The economics of metrology: an exploratory study of the impact of measurement science on U.S. productivity

By: Albert N. Link

Link, A.N. "The Economics of Metrology: An Exploratory Study of the Impact of Measurement Science on U.S. Productivity," *Economics of Innovation and New Technology*, 2021,
DOI: 10.1080/10438599.2021.1895905.

Abstract:

Metrology is the study of measurement science. Publicly funded outputs from measurement science have public good characteristics, and thus scholars have previously investigated the economic impact of such outputs on aggregate productivity as a first look at the impact of such public funds on economic activity. This study is the first to explore the relationships between one output from measurement science—calibration tests at the U.S. National Institute of Standards and Technology (NIST)—and aggregate productivity. The finding of a positive relationship is suggested to be a springboard for future research on the economics of metrology.

Keywords: Metrology | measurement science | program management | calibration tests | public goods | R&D

Article:

1. Introduction

Metrology, the study of measurement science, is not a new topic to researchers in general; however, it is a topic that has yet to occupy the attention of many economists. This is somewhat surprising because the importance of measurement science has not only been acknowledged by classical as well as prominent contemporary economists, but also because measurement science activity has long attracted significant policy attention as well as policy-allocated resources.

Starting at the beginning in an effort to place metrology in context,[1] the following statement, dated 1821, is attributed to John Quincy Adams, the sixth president of the United States:[2]

> Weights and measures may be ranked among the necessaries of life to every individual of human society. They enter into the economical arrangements and daily concerns of every family. They are necessary to every occupation of human industry; to the distribution and security of every species of property; to every transaction of trade and commerce; to the labors of the husbandman; to the ingenuity of the artificer; to the studies of the philosopher; to the researches of the antiquarian, to the navigation of the mariner, and the marches of the soldier; to all the exchanges of peace, and all the operations of war. The knowledge of them, as in established use, is among the first elements of education, and is often learned by those who learn nothing else, not even to read and write. This knowledge is riveted in the memory by the habitual application of it to the employments of men throughout life.

President Adam's perspective complements that of Lord William Thomas Kelvin, who, in a May 1883 lecture to the Institution of Civil Engineers is acknowledged to have said:[3]

> I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the state of Science, whatever the matter may be.

Even in light of these historical references to measurement science and economic activity, and even in light of the seminal work of Swann (2009),[4] who appropriately placed measurement science in juxtaposition with the writings of Adam Smith (1776/1914) and Alfred Marshall (1920), metrology-related research remains sparse. Related to the topic of this paper, there have been only a limited number of contributions to the academic literature related to the statistical relationship between measurement science activity and economic activity.[5] These studies include, for example, Temple and Williams (2002) with respect to changes in total factor productivity in the United Kingdom, and Choudhary, Ali, and Zhao (2013) with respect to bilateral trade among European Union countries.[6]

---

[1] According to Himbert (2009, 26), the first economic use of measurement might trace as far back in time as to the activities that are claimed to have occurred in Mesopotamia in 6000 BC: "Among the oldest testimonies of measurement processes in the mid-eastern civilisations, one has to mention the clay balls (6000 BC) found in Mesopotamia: to assess for instance the size of a flock of sheep, the owner was sealing into a large clay sphere as many small balls as there were individuals in the flock, e.g. lambs. The seal was broken, if necessary, to give reliable evidence of the earlier characteristics of the flock."

[2] This passage is quoted from Richardson (1976, 1).

[3] See https://digital.nls.uk/scientists/biographies/lord-kelvin/.

[4] See also Swann (2010).

[5] I thank an anonymous reviewer for point out that the study of metrology "can be considered the less famous, and younger, sibling of the economics of standardization." There is a rich literature on the economics of standardization that traces to Hemenway (1975) and to the writings of David and others; see the references in David and Greenstein (1990).

[6] See also the U.K report by Lambert (2010) and the chapter therein by Temple, the references in Blind, Jungmittag, and Mangelsdorf (2011), and the excellent summary study by King, Lambert, and Temple (2017).

One possible explanation for the paucity of contemporary research on the economics of metrology may be the scarcity of data related to measurement activity at a national level. And, another possible explanation may, relatedly, be due to the absence of published academic papers on the topic which could be used as springboards for subsequent studies.

In this paper, I present preliminary findings from an exploratory study of the impact of calibration testing, one knowledge transfer mechanism based on measurement science, on U.S. productivity. Other researchers have investigated similar relationships for other countries as noted above, but much of that policy research has remained codified in the reports of the sponsoring governments. For example, Robertson and Swanepoel (2015), in a detailed report sponsored by the Department of Industry, Innovation and Science of the government of Australia, summarized a number of government studies that looked at the relationship between a country's stock of measurement standards and Gross Domestic Product or total factor productivity.[7] However, the absence of such aggregate studies that relate to the United States is noticeable. This paper represents an effort to contribute to an understanding of the aggregate economic importance of metrology.

The remainder of this paper is outlined as follows. In the following Section 2, I briefly describe the history of the National Institute of Standards and Technology (NIST), the national metrology laboratory in the United States, and one aspect of its measurement science activity as reflected through calibration tests. I also offer a general mathematical framework to describe the demand for such measurement science-based mechanisms.

In Section 3, I offer an empirical framework for exploring the impact of calibration tests on U.S. productivity.

Finally, in Section 4, I discuss possible avenues for future studies of the economics of metrology.

2. Measurement science at NIST[8]

Briefly, the U.S. public sector's involvement in metrology and resulting measurement science-based standards traces to the Articles of Confederation signed on July 9, 1778. Therein it is stated:

> The United States, in Congress assembled, shall also have the sole and exclusive right and power of regulating the alloy and value of coin struck by their own authority or by that of the respective States; fixing the standard of weights and measures throughout the United States …

This responsibility of 'fixing the standard of weights and measures' was repeated in Article 1 of the Constitution of the United States:

---

[7] The summary by Robertson and Swanepoel (2015) focused on the following specific countries: Australia, France, Germany, and New Zealand. The National Institute of Standards and Technology (NIST) documents the global number of metrology laboratories; see, https://www.nist.gov/iaao/national-metrology-laboratories.

[8] A more detailed history of NIST is in Link (2019) and in the NIST authored references therein.

> The Congress shall have power … To coin money, regulate the value thereof, and of foreign coin, and fix the standard of weights and measures …

The French government held an international conference in 1872, which included the participation of the United States, to establish procedures for the preparation of prototype metric standards in response to growing interest in the use of the metric system in scientific research. Then, on May 20, 1875, the United States participated in the Convention of the Meter in Paris, and it was one of the eighteen signatory nations to the Treaty of the Meter.[9] After this event, in a Joint Resolution before Congress on March 3, 1881, it was resolved that:

> The Secretary of the Treasury be, and he is hereby directed to cause a complete set of all the weights and measures adopted as standards to be delivered to the governor of each State in the Union, for the use of agricultural colleges in the States, respectively, which have received a grant of lands from the United States, and also one set of the same for the use of the Smithsonian Institution.

Following a long history of U.S. leaders calling for uniformity in science, traceable at least to the several formal proposals for the establishment of a Department of Science in the early 1880s, and coupled with the growing inability of the Office of Weights and Measures to handle the explosion of arbitrary standards in all aspects of federal and state activity, it was inevitable that a standards laboratory would need to be established. The March 3, 1901 Act (Public Law 177-156), often referred to as the Organic Act of 1901, was passed by Congress. The Office of Weights and Measures was then renamed the National Bureau of Standards (NBS).

In the mid-1980s, Congress considered 'several initiatives to improve American competitiveness in world-wide markets' (Schooley, 2020, p. 613). These considerations were eventually codified in the Omnibus Trade and Completeness Act of 1988 (Public Law 100-418). Stated therein:

> It is the purpose of this Act to rename the National Bureau of Standards as the National Institute of Standards and Technology [NIST] and to modernize and restructure that agency to augment its unique ability *to enhance the competitiveness of American industry* [my emphasis added].

This mission of NIST is: 'To promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life.' And, NIST seeks to achieve this mission through three core competencies: 'measurement science, rigorous traceability, and development and use of standards.'[10]

One for-fee service that NIST provides in pursuit of its mission is calibration testing. Calibration tests are a knowledge transfer mechanism, that is, calibrations to a national standard are a vehicle through which NIST advancements in metrology are transferred to private and public sector organizations to ensure standardized measurements. And, from an economic theory perspective,

---

[9] See, De Simone and Treat (1971) for an history of the metric system in the United States.
[10] See, https://www.nist.gov/about-nist/our-organization/mission-vision-values.

standardized measurements reduce transaction costs between buyers and sellers (Swann 2009, 60):

> The accurate measurement of product characteristics makes it easier to demonstrate quality and safety, and hence to sustain a price premium for superior products. Because of this, measurement also plays an important role in the reduction of market failure.[11]

According to NIST (USDOC 2019, 24), calibration tests are defined as:

> The NIST laboratories provide unique physical measurement services for their customers, including calibration services, special tests, and measurement assurance programs. NIST designs its calibration services to help manufacturers and users of precision instruments achieve the highest possible levels of measurement quality and productivity. NIST calibrations often serve as the basis for companies that provide commercial calibration services and calibration equipment.

Figure 1 shows the number of calibration tests performed at NIST for other organizations (i.e. for private-sector firms and public-sector agencies) over fiscal years FY 1999 through FY 2018. Two distinctive patterns of year-after-year calibration tests are noticeable in Figure 1. The first pattern relates to the increase in calibration tests from FY 2002 to FY 2003. In the source documents for these data,[12] NIST points out:

> … [in FY 2003 NIST] accredited 72 [new] calibration laboratories in fields ranging from dimensional metrology to optical and chemical. Through this overall approach, NIST efficiently leverages its primary calibration services to support a broader base of secondary calibrations conducted within the private sector.

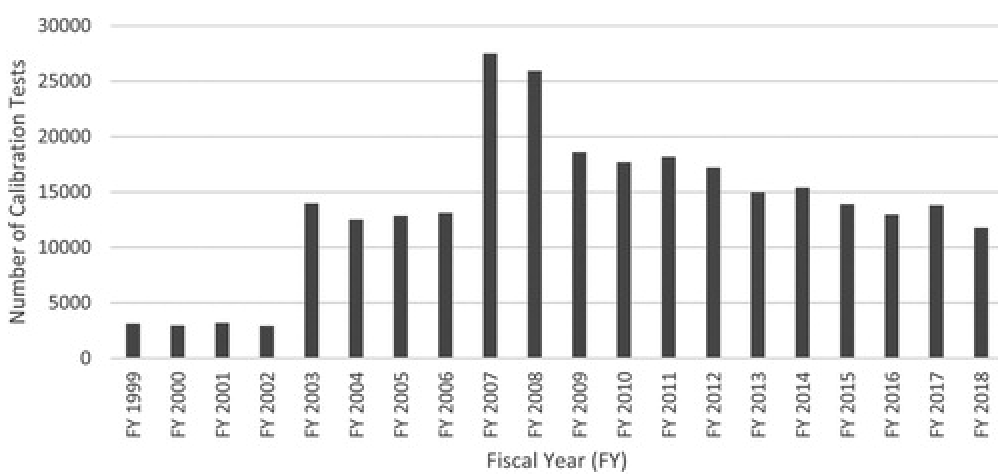

Figure 1. Calibration Tests at NIST, FY 1999 through FY 2018.
Source: https://www.nist.gov/tpo/department-commerce.

[11] Swann's (2009) reference to market failure refers to the public good characteristics of measurement standards and the associated underinvestment in measurement standards research by the private sector.
[12] See, https://www.nist.gov/tpo/department-commerce.

The second pattern in Figure 1 relates to the increase in calibration tests from FY 2006 to FY 2007. In the source documents for these data, NIST explains:

> … [the] number of calibration tests performed in FY 2007 and FY 2008 was significantly higher than the number of tests performed in FY 2005 and FY 2006 due principally to a surge in the calibration testing for the military and its contractors.

The decline from FY 2008 to FY 2009 was sharp, possibly reflecting the economic effects of the Great Recession.

Calibration testing is not the only measurement science-based activity conducted at NIST that has the potential to affect the productivity of the country. There are other mechanisms through which embodied measurement advancements leave NIST and enter the economy. The number of patents granted to NIST by the U.S. Patent and Trademark Office is one such mechanism, but calibration tests have the advantage of capturing elements of the market's demand for the embodied scientific advancements. Private and public sector organizations pay for calibration tests, and thus one might reasonably assume that the purchaser of the tests will in fact employ the test results into its production processes. Patents granted (and the patented technology can be licensed from NIST) are primarily a supply-side mechanism, and information is not available on which patents are licensed and how a licensee uses the embedded technical knowledge.[13]

One might think of the data in Figure 1 as reflecting the aggregate demand for a measurement science-based standard. The following model, posited for a manufacturing firm for illustrative purposes but also applicable at an aggregate level, illustrates that measurement science-based standards enter the economy (i.e. are demanded by a manufacturing firm) to the extent that the marginal benefit of adopting a measurement standard equals the marginal cost of doing so.

When a manufacturing firm adopts a measurement standard, it is in effect capturing new knowledge. For the adopting firm, this new knowledge is embodied in a measurement standard that has perceived value to the firm (and thus to society), but the firm cannot develop this new knowledge at a reasonable cost on its own because of the public good nature of the standard; hence, there is an underinvestment in related measurement science research from a social perspective.[14] The measurement standard is therefore provided at a cost (lower than the cost for the firm to develop it on its own) by a third party, namely by a public sector metrology laboratory or simply by the public sector.[15]

The value to the firm from adopting a measurement standard is twofold. The measurement standard increases the probability that, among other things, the manufacturing process within the

---

[13] While the empirical analysis presented in this paper represents, to the best of my knowledge, the first study to explore the relationships between one output from measurement science and aggregate productivity, NIST has a long history of sponsoring case studies to examine the economic productivity-enhancing outputs and outcomes associated with its measurement science investments. Many of these studies are documented at https://www.nist.gov/director/outputs-and-outcomes-nist-laboratory-research, but a more detailed summary of these studies is in Link and Scott (2012).
[14] This is the market failure referred to in footnote 11.
[15] The public sector does not develop standards in isolation from the private sector's needs. Many standards are consensus standards developed for and with industry.

firm will be more successful than without the measurement standard, and the measurement standard will increase the market value of any manufacturing output from the firm that results because of reduced information asymmetries and transactions cost.[16]

Let the probability (*p*) that the manufacturing process results in a successful marketable output (*Q*) be represented by the concave function *p*(*q*), where *q* indicates the quality or marketability of the output. Also, let the net revenues, *R*, associated with the production and sale of the resulting output be represented by the concave function *R*(*q*).

Let the scope of use of the measurement standard be represented by *S*, where *S* might be thought of empirically as a newly defined input in the firm's production process. The quality, *q*, of the output, *Q*, is itself assumed to be a concave function, *q*(*S*), of the level of use of the measurement standard. Thus, the expected (*e*) net revenues from the production and sale of the resulting output will be a function of *S*:[17]

$$R^e = p\big(q(S)\big) \cdot R\big(q(S)\big), \tag{1}$$

and the marginal net expected revenues (MR_S) per unit of the metric for the scope of the firm's activities that use the measurement standard in the production and sale of the output will be:[18]

$$MR_S = \ p\big(q(S)\big) \cdot R'\big(q(S)\big) + R\big(q(S)\big) \cdot p'\big(q(S)\big). \tag{2}$$

There are, of course, costs to using a measurement standard both in terms of the physical and intellectual effort required to integrate the measurement standard into the manufacturing process as well as the *per se* costs of the measurement standard. Assuming that these costs include both fixed and variable components, the cost function (*c*) can be represented by:[19]

$$c = c(S) where c(0) > 0, c'(S) > 0, and c''(S) > 0. \tag{3}$$

The optimal level of use of a measurement standard,[20] assuming the firm seeks to maximize the expected level of profit (π) from integrating a measurement standard, will be some S^* that maximizes the expected profits associated with the process of integrating the standard:

$$\pi^e(S) = p\big(q(S)\big) \cdot R\big(q(S)\big) - c(S) \tag{4}$$

that is, S^* will be that level of *S* that equates marginal net expected revenue, MR_S, to the marginal cost, *MC*, of the measurement standard integrating process:

$$p\big(q(S)\big) \cdot R'\big(q(S)\big) + R\big(q(S)\big) \cdot p'\big(q(S)\big) = c'(S). \tag{5}$$

---

[16] See Tassey (2017) for a comprehensive overview of the economics of standards.
[17] The firm will choose the best *Q* given its choice for *S*.
[18] The prime symbol (′) denotes a first derivative; here the derivative is with respect to *S*.
[19] The double-prime symbol (″) denotes a second derivative.
[20] By optimal level of use, I mean the scope of activities that benefit from the measurement standard. A measurement standard is fixed in the sense that it is either used or not used.

This final relationship is not used explicitly to formulate the empirical framework in Section 3. Rather, the model illustrates systematically that the firm will integrate measurement science-based standards into its production process to the extent that the marginal benefit equals the marginal cost of doing so.[21]

3. Empirical analysis

The empirical framework that I consider in this paper is:

$$CalibrationTests = f(NISTR\&D) \tag{6}$$

and

$$Economic\ Performance = f(Calibration\ Tests, National\ R\&D) \tag{6}$$

Calibration Tests and *Economic Performance* are the focal variables of this exploratory study. The hypothesis underlying equation (6) is that *Calibration Tests* are dependent on the research base at NIST, and the research base at NIST is assumed to be related to its research and development (R&D) budget. The hypothesis underlying equation (7) is that measurement science-based outputs, as reflected through *Calibration Tests*, are positively related to *Economic Performance*. Also entering equation (7) is the variable *National R&D* because it is well known that national investments in R&D are a primary driver of economic performance in advanced economies (Hall, Mairesse, and Mohnen 2010). Equation (7) mirrors the framework that others have used,[22] as applied here for calibration tests.

The data in Figure 1 pertain to the variable *Calibration Tests*. The R&D activity in NIST's laboratories to support its metrology research in equation (6) is measured in two ways. First, it is measured in terms of the laboratory's annual research budget, *NIST Lab R&D*; second it is measured in terms of NIST's laboratory research intensity as quantified by the ratio of the NIST laboratory research budget divided by the total NIST agency budget, *NIST Lab R&D Intensity*. Finally, a binary control variable is added to the specification of equation (6) to control for institutional effects on the number of calibration tests per year as reflected in Figure 1 and as discussed above, *Dmy Calibration Tests*.

In equation (7), *Economic Performance* is measured by a multifactor productivity index relevant to the U.S. private non-farm business sector of the economy.[23] *National R&D* is measured in terms of total U.S. investments in R&D.

All of the variables used to estimate equations (6) and (7) as a system are defined in Table 1. For estimation purposes, several of the continuous variables enter the regression specification of equations (6) and (7) in logarithmic terms (*log*) for ease of interpretation (i.e. the estimated

---

[21] … as economic theory would predict.
[22] See Robertson and Swanepoel (2015).
[23] The Department of Commerce, which publishes this index, uses the adjective *multifactor*. Economists frequently refer to this index using the adjective *total factor*.

coefficients are elasticity measures) and to control for possible non-linearity. Descriptive statistics on all of these variables are in Table 2.

Table 1. Definition and Data Source for the Variables Relevant to Equation (1).

Variable	**Definition**	**Source**
Calibration Tests	Number of calibration tests performed at NIST by fiscal year	https://www.nist.gov/tpo/department-commerce
NIST Lab R&D	NIST laboratory R&D budget ($2020 millions) by fiscal year	https://www.aaas.org/programs/r-d-budget-and-policy/historical-trends-federal-rd
NIST Lab R&D Intensity	Ratio of the NIST laboratory R&D budget to the NIST agency budget by fiscal year	Calculated
Economic Performance	Multifactor productivity index for the U.S. private business sector (2012 = 100)	https://www.bls.gov/mfp/tables.htm
National R&D	Total U.S. R&D by calendar year ($2012 millions)	https://ncses.nsf.gov/pubs/nsf20307/#&
Dmy Calibration Tests	=1 for fiscal years 1999–2002, 2007, and 2008; 0 otherwise	Calculated

Table 2. Descriptive Statistics on the Variables in Equations (6) and (7) (n=20)

Variable	**Mean**	**Standard Deviation**	**Minimum**	**Maximum**
Calibration Tests	13631.70	6796.26	2924	27489
NIST Lab R&D	577.70	116.60	414.60	753.10
NIST Lab R&D Intensity	0.609	0.112	0.423	0.782
Dmy Calibration Tests	0.300	0.470	0	1
Economic Performance	96.943	4.575	87.719	102.794
National R&D	413858.90	59229.37	320086	525256

Equations (6) and (7) were estimated as a two stage least squares (2SLS) system. The regression results in columns (1) and (2) of Table 3 relate to R&D in NIST laboratories being measured by *NIST Lab R&D*; the regression results in columns (3) and (4) relate to R&D in NIST laboratories being measured *by NIST Lab R&D Intensity*.

Table 3. Regression Results from Specifications of Equations (6) and (7) as a 2SLS System (n=20) (standard errors in parentheses and *p* values in brackets)

	Dependent Variable			
	(1) *log (Calibration Tests)*	**(2) *log (Economic Performance)***	**(3) *log (Calibration Tests)***	**(4) *log (Economic Performance)***
log (NIST Lab R&D)	1.3366 (0.8426) [*p*=.1311]	—	—	—
NIST Lab R&D Intensity	—	—	2.8900 (1.3524) [*p*=.0474]	—
Dmy Calibration Tests	−0.4866 (0.3623) [*p*=.1970]	−0.0170 (0.0089) [*p*=.0762]	−0.4709 (0.3213) [*p*=.1610]	−0.0143 (0.0106) [*p*=.1977]
log (Calibration Tests)	—	0.0319 (0.0083) [*p*=.0014]	—	0.0378 (0.0105) [*p*=.0024]

	Dependent Variable			
	(1) ***log (Calibration Tests)***	**(2)** ***log (Economic Performance)***	**(3)** ***log (Calibration Tests)***	**(4)** ***log (Economic Performance)***
log (National R&D)	—	0.1799 (0.0325) [p<.0001]	—	0.1665 (0.0391) [p=.0006]
Intercept	1.0099 (5.412) [p=.8542]	1.9557 (0.3815) [p=.0001]	7.7195 (0.8880) [p<.0001]	2.0732 (0.4528) [p=.0003]
R-squared		0.9347	0.4585	0.9141
F-level		76.36 [p<.0001]	7.20 [p=.0054]	56.75 [p<.0001]
Durbin-Watson	0.5696	1.76263	0.5284	1.5101

The first stage regression results in columns (1) and (3) support the hypothesis underlying the construction of equation (6). The estimated coefficient on *log* (*NIST Lab R&D)* reported in column (1) is positive and significant at a 13 percent level; the estimated coefficient on *NIST Lab R&D Intensity* reported in column (3) is also positive and significant at a 5 percent level. Data limitations prevent a series of lagged values of *NIST Lab R&D* or *NIST Lab R&D Intensity* from being considered; however, when this variable is replaced with a one-year lagged value, the results are virtually unchanged.[24]

The second stage regression results in columns (2) and (4) are similar to each other.[25] From column (2), a 10 percent increase in calibration tests at NIST is associated with a 0.32 percent increase in the U.S. multifactor productivity index. From column (4), a 10 percent increase in calibration tests at NIST is associated with a 0.38 percent increase in the U.S. multifactor productivity index. Both of the estimated elasticities are significant at the 1 percent level or better. As expected, the national R&D elasticity of multifactor productive is positive, significant, and larger in numerical value than the calibration tests elasticity.

4. Discussion and suggestions for future research

The key finding from this exploratory study is that there is a positive and statistically significant relationship between calibration tests, a measurement science-based activity at the U.S, metrology laboratory, NIST, and measured U.S. productivity. However, although this finding is to the best of my knowledge the first such aggregate empirical finding relevant to the United States, it must be interpreted with caution.

First, one should not infer from this exploratory study that calibration tests are the primary measurement science-based activity at NIST. On the contrary, NIST's metrology research is reflected through its role in the promulgation of various voluntary and mandated standards, the

[24] These results are available from the author on request.

[25] In constant dollars, the NIST agency budget is less variable over time than the NIST laboratory R&D budget. Thus, changes in *NIST Lab R&D Intensity* mirrors changes in *NIST Lab R&D*; the correlation coefficient between the two regressors is 0.881 (p<.001). As a result, the predicted values of *log (Calibration Tests)* generated by the models in columns (1) and (3) are similar. This, in turn, explains the similarity of the second-stage results in columns (2) and (4).

development of standard reference materials (SRMs), the development of test methods, and more. The fact is data related to calibration tests over time are the measurement standards activity at NIST that is publicly available for sufficient years to support this exploratory study. To formulate a more accurate description of the role of the economics of metrology in the United States, additional research is needed on the collective research activity at NIST.

Second, the analysis in this paper implicitly assumes that calibration tests are homogeneous activities, homogeneous in the sense that each test has an equal impact on U.S. productivity. This is not the case; firms that purchase calibration tests logically use the results from those tests over various activities and over varying time periods. Through case studies we might learn more about their heterogeneous nature and use of calibration tests (and of various standards, SRMs, and test methods). Such heterogeneity can be gleaned from the case studies that NIST has sponsored,[26] but more information is needed if the economics of metrology is to become more of a mainstream research topic.

Relatedly, the preliminary calibration elasticities estimated in this paper are lower bounds on the impact of calibration tests on economic activity. A firm might have one of its measurement standards calibrated at NIST, but it might internally use that traceable-to-NIST standard many times over. Thus, the calibration test at NIST results in a much greater impact on economic activity though multiple applications than is estimated herein. Again, through case studies of calibrated standards, a more precise estimate of the economic returns to NIST's R&D activity might be estimated.

And third, institutional knowledge about the context of activities in public agencies does not always accompany academic research that focuses solely on the measurement of activities in public agencies. Contextual information is difficult to obtain, and even when obtained it might not apply equally to all aspects of an agency's activities. This shortcoming is evident in the parsimonious specification of equation (6) in this paper and the cursory evidence available to construct the control variable *Dmy Calibration Tests*. Again, case studies might represent a needed step to overcome this shortcoming.

Finally, as Dasgupta (2021) and others have noted, it is important to move away from Gross Domestic Product or multifactor / total factor productivity as measures of economic wellbeing. Dasgupta (2021, 5) wrote:

> The contemporary practice of using Gross Domestic Product (GDP) to judge economic performance is based on a faulty application of economics. GDP is a flow (so many market dollars of output per year), in contrast to inclusive wealth, which is a stock (it is the social worth of the economy's entire portfolio of assets). Relatedly, GDP does not include the depreciation of assets, for example the degradation of the natural environment (we should remember that 'G' in GDP stands for gross output of final goods and services, not output net of depreciation of assets). As a measure of economic activity, GDP is indispensable in short-run macroeconomic analysis and management, but it is wholly unsuitable for appraising investment projects and identifying sustainable development.

[26] See footnote 13 and see, as a recent example, Leech and Scott (2011).

While the analysis in this paper relies on a traditional productivity index, and while the empirical literature cited in this paper is based on similar indices as well as indices related to GDP, the long-run economic impacts from metrology might be understated if future research relies on traditional measures of economic performance. Thus, to the extent that this paper and the papers cited herein motivate additional studies of the economic impacts of measurement science, perhaps such future studies will also consider broader measures of economic performance.[27]

Acknowledgements

I appreciate the many helpful comments and suggestions on earlier versions of this paper from my colleague Martijn van Hasselt and from my virtual colleagues John Scott (Dartmouth College) and Greg Tassey (University of Washington and former Chief Economist at NIST).

References

Blind, Knut, Andre Jungmittag, and Axel Mangelsdorf. 2011. *The Economic Benefits of Standardization: An Update of the Study Carried Out by DIN in 2000*. Berlin: DIN German Institute for Standardization.

Choudhary, M., Paul Temple Ali, and Lei Zhao. 2013. "Taking the Measure of Things: The Role of Measurement in EU Trade." *Empirica* 40: 75–109.

Dasgupta, Partha. 2021. *The Economics of Biodiversity: The Dasgupta Review*. London: HM Treasury.

David, Paul A., and Shane Greenstein. 1990. "The Economics of Compatibility Standards: An Introduction to Recent Research." *Economics of Innovation and New Technology* 1: 3–41.

De Simone, Daniel V., and Charles F. Treat. 1971. *A History of the Metric System Controversy in the United States*. Gaithersburg, MD: National Institute of Standards and Technology.

Hall, Bronwyn H., Jacques Mairesse, and Pierre Mohnen. 2010. "Measuring the Returns to R&D." In *Economics of Innovation*, edited by B. Hall, and N. Rosenberg, 1033–1082. Amsterdam: Elsevier.

Hemenway, David. 1975. *Industrywide Voluntary Product Standards*. Cambridge, MA: Ballinger Publishing Company.

Himbert, Marc E. 2009. "A Brief History of Measurement." *The European Physical Journal, Special Topics* 172: 25–35.

King, Michael, Ray Lambert, and Paul Temple. 2017. "Measurement Standards and Productivity Spillovers." In *Handbook of Innovation and Standards*, edited by R. Hawkins, K. Blind, and R. Page, 162–186. Cheltenham, UK: Edward Elgar Publishing.

Lambert, Ray. 2010. *Economic Impact of the National Measurement System*. London: Department for Business Innovation and Skills.

[27] I thank an anonymous reviewer for his/her encouragement to emphasize this point.

Leech, David P., and John T. Scott. 2011. *The Economic Impacts of Documentary Standards: A Case Study of the Flat Panel Display Measurement Standard (FPDM)*. Gaithersburg, MD: National Institute of Standards and Technology.

Link, Albert N. 2019. "Technology Transfer at the US National Institute of Standards and Technology." *Science and Public Policy* 46: 906–912.

Link, Albert N., and John T. Scott. 2012. *Planning Report 11-1: The Theory and Practice of Public-Sector R&D Economic Impact Analysis*. Gaithersburg, MD: National Institute of Standards and Technology.

Marshall, Alfred. 1920. *Industry and Trade*. London: Macmillan and Co.

Richardson, Elliot L. 1976. *"Brief History of Measurement Systems, with a Chart of the Modernized Metric System."* National Bureau of Standards Special Publication 304A. Washington, DC: U.S. Department of Commerce.

Robertson, Kristel, and Jan A. Swanepoel. 2015. *The Economics of Metrology*. Canberra: Office of the Chief Economist, Department of Industry, Innovation and Science, Australian Government.

Schooley, James F. 2020. *Responding to National Needs: The National Bureau of Standards Becomes the National Institute of Standards and Technology, 1969–1993*. Washington, DC: National Institute of Standards and Technology.

Smith, Adam. 1776/1914. *An Inquiry Into the Nature and Causes of the Wealth of Nations*. London: J.M Dent & Sons.

Swann, G.M. Peter. 2009. *The Economics of Metrology and Measurement*. London, UK: Report for National Measurement Office, Department for Business, Innovation and Skills.

Swann, G.M. Peter. 2010. *The Economics of Standardization: An Update*. London, UK: Report for the Department for Business, Innovation and Skills.

Tassey, Gregory. 2017. "The Roles and Impacts of Technical Standards on Economic Growth and Implications for Innovation Policy." *Annals of Science and Technology Policy* 1: 215–316.

Temple, Paul, and Geoffrey Williams. 2002. "Infra-technology and Economic Performance: Evidence from the United Kingdom Measurement Infrastructure." *Information Economics and Policy* 14: 435–452.

U.S. Department of Commerce (USDOC). (2019.). *Annual Report on Technology Transfer: Approach and Plans, Fiscal Year 2019 Activities and Achievements, U.S. Department of Commerce*. Gaithersburg, MD: National Institute of Standards and Technology.