receive

$$k_t^{1-\alpha} = \frac{sA}{\lambda+\delta+g} + \left(k_0^{1-\alpha} - \frac{sA}{\lambda+\delta+g}\right)e^{-(1-\alpha)(\lambda+\delta+g)t}. \tag{A13}$$