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A Kinetics-Based Approach to Production: Theory and Evidence

Bernard C. Beaudreau

Department of Economics, Université Laval Québec, Québec, Canada
Email: bernard.beaudreau@ecn.ulaval.ca

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Abstract

Production theory has, over the course of the past two centuries, been besieged by criticism, ranging from its weak fundamentals to its lack of coherence with the physical sciences. Yet, no real alternatives have emerged with the result that neoclassical production theory continues to hold sway much as it did over the past century. This paper presents a consilient theory of production, one that is grounded in classical mechanics, is empirically validated, and sheds light on myriad productivity-related phenomena. Specifically, a two-tiered approach to modeling production is proposed. In the first tier, a kinetics-based theory is developed where output is an increasing function of energy consumption, in keeping with basic physics. In the second tier, the organization of energy-based material processes (the first tier) is modeled. The resulting model is estimated using U.S. manufacturing two-digit SIC data from 1947 to 1989.

Keywords

Energy Use, Speed, Machine Kinetics, Measures of Productivity

1. Introduction

Economics is, by definition, the science of wealth, a fact that places wealth and its creation at the center of the analysis. Understanding wealth is, as such, the key to, and basis of economics as an intellectual endeavor. Getting wealth right, it therefore follows, is a *sine quo non* condition of success in all other sub-fields (e.g. labor economics, macroeconomics, industrial organization). Unfortunately, despite over two centuries of effort, wealth and its creation remain a challenge, as evidenced by the many puzzles and paradoxes that characterize the literature, including the decades-old productivity slowdown and the current information paradox.[1]

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[1] Greg Mankiw has gone as far as to refer to production theory as "primitive".

This raises the question of scientific validity, namely when is a hypothetical model of wealth valid or correct? Clearly, it can be internally valid (i.e. to the profession) if it is accepted by the majority, for example, classical production theory according to which output is an increasing function of labor, which for decades was internally validated/valid/correct. It wasn't however until its shortcomings, specifically regarding the role of capital in the creation of wealth (mid-19th century), were identified that it was abandoned and replaced by the new-classical or neo-classical approach.

There is also external validity. That is, to what extent is production theory valid outside of economics? After all, economists are not the only scholars/intellectuals that study the wealth-creating process. As it turns out, the question of external validity came to a head in the early 20th century when a growing chorus of scholars openly doubted the validity of neoclassical production theory. Among these were Nobel Prize laureate Frederick Soddy, Thorstein Veblen, Howard Scott, Walter Rautenstrauch, Frederick G. Tryon, and Woodlief Thomas. In general, they were either engineers or scientists, schooled in basic mechanics and thermodynamics, who felt that production theory was woefully inadequate—not to mention incomplete—as it abstracted from the key input in all known material processes, namely energy/force.

This oversight came back to haunt the profession in the 1970s when the price of petroleum and other forms of energy quadrupled in price. Not having heeded earlier advice, the profession found itself unable to analyze the effect of higher prices on output, employment and productivity. In 1975, Ernst Berndt and David Wood responded with the KLEMS (capital, labor, energy, materials, services) framework, which consisted of increasing the dimensionality of the basic neoclassical model, the result of which was three new output elasticities, namely the energy, the materials, and the services output elasticities. Assuming competitive factor markets, they went on to show, surprisingly, that energy, the cornerstone of all material processes, and the only source of work (mechanics), was relatively unimportant in generating wealth. Rather, machines and equipment, and labor were the key productive inputs.

This highlights the current dilemma in economics, namely that while being internally valid, formalizations like KLEMS are increasingly under attack externally, for example, the challenge posed by the workerless factory. According to neoclassical production theory, no output should result as the labor input is essentially zero. Yet, output is produced, oftentimes more than previously, thus putting the onus on capital, or machinery and equipment. However, according to classical mechanics, tools, not being sources of energy, are not physically productive, leaving us with a conundrum, namely that the workless factory should not be productive—yet it is.[2]

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[2] According to classical mechanics, tools (basic and complex) are not a source of energy and hence are not physically productive, but rather provide mechanical advantage. A good example is a hammer which, without a hand to hold, would be unproductive. All machinery and equipment can be seen as a combination of three basic tools, namely, the lever, the inclined plane and the hydraulic press.

Which brings us to the purpose of this paper, namely to provide a model of wealth that is internally and externally valid. To this end, we begin by examining non-mainstream contributions, from Frederick Soddy to Nicholas Georgescu-Roegen. This will be followed by a series of engineering-inspired models that capture the material aspects of the wealth-creating process, culminating in what we refer to as the kinetics-based theory of production in which the laws of kinetics are integrated into functional representations of production processes.[3] As internal and extenal validity is, in large measure, based on the predictive power of the model, we estimate our model using aggregate and sectoral U.S. manufacturing data.

2. Literature Review

It is often thought or believed that of all the non-mainstream economists, there was none greater than German political economist Karl Marx. After all, he is credited with single-handedly changing the course of political economy, especially distribution theory. A careful reading of the first seven chapters of *Das Kapital*, published in 1867, reveals what is a characteristically classical approach to wealth, putting labor at the core of production and hence of wealth. Like his classical forebearers, he held labor to be at the center of all wealth creation. However, if one takes the time to read *Das Kapital* from cover to cover (which few do) in Chapter 15 one discovers a more compelling description of wealth creation in the age of machinery, one that is based on classical mechanics.

> *All fully developed machinery consists of three essentially different parts, the motor mechanism, the transmitting mechanism, and finally the tool or working machine. The motor mechanism is that which puts the whole in motion. It either generates its own motive power, like the steam-engine, the caloric engine, the electromagnetic machine, etc., or it receives its impulse from some already existing natural force, like the water-wheel from a head of water, the wind-mill from wind, etc. And to this day it constantly serves as such a starting-point, whenever a handicraft, or a manufacture, is turned into an industry carried on by machinery.* (Marx, 1867, Chapter 15)

Clearly, there was more to Marx's thought than the simple labor theory of value. In fact, one could argue that he was well aware of classical mechanics and the role of forece in material processes, not to mention the role of tools in material processes.

Perhaps the most influential of 19th century iconoclasts—in large part, much in spite of himself,—was William Stanley Jevons, the father of neoclassical production theory. In the "The Theory of Political Economy" published in 1874, he outlined what was to become neoclassical production theory, namely that wealth is an increasing, continuous, twice-differentiable function of homogenous labor and capital. A lesser known, but equally important contribution, of his was "The Coal Question An Inquiry Concerning the Progress of the Nation, and the

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[3] It is important to point out that such representations are specific to economics and not encountered in either industrial engineering, applied physics, or physics per se.

Probable Exhaustion of Our Coal-Mines," published in 1865 in which he addressed the question of Great Britain's dwindling coal reserves. In the opening salvo, he declared:

> *Day by day it becomes more evident that the Coal we happily possess in excellent quality and abundance is the mainspring of modern material civilization. As the source of fire, it is the source at once of mechanical motion and of chemical change. Accordingly it is the chief agent in almost every improvement or discovery in the arts which the present age brings forth. It is to us indispensable for domestic purposes, and it has of late years been found to yield a series of organic substances, which puzzle us by their complexity, please us by their beautiful colours, and serve us by their various utility.*
>
> *And as the source especially of steam and iron, coal is all powerful. This age has been called the Iron Age, and it is true that iron is the material of most great novelties. By its strength, endurance, and wide range of qualities, this metal is fitted to be the fulcrum and lever of great works, while steam is the motive power. But coal alone can command in sufficient abundance either the iron or the steam; and coal, therefore, commands this age—the Age of Coal.*
>
> *Coal in truth stands not beside but entirely above all other commodities. It is the material energy of the country—the universal aid—the factor in everything we do. With coal almost any feat is possible or easy; without it we are thrown back into the laborious poverty of early times.* (Jevons, 1865: p. xi)

Paradoxically, some nine years later (i.e. in 1874), coal or the energy input had disappeared completely from what is largely considered to be his *magnum opus*, namely "The Theory of Political Economy," where capital is included in the production function and, more importantly, is assumed to be physically productive. In short, both labor and capital were assumed to by physically production and more importantly, were substitutable. One could argue that internal validity (i.e. vis-a-vis the debate over the role of capital in wealth) is what prevented Jevons from incorporating energy into the corpus of neoclassical analysis.

Perhaps the greatest of British iconoclasts was Nobel-prize laureate chemist Frederick Soddy, who after his pioneering work with Ernest Rutherford on atomic transmutation turned his attention to economics, largely in response to the alleged "mis-specification" of production theory, more to the point, to the absence of energy from the analysis. The gist of his critique can be found in the following allegory:

> *At the risk of being redundant, let me illustrate what I mean by the question, How do men live? by asking what makes a railway train go. In one sense or another the credit for the achievement may be claimed by the so-called "engine-driver", the guard, the signalman, the manager, the capitalist, or share-holder, or, again, by the scientific pioneers who discovered the nature of fire, by the inventors who harnessed it, by Labour which built the railway and the train. The fact remains than all of them by their united efforts could not drive the train. The real engine-driver is the coal. So, in the present state of science, the answer to the question how men live, or how anything lives, or how inanimate nature*

> *lives, in the sense in which we speak of the life of a waterfall or of any other manifestation of continued liveliness, is, with few and unimportant exceptions, By sunshine. Switch off the sun and a world would result lifeless, not only in the sense of animate life, but also in respect of by far the greater part of the life of inanimate nature.* (Soddy, 1924: p. xi)

In short, according to Soddy, energy was the cornerstone of all human activity, including production. Labor, capital, information, technology etc. are all accessory inputs, necessary for but not the actual source of wealth. Despite much promise, the proposed Cartesian economics, based on the laws of basic physics (mechanics and thermodynamics) failed to make inroads into mainstream economics.

As it turned out, the torch of "production theory" iconoclasticism would soon cross the ocean, surfacing in North America. However, the resulting strain would be less ideological and more practical. Specifically, the late 19th-century conversion from belting and shafting to electric unit drive (i.e. individual electrical motors integrated in machinery) had witnessed a non-negligible increase in energy use in U.S. manufacturing, one that produced a sizeable increase in output against a backdrop of lower capital expenditure/stock. The latter owed to the fact that electric generators and motors were less costly than the elaborate shafting and belting they replaced. With the passage of time, it became increasingly obvious that energy use in general, and electric power in particular, had become the driving force, increasing output and wealth.

F.G. Tryon of the Institute of Economics (Brookings Institution) was among the first to point to the incongruity between production processes as modeled in economics and those he observed in early 20th century America.

> *Anything as important in industrial life as power deserves more attention than it has yet received by economists. The industrial position of a nation may be gauged by its use of power. The great advance in material standards of life in the last century was made possible by an enormous increase in the consumption of energy, and the prospect of repeating the achievement in the next century turns perhaps more than on anything else on making energy cheaper and more abundant. A theory of production that will really explain how wealth is produced must analyze the contribution of this element of energy.*
>
> *These considerations have prompted the Institute of Economics to undertake a reconnaissance in the field of power as a factor of production. One of the first problems uncovered has been the need of a long-time index of power, comparable with the indices of employment, of the volume of production and trade, of monetary phenomena, that will trace the growth of the factor of power in our national development* (Tryon, 1927: p. 281).

One year later (i.e. in 1928), Woodlief Thomas of the Division of Research and Statistics of the Federal Reserve Board, published an article in the American Economic Review entitled "The Economic Significance of the Increased Efficiency of American Industry," in which he attributed the "striking changes" in American industry" to power-related developments:

> *Large-scale production is dependent upon the machine process, and the increasing use of machinery and power and labor-saving devices has accompanied the growth in size of productive units. The growing use of power in manufacturing, for example, is reflected in the increase in horsepower of installed prime movers. This does not tell the whole story, moreover, for owing to increased use of electricity, the type of power used is now more efficient—requiring less fuel and labor for its production. Out of a total installed horsepower in factories of thirty-six million in 1925, twenty-six million or 72 per cent was transmitted to machines by means of electric motors, as compared with 55 percent in 1919, 30 per cent in 1909, and only 2 per cent in 1899. Between 1899 and 1925 horsepower per person employed in factories increased by 90 percent and horsepower per unit of product increased by 30 percent… Power has been substituted for labor not only through machines of production but also in the form of automatic conveying and loading devices.* (Thomas, 1928: p. 130)

In little time, this incongruity reached academia, specifically Columbia University where a group of engineers, known as the Technocracy Alliance outrightly rejected mainstream approaches to understanding wealth (essentially neoclassical production theory), arguing that they ignored mechanics, thermodynamics, process engineering and with the then state of the art regarding material processes in general.

With the passage of time, it became increasingly obvious that while neoclassical production theory continued to hold sway within the profession (i.e. internally valid), it came under increasing scrutiny outside (i.e. external validity). However, as energy consumption and output increased monotonically throughout the post-WWII period, there was little internal or external pressure on production theory. Growth theorists (e.g. Robert Solow, Moses Abramovitz, Edward Denison, Zvi Griliches) contented themselves with the view that all non-labor and non-capital sources of growth (e.g. energy) could be included in a portmanteau variable, namely the Solow residual. In essence, all that could not be explained by labor and capital, two non-physically productive inputs, would be included in the residual.

The problem with residuals in growth theory, as it turned out, was not with their existence, but rather with their disappearance. And this is what happened in the 1970s when the Solow residual suddenly disappeared, ushering in the productivity and growth slowdown, a slowdown that has not since been reversed. Among the alleged causes was the 1973 OPEC oil embargo. Unfortunately, because energy was absent from production theory, it was unclear if and how higher oil prices could impact GDP. The response was not long in coming. In 1975, Ernst Berndt and David Wood proposed the KLEMS approach to study the effects of oil prices shocks—and energy price shocks in general—on the economy. The upshot was damning of the energy input: only 4 - 5 percent of output could be attributed to it. Hence, the OPEC oil shock could only lead to a downturn in the presence of factor input complementarities, specifically the capital-energy complementarity—or substitutability.

At roughly the same time, the internal validity of standard neoclassical production theory came under fire from a Romanian economist, Nicholas Georgescu-Roegen, who argued that like all other material processes in the universe, production can and indeed should be seen as entropy increasing, hence as an irreversible process. His principal target was the standard neoclassical approach to wealth creation which, in its simple version, was reversible.

The Critics: Big on Principles, Small on Improvements

As has been shown, the majority of what we refer to as the non-mainstream critics lamented the absence of energy from production theory and from economics in general. However, unfortunately, they stopped short of providing workable/credible alternatives. For example, no one proposed an alternative theory of material processes based on energy—essentially on the principles of classical mechanics. Similarly, no one took the time to analyze or examine the underlying mechanics, namely of the exact way in which energy is combined with tools and conventionally-defined workers to produce wealth.[4] At the very best, we have the KLEMS approach where energy is simply added, along with materials and services, to capital and labor without much fore- or after-thought to the list of substitutable/complementary factor inputs. Just how energy interacts with capital and labor was left unspecified, other than invoking a sense of complementarity.

In the next section, we present a physics-based theory of material processes, where this interaction takes the form of either machine kinetics and/or chemical kinetics. That is, in displacement-based material processes (translational and rotational), more energy per unit of capital will affect output via the law of kinetics in general, and via machine speed in particular. In non-displacement-based material processes, more energy per unit of capital will lead to greater operating temperatures, greater material breakdown and higher costs (via Arrhenius' Law). In the remainder of this section, we examine the literature—however scant—on the role of speed/kinetics in production and in productivity growth, starting with William Longston's testimony on working conditions in early 19th-century textiles industry before the Committee on the Factories Bill.

> *9400. It appears by this document that the work done is very greatly increased between the years 1810 and 1832; has the machinery been so altered as to produce that amazing difference, or does it result from accelerating the speed of the machinery?—It is from accelerating the speed generally; and another cause is, that more and more exertion is required from the individual working at the machine; these are the two causes.* (Committee on Factories Bill, 1832: p. 430)

The General Electric Company, as early as 1937, pointed to increased machine speed—controlled machine speed—as one of the defining features of modernity and of productivity growth. Under the title of *Today is the Day of Speed*, it maintained that:

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[4] One could attribute this to, among other factors, their epistempological roots. For example, engineers are not trained to model formally material processes, but rather to understand and improve them.

> Our transportation systems, our industrial processes, our factory machinery—all *these have felt the magic hand of speed,—controlled speed that has given us more things to enjoy and more time in which to enjoy them*; *that has produced more goods for more people at less cost and that has created a better standard of living for the average man. These are the benefits of ever-increasing speed and accurate control.*[5]

Henry Ford, in his description of mass production, pointed to machine speed as the key element in his new technique:

> *Mass production is not merely quantity production for this may be had with none of the requisites of mass production. Nor is it merely machine production, which also may exist without a resemblance to mass production. Mass production is the focusing upon a manufacturing project of the principles of power, accuracy, economy, system, continuity and speed.* (Ford, 1926: p. 821)

Graham Laing, in a book entitled "Towards Technocracy," pointed to machine speed as a key factor in the unprecedented productivity gains in the 1920s and 1930s.

> *Industrial processes have been speeded up, new inventions are being added to manufacturing, new economies of personnel and of management have been made in industry. The 1929 production can undoubtedly be achieved with thousands, and probably millions, fewer workers.* (Laing, 1933: p. 23)

Alfred Chandler, in his definitive work on the early 20th century, echoed this view, generalizing it to the U.S. economy as a whole.[6]

> *In modern mass production, as in modern mass distribution and modern transportation and communications, economies resulted more from speed than from size. It was not the size of the a manufacturing establishment in terms of the number of workers and the amount and value of productive equipment, but the velocity of throughput and the resulting increase in volume that permitted economies that lowered costs and increased output per worker and per machine.* (Chandler Jr., 1977: p. 244)

Sidney Sonenblum, in his work on electrification and productivity growth in manufacturing, also pointed to speed, or the accelerating the rate of throughput as a key element in productivity growth:

> *During these years, the focus of managerial attention shifted from enlarging the scale of operations to increasing operating efficiency by speeding up the rate of throughput in the plant. High priority was assigned to modifications of factory design and layout in order to better integrate worker and machine tasks. Advances in the electrification of machine drive were indispensable to the realization of these new objectives and may, indeed, have served to stimulate the new managerial perspectives that emerged.* (Sonenblum, 1990: p. 291)

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[5] Source: The General Electric Machine Tool Speed Show, http://www.youtube.com/watch?v=CUYajEF7XU.

[6] Alfred Chandler's *Economies of Speed* are consistent with Dale Jorgenson and Nathan Rosenberg's views of the role of energy in productivity growth in general and with productivity growth in 20th century U.S. manufacturing (Jorgenson 1981, 1984; Rosenberg 1972, 1983). In fact, one could argue that speed provides the missing link in their work, connecting energy use directly with productivity.

Running through each of these accounts of speed and its role in productivity is the notion of control. General Electric referred to "accurate control," while Ford referred to "accuracy, system and continuity." Hence, speed and control are to be understood as complementary inputs. Theoretically, control can be defined in terms of four functions: 1) constancy of speed 2) minimal breakdown-related downtime, 3) sub-process coordination and 4) machine programming. Put differently, the better able is the firm/engineer at maintaining a constant speed, the greater the output. The same holds for machine breakdown. As not all machines/sub-processes operate at the same speed, it is essential—in order to avoid bottlenecks—to coordinate speeds throughout the plant. Lastly, because firms typically produce many different goods/models of goods with the same machinery, it stands to reason that more efficient machine programming will reduce downtime and hence, increase the average operating speed per period of time.

According to Warren T. Devine, control technologies underwent a series of innovations in the 20th century that were instrumental in increasing machine speed. In a nutshell, hydraulic drive and control mechanisms gave way to servomechanisms, which in the 1950s, gave way to numerical control, which reduced machine downtime considerably. Not only would productivity rise as the result of greater machine speeds (i.e. owing to greater energy use), the machines themselves would be more fully utilized in any given time period. He noted:

> *Numerically-controlled machinery had a number of advantages over conventional manually controlled machinery. The time required to get a newly designed part into production—the machine setup time—was sometimes as much as 65 to 75 percent less with numerical control.* (Devine, 1990: p. 50)

In a 1966 report entitled "Technological Trends in Major American Industries," the U.S. Department of Labor pointed to control technologies in the form of the computerization of data processing and increased mechanization (read: faster speeds) as the leading innovations of the post-WWII period. Under the heading of "Trend Toward Increased Mechanization," it pointed out that:

> *Improvements in machinery that do not involve drastic departure from conventional design will continue to be an important factor in raising productivity in many industries. Faster operation, larger size, automatic loading and unloading devices and automatic lubrification significantly reduce the amount of labor required per unit of output. The integration of a number of separate operations into one large specialized machine which performs a long cycle of operations with a minimum of intervention by the machine tender constitutes a more advanced type of mechanization.* (U.S. Department of Labor, 1966: p. 5)

Clearly, machine speed and its relationship to energy use, specifically, to electric power use appear to have been key elements in raising overall productivity. In the next section, we attempt to formalize this both in terms of a theoretically-consilient and empirically consistent model of output. By theoretically consilient, it should be understood the property of being consistent or in-keeping with the principles of related fields such as classical mechanics, thermodynamics and process engineering. By empirically consistent, it should be understood the property of being consistent with the data—that is, is confirmed by the data. Put differently, models of production should at the very least be able to confirm the relevant underlying laws of physics in material processes.

3. Model

In keeping with Beaudreau (1998) who classified inputs in terms of two main categories, namely broadly-defined energy and organization, we propose a two-tiered approach to understanding production. The first tier is purely physical and is governed by the laws of physics, specifically, the laws of machine and chemical kinetics. Neither tools and/or equipment nor conventionally-defined labor (supervisors) is physically productive, and hence is parametric to this tier. Tier I is universal in its application and reach, accessible to industrial engineers, to physicists as well as to economists and production specialists, thus ensuring both internal and external validity. The second tier is the organization tier which focuses on the definition and supervision of first tier material processes. It focuses on defining and the overseeing—in short, the organization—of machines. It focuses on what Alfred Marshall referred to, in 1890, as machine operatives. It is important to point out that such operatives are not a source of power/energy and hence are not physically productive; hence they cannot be substituted for primary power. Traditional factor substitution is, as such, rendered unfeasible and theoretically impossible across our two tiers. Machinery and equipment, not being sources of power, cannot be substituted for energy.[7] (**Table 1**)

Table 1. Manufacturing processes and corresponding kinetics.

Type	Kinetic Law	Examples	Acceleration
Mechanical-Translational	Translational Kinetics $e = \frac{1}{2}\mu v^2$	Material Handling Transportation	Greater Speed
Mechanical-Rotational	Rotational Kinetics $e = \frac{1}{2}I\omega^2$	Grinding, Shaping, Assembling, Reducing	Greater Speed
Chemical/Thermal	Chemical Kinetics $\ln(r) = \frac{E_a}{RT} + \ln(A)$	Refining, Electrolysis Cracking	Higher Temperature Higher Voltage

Variable definitions: e = kinetic energy, μ = mass, v = velocity, I = moment of inertia, ω = angular velocity, r = rate constant, E_a = activation energy, R = activiation energy constant, T = temperature, A = frequency factor.

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[7] While this result will appear to counterintuitive to students of economics, it will come as no surprise to applied physicists, process engineers and material scientists, highlighting the chasm between the two groups who nonetheless share the same goal, that of understanding production processes.

3.1. Tier I: Mechanical and Chemical Kinetics at the Sub-Process and Plant Levels

We begin by defining the firm/value chain as a series of n sub-processes which can be of two types, namely mechanical and chemical. Mechanical sub-processes (i.e. $y_i^m(t)$ $\forall i = 1,2,3,\cdots,n^m$, n^m = the number of mechanical processes-rotational and translational) are governed by the laws of rotational and translational kinetics, while chemical sub-processes (i.e. $y_i^c(t)$ $\forall i = 1,2,3,\cdots,n^c$, n^c = the number of chemical processes) are governed by the laws of chemical kinetics. By definition, $n = n^m + n^c$. Included in the mechanical sub-process category are the material-handling processes (pumps, conveyor belts, etc.) between the various sub-processes. That is, in sequential production processes, the output of one sub-process is transferred to, and becomes the input for the next sub-process.

Assuming that all subprocesses contribute equally to the final product, the overall rate of output $y(t)$ can be defined as the minimum of the $n^m + n^c$ sub-process rates of output $y_i^m(t)$, $y_i^c(t)$, shown here as Equation (1).

$$y(t) = \min\left[y_1^m(t), y_2^m(t), \cdots, y_{n^m}^m(t); y_1^c(t), y_2^c(t), \cdots, y_{n^c}^c(t)\right] \tag{1}$$

$$y_i^m(t) = s_i^m(t) k_i^m(t) \quad \forall i = 1,2,\cdots,n^m \tag{2}$$

$$y_i^c(t) = s_i^c(t) k_i^c(t) \quad \forall i = 1,2,\cdots,n^c \tag{3}$$

$$s_i^m(t) = v_i^m = \left[\frac{e_i^m(t)}{\mu_i^m}\right]^{0.5} \quad \forall i = 1,2,3,\cdots,n^m \tag{4}$$

$$s_i^c(t) = A_i^c exp^{\left[\frac{-E_{ai}^c}{RT_i^c\left(e_i^c(t)\right)}\right]} \quad \forall i = 1,2,\cdots,n^c \tag{5}$$

$$y_i^m(t) = e_i^m(t)^{[0.5]} k_i^m(t) \quad \forall i = 1,2,\cdots,n^m \tag{6}$$

$$y_i^c(t) = A_i^c exp^{\left[\frac{-E_{ai}^c}{RT_i^c\left(e_i^c(t)\right)}\right]} k_i^c(t) \quad \forall i = 1,2,\cdots,n^c \tag{7}$$

$$\begin{gathered} y(t) = \min\left[s_1^m(t) k_1^m(t), s_2^{rm}(t) k_2^m(t), \cdots, s_{n^m}^m(t) k_{n^m}^{rt}(t);\right. \\ \left. s_1^c(t) k_1^c(t), s_2^c(t) k_2^c(t), \cdots, s_{n^c}^c(t) k_{n^c}^c(t)\right] \end{gathered} \tag{8}$$

Mechanical sub-processes are assumed to be governed by the laws of basic machine kinetics (translational and rotational), according to which output $y_i^m(t)$ is an increasing function of machine velocity/speed $s_i^m(t)$ and the machines themselves, denoted by $k_i^m(t)$.[8] The individual n^m machine speeds, defined as the machine rates of output per unit time, are governed by the law of translational and rotational kinetics (Equations (4) and (5)) $e = \frac{1}{2}\mu v^2$, where e

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[8] $k(t)$ should be viewed as a scaler, and not a physically productive factor input. Theoretically, it can be seen as u, mass in the law of translational kinetics. As such, it as well as the scaler ½ will be dropped from the analysis.

= kinetic energy, μ = mass, and v = velocity) and $e=\frac{1}{2}I\omega^2$, where I = moment of inertia, ω = angular velocity. A similar quadratic relationship between energy use and the velocity/speed exists for thermal and chemical sub-processes where $r_i^c(t)$, the rate constant (Arrhenius Equation), is increasing but at a decreasing rate in $T_i^c(e_i^c(t))$, the temperature of the reaction which is increasing in $e_i^c(t)$, energy use (i.e. joules per mole).

3.1.1. The Statistical Role of Machine Downtime[9]

Thus far, we have abstracted from a key feature of the *de facto* operation of mechanical and chemical sub-processes, namely the presence of downtime.[10] While Equations (1)-(8) define output per period *t* for a given energy consumption per period *t*, they ignore the presence of machine/process downtime, a phenomenon which will have a bearing on the measured rate of energy use and output as reported in the data. In short, it will alter the predictions of mechanical and chemical kinetics. For example, following a shutdown, a machine restart, complete with accompanying increase in energy consumption, will have more of a linear than quadratic effect on sub-process output, defined over the set period of time. More specifically, if the machine is inoperative for half the year, then operating it over a full year at the same speed will double energy consumption and double output.

Formally, this is captured with the introduction of a new variable $\gamma_i^j(t)$ $\forall i=1,2,\cdots,n^j$, $j=m,c$, where $\gamma_i^j(t)$ is increasing in downtime, and bounded between zero and 0.5. With no downtime (i.e. $\gamma_i^j(t)=0$), the original relationship holds—that is, machine speed is increasing in the square root of energy consumption. However, when $\gamma_i^j(t)$ is positive, the relationship between energy consumption and output becomes increasingly linear.[11] It is important to keep in mind that in this case machine speed is an average over the time period *t*, thus affected by downtime. According to Jerome (1934):

> *Such an acceleration of running speed has been made possible by the more durable machine parts and better lubricating systems. Interchangeability of parts in machines produced in large quantities has also contributed to the acceleration in actual running speed by reducing stoppages or repair.* (Jerome, 1934: p. 249)

We capture this process by including $\gamma_i^j(t)$ into Equation (9). The higher is

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[9] Downtime alters the nature of the measured relationship between energy use and output, and thus must be taken into account. Were data on energy use and output only to include uptime, then this would not be necessary.

[10] Machine downtime in turn can be broken down into: 1) maintenance, 2) idleness due to lack of coordination between sub-processes and 3) retooling for a new product. To capture these effects, we define machine speed in terms of Equation (2) where $\gamma_i(t)$ captures sub-process *i* downtime in period *t*.

[11] Formally, average machine speed over a 30-day period can be defined as $\left[\frac{e}{n}\right]^{0.5}$, where e = energy consumption over the 30 day period, and n = number of uptime days (i.e. days of operation). Increasing n will not increase average machine speed defined as output per period *t*, as it leaves the ratio of overall energy consumption to *n*, the number of operating days unchanged. As such, in this case output will be linear in energy consumption.

$\gamma_i^j(t)$, the higher is average downtime per *t*, and hence the higher is the output elasticity.[12]

$$s_i^m(t) = e_i^m(t)^{\left[0.5+\gamma_i^m(t)\right]} \quad \forall i = 1, 2, \cdots, n^m \tag{9}$$

Thermal and chemical sub-processes can be described by the chemical and thermal law of kinetics (Arrhenius Equation) according to which chemical reaction rates are an increasing function of temperature (energy consumption), E_{ai}^c being activation energy for sub-process *i* and *R* being the activation energy constant (8.314). As in the previous case, increasing $T_i^c\left(e_i^c(t)\right)$, temperature of the *i*th chemical sub-process by increasing energy use (joules per mole), will result in a higher reaction rate (i.e. $r_i^c(t)$), which is akin to an increase in mechanical machine speed (Equation (4)).

The role of speed in chemical kinetics is well understood in the literature:

The rate of reaction is the time taken for a reaction to complete. The ultimate goal of any industry is to make as much money as possible, so industries are keen to try and have as fast a rate as possible.

High rates of reaction are achieved by increasing the concentration/pressure of the reaction mixture. This works because for a reaction to occur, particles of the reactants must collide with each other. Not only must they collide, but they must have enough energy to overcome the activation energy of the reaction, and they must be correctly orientated (in other words, if the reacting bit of one molecule is facing the wrong way during a collision the reaction won't occur).

Hence, increasing the temperature gives the particles more energy, meaning more particles will have enough energy to overcome the activation energy, and increasing the concentration/pressure means the particles are closer together, so will collide more often. Both of these factors increase the frequency of successful collisions, and hence increases the rate of reaction.[13]

Hence, an increase in machine down time will render the relationship between energy use in chemical and thermal reactions more linear than the non-linearity in a single reaction as specified in Equation (5). As it is difficult to functionally integrate this feature in Equation (5), we choose to do so in general terms in Equation (10), where the speed of chemical and thermal sub-processes is defined as a function of Equation (5) (Arrhenius Equation), and $\gamma_i^c(t)$, average machine down time. The latter will, in general, decrease $s_i^c(t)$.

$$s_i^c(t) = s_i^c(t)\left[A_i^c exp^{\frac{-E_{ai}^c}{RT_i^c\left(e_i^c(t)\right)}}, \gamma_i^c(t)\right] \tag{10}$$

As such, the individual chemical and thermal reaction rates are governed by two factors, namely chemical kinetics (Arrhenius' Law), and by capital utilization rates which are a function of sub-process downtime.[14]

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[12] This owes to the fact that restarting idle machines will increase output by more than increasing the speed for of machines that at already operating at capacity.

[13] Source: https://socratic.org/questions/why-is-the-rate-of-reaction-important-in-industry.

[14] It is important to note that as in translational and rotational kinetics, the reaction rates are increasing in temperature, but at a decreasing rate.

Equations (11) and (12) summarize the two types of sub-process production functions considered here, the first for mechanical processes, and the second for chemical and thermal-based processes.

$$y_i^m(t) = e_i(t)^{\left[0.5+\gamma_i^m(t)\right]} k_i^m(t) \quad \forall i = 1,2,\cdots,n^m \tag{11}$$

$$y_i^c(t) = s_i^c(t)\left[A_i^c exp^{\frac{-E_{ai}^c}{RT_i^c\left(e_i^i(t)\right)}}, \gamma_i^c(t)\right] k_i^c(t) \quad \forall i = 1,2,\cdots,n^c \tag{12}$$

3.1.2. Upper Limits of $s(t)$

We assume that for a number of reasons the $s_i^j(t)'s \quad \forall i = 1,2,\cdots,n^j, \quad j = m,c$, are bounded from above. In other words, for each sub-process, there exists a maximum speed beyond which it is impossible to go.[15] It can be defined as a combination of 1) the asymptote of translational/rotational chemical/thermal speed 2) material tolerances and 3) average downtime (owing to maintenance, retooling, etc). In other words, there will come a time when the energy costs of increasing machine/process speed will be prohibitive.

Equations (8) and (9) define the sub-process/process technologies available to firms at time *t*. It consists of the menu of set of sub-process speeds/rates—and corresponding energy use levels—available to the firm as well as the levels of sub-process capital at time *t*. What is immediately obvious is that the overall speed of production—and hence, overall productivity of the process—will depend on individual sub-process machine speeds, more specifically on the lowest/slowest sub-process speed.[16] Further, it illustrates a number of important phenomena, namely the relationship between energy use (machine and chemical kinetics), and secondly the corresponding process speeds/reaction rates. In the case of translational and rotational mechanical processes, it increases exponentially—that is, doubling speed will quadruple energy use. For example, doubling the speed of a conveyor belt will quadruple energy consumption.

3.1.3. Tier I: Summary

It is our view that these equations provide insightful formalizations of the nuts and bolts of material processes over the past two centuries. As shown in the previous chapters, rising productivity was associated with greater energy use per unit of capital, resulting in higher machine speeds. As Harry Jerome and Alfred Chandler pointed out, the productivity gains registered in the late 19th/early 20th centuries owed in large part to increasing machine speeds (Jerome, 1934; Chandler Jr., 1977). Faster speeds increased the rated capacity of existing machinery and equipment, ushering in important increases in conventionally-defined labor and

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[15] $s_i^j(t)^{\max} = \bar{s}_i^j$ can be viewed as a combination of the asymptote of $s_i^m(t) = e_i^{0.5}$ as $e_i \to \infty$ and the physical upper limits of machine speed.

[16] In this case, machine speed defines total factor productivity—or capital productivity. This would continue to hold if labor was included. It is important to keep in mind that in modern material processes, labor is a supervisory input. Hence, faster machines will raise output per unit labor (supervisory) input, despite no more effort on its part.

capital productivity. As the experience at Ford Motor showed, the use of electric-powered conveyor belts and chains was a key component in the success of the assembly line at the Ford Motor Company.

3.2. Tier II: Organization and the Demand for Supervision and Tools

While early models of production (i.e. classic) viewed labor as being physically productive (e.g. classical theory of value), by the end of the century, most mainstream economists, including neoclassical writers, viewed labor for what it had become, namely what Alfred Marshall referred to as "machine operatives." Take, for example, the following excerpt from Alfred Marshall's *Principles of Economics* where he refers to labor as "managers":

> *We may now pass to the effects which machinery has in relieving that excessive muscular strain which a few generations ago was the common lot of more than half the working men even in such a country as England… in other trades, machinery has lightened man's labours. The house carpenters, for instance, make things of the same kind as those used by our forefathers, with much less toil for themselves… Nothing could be more narrow or monotonous than the occupation of a weaver of plain stuffs in the old time. But now, one woman will manage four or more looms, each of which does many times as much work in the course of a day as the old hand loom did; and her work is much less monotonous and calls for much more judgment than his did.* (Marshall, 1890: p. 218)

This change was echoed in official statistics. For example, the *U.K. Board of Trade*, in its *Censuses of Production*, no longer referred to workers or production workers, but rather to "operatives." More recently, labor economics, specifically, the literature on skills and tasks, views labor as "operatives." The concept of labor productivity, it therefore follows, took on a new meaning, specifically as a measure of output per machine manager or operative. Implicitly, labor was not physically responsible for/involved in generating wealth, but rather was responsible for overseeing/managing the corresponding machines. To capture this, we model the demand for supervision/machine operatives as a function of output, specifically of the desired output. The greater the desired or targeted level of output on the part of firms, the greater the demand for supervision.[17]

As machine operatives are involved in all *n* subprocesses defined by Equation (1), it stands to reason that the demand for supervision will depend on a number of factors, from the individual sub-process supervision technology, to average overall process speed, to the overall scale of operation. For example, if the firm automates a given sub-process, then it would stand to reason that the demand for supervision per unit of output would fall as a result. The same would hold for an increase in machine speed. Only with an increase in the overall scale of operations (i.e. all sub-processes are increased by the same factor) will the demand for supervision per unit of output stay the same.

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[17] This is an important distinction as it does not imply causality–and hence, physical productivity.

$$l(t) = \alpha\left[s(t), \omega(t)\right] y(t) \tag{13}$$

The firm level demand for supervision can be formalized as Equation (13), where $l(t)$ refers to the number of machine operatives or supervisors, α refers to the overall (i.e. all sub-processes combined) demand for supervision per unit $y(t)$, which is a function of $s(t)$, average process speed at time t and $\omega(t)$, the level of automation at time t.[18] As such, an increase in $s(t)$, machine speed, will result in an increase in $y(t)$ per unit $l(t)$. However, it bears reminding that such an increase owes not to labor's intrinsic properties or productivity, but rather to greater machine speed and more output per unit capital (i.e. machinery) and supervision.[19]

Similarly, innovations in ICT-based technological change will affect labor demand. Specifically, innovations in machine control technology will, in general, reduce α, thus reducing the demand for supervision per unit output—in some cases, reducing it to zero (i.e. the case of total factory automation). Measured output per machine operative will, consequently, rise, again in no part due to the intrinsic value or contribution of conventionally-defined labor.

$$k(t) = \beta\left[s(t), \eta(t)\right] y(t) \tag{14}$$

Like the supervisory input, we view tools (capital) as an organizational input, one that defines a given material process, but not one that is physically productive (Alting, 1994). According to classical mechanics, tools provide mechanical advantage, which is defined as the advantage gained by the use of a mechanism in transmitting force; specifically, the ratio of the force that performs the useful work of a machine to the force that is applied to the machine. The demand for tools can, as such, be modeled analogously to that of supervision—that is, as a function of projected output, $y(t)$. According to Equation (14), the demand for tools is an increasing function of the latter variable, with $\beta\left[s(t), \eta(t)\right]$ being the corresponding scaler—that is, aggregate (i.e. combined process) capital/machines per unit of output $y(t)$. As can be seen, the per unit output demand for tools (capital) is a decreasing function of $s(t)$ overall process speed, and of $\eta(t)$, the overall level of second-law efficiency (in short, the productivity of energy). The more efficient is the energy input, the less capital is required per unit output.

3.3. Aggregating Across Firms within an Industry/Sector

Aggregating across firms within a given industry/sector, we obtain Equations (15)-(19), which describe aggregate industry/sector output in terms of the industry/sector average speed of the overall production processes $S(t)$, as well as the supervisory $N(t)$ and capital requirements $K(t)$ of the latter. While processes

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[18] In this section, we chose to examine the demand for supervision at the more aggregate level—that is, not at the individual sub-process level.

[19] As such, it is by no means clear that labor's remuneration should rise as a result. If anything, there is reason to believe that it would decrease globally as less supervision is required for a given level of output.

at the firm/industry/sector level will involve rotational, translational and chemical kinetics-based sub-processes, we will focus on the former.[20] *Ceteris paribus*, the greater is aggregate energy use per unit $K(t)$, the greater is the aggregate average speed $S(t)$, and the greater is overall average productivity (i.e. $Y(t)$).[21] Furthermore, the greater is the rate at which firms in general are able to reduce average machine downtime (i.e. $\Gamma(t)$), the greater is average machine speed per period t, and hence, the greater is aggreagate productivity and output. However, this makes for a lower energy output elasticisty as successive increases in energy will serve to increase machine speed and not start up idle machines.

Tier I

$$Y(t) = S(t)K(t) \tag{15}$$

$$S(t) = E(t)^{[0.5+\Gamma(t)]} \tag{16}$$

$$Y(t) = E(t)^{[0.5+\Gamma(t)]}K(t) \tag{17}$$

Tier II (Table 2)

$$N(t) = A[S(t),\Omega(t)]Y(t) \tag{18}$$

$$K(t) = B[S(t),H(t)]Y(t) \tag{19}$$

4. Production Activity Indexes

This approach to production has important implications for conventional productivity indexes. Specifically, the conventional concepts of labor and capital productivity are deemed to be theoretically invalid as they assume (incorrectly) that labor and capital are physically productive, when in fact they are organizational (Tier II) variables and, as argued earlier, not physically productive. Theoretically, the only physically productive factor is energy, implying that the only scientifically-legitimate "productivity index" is that of energy.[22] In light of this and the need for production indexes, we present a new index, namely the production per factor input index, or production per factor index for short (PFI).

It is important to point out what these indexes are and are not. First, they are production per factor measures and not productivity measures, the exception

Table 2. Production per factor indexes-PFI.

Index	Definition	Parameters
Energy PFI	$y(t)/e(t)$	$e_i(t) - 0.5 + \gamma^i(t)k_i(t)$
Labor PFI	$y(t)/n(t)$	$1/\alpha[s(t), i(t)]$
Capital PFI	$y(t)/k(t)$	$1/\beta[s(t), \eta(t)]$

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[20] This can be justified on the grounds that in all three cases, velocity/reaction rates/speed is increasing quadratically in energy consumption.

[21] Average speed here is measured across all n sub-processes.

[22] Clearly, if labor is a source of energy, then the notion of labor productivity is also theoretically legitimate.

being the Energy PFI, which de facto measures the average physical productivity of energy. The Labor PFI and Capital PFI are simple measures of output per factor input, which vary over time according to underlying technology parameters such as machine speed, information technology and second-law efficiency.

For example, an increase in machine speed will, *ceteris paribus*, increase the labor and capital PFIs. However, neither factor will have contributed to the increase. As such, it cannot be maintained that either of the factors is more productive. Rather, both are witnesses, of sort, of greater output, without being responsible for it.

5. Empirical Evidence

The tiered approach to understanding material processes has important implications for the associated empirics. For example, traditionally, output has been regressed against all factor inputs (e.g. the KLEMS method). This approach is abandoned on the grounds that it is theoretically unjustifiable (i.e. physically-productive versus organizational inputs) and serves to confuse rather than illuminate. Labor is not and has not been physically productive for over two centuries (starting with the introduction of the steam engine). Capital has never been, nor will never be physically productive. Neither can be substituted for each other as each fulfills an entirely different function. Moreover, neither can be substituted for energy as neither is a source of energy. Hence, for these and innumerable other reasons, we proceed by: 1) testing the predictions of machine and chemical kinetics in economics and 2) testing the derived input demand for organization—specifically conventionally-defined labor.[23]

5.1. Tier I: Testing the Theory of Industrial Kinetics

This approach to modeling material processes differs from conventional approaches in that capital (and labor) is assumed to be an organizational input (Beaudreau, 1998), providing the setting for what we consider to be the most fundamental relationship in all material processes, namely of energy transforming material inputs, creating wealth.[24] Hence, in keeping with classical mechanics, only energy is physically productive. As such, output is an increasing function of machine speed, machines, and control devices the latter affecting the utilization of machine utilization. The underlying idea is that most machinery is used to accomplish numerous tasks per period t, requiring retooling/downtime. Control devices, especially reprogrammable control devices, reduce downtime, thus increasing utilization rates and average machine speed per period t. Average, aggregate machine speed is defined by Equation (6), where it is a function of energy use and $\gamma(t)$, the rate of growth of machine utilization due to increasing

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[23] The dearth of data on capital, especially at the disaggregated level, precludes us from testing for the derived demand for capital (tools).

[24] This is consistent with basic process engineering where capital is seen in terms of tools, providing mechanical advantage, but not being a source of energy *per se*. Interestingly, labor as a factor input is ignored altogether. See Alting (1994) and Beiser (1983).

use of/advances in control technologies. It is important to point out that small changes in utilization rates will have important effects on $\gamma(t)$ at time t for the simple reason that these changes will be applied to all $k(t)$, the entire capital stock.

In this section, we present previous aggregate estimates of the energy use/electric power output elasticity ($0.5 + \Gamma(t)$) as well as new disaggregated results. Equation (9) maintains that the output elasticity for energy use should be in the $0.5 + \gamma(t)$ range. Given that $\gamma(t)$ is variable, it stands to reason that the energy output elasticity should vary across firms, industries and countries. However, at the very least, a ten percent increase in energy use should result in a five percent increase in aggregate machine speed and hence, a five percent increase in output per period of time, assuming that the corresponding maximum machine speed has not been reached.

Beaudreau (1995, 1998), Kummel, Lindenberger and Eichorn (2000) provided direct—as opposed to indirect—estimates of the energy—in this case, electricity use—output elasticity in U.S., German and Japanese manufacturing.[25] Recently, Giraud and Kahraman (2014) provided estimates of the primary energy output elasticity for 50 countries, reporting elasticities between 0.6 and 0.7. Referring to **Table 3** which presents electricity use output elasticities, we see estimates in the range of 0.30 to 0.7474, with the average at 0.5303.[26] These estimates were obtained using a number of techniques, ranging from OLS to cointegration models.

Using similar data, we estimated a simple three factor input production function for U.S., German, Japanese, Canadian, British, and Finnish manufacturing.[27] Three econometric specifications were employed, namely 1) linear, 2) log-linear and 3) log differences.[28] Ordinary least squares was used in the case of the latter, while an OLS-AR(1) approach was used in the case of the former. The results are presented in **Tables 4-6**, where we see estimates of the EP (electric power use) coefficients in the predicted range of $0.50 + \gamma$. For example, in the linear case, estimates ranging from 0.4902 in the case of the U.S. to 0.9141 in the case of Britain were obtained. The Canadian elasticity was an anomaly at 0.2451. As collinearity was suspected, the tests were repeated without labor. The resulting electric power use elasticities are 0.7379, 0.7889, and 0.8412, respectively for the log-linear, differences in logs, and linear cases.

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[25] For indirect estimates, see Berndt and Woods (1975). Indirect estimates subsume perfect competition in all factor markets. Direct estimates, on the other hand, make no such assumption.

[26] Beaudreau (1998) conducted a simple growth accounting exercise using these output elasticities as well as input-output growth rates before and after 1973. He was able to show that factor input growth (energy, capital and labor) accounted for almost all of the variation in manufacturing output growth. See the results in the Appendix.

[27] Output, labor and electricity use data were obtained from United Nations *Industrial Statistics Yearbook* (1960-1988); capital data were obtained from OCED, *Flows and Stocks of Fixed Capital 1989*. These data are available from the author upon request.

[28] We opted to estimate the output elasticities directly as opposed to indirectly. This owed to a number of factors, including the nature of our work (i.e. estimating the production function itself) and the belief that factor markets are not competitive, especially the electricity market, making indirect estimation techniques inappropriate.

Table 3. Estimates of the electricity-use output elasticity-manufacturing.

Method	Source	Country and Period	Estimate (t-stat)
OLS	Beaudreau (1995)	U.S. (1950-1984)	0.5330 (10.791)
OLS	Beaudreau (1998)	U.S. (1958-1984)	0.4483 (12.469)
		Germany (1962-1988)	0.7474 (3.135)
		Japan (1962-1988)	0.6055 (3.017)
LINEX	Kummel, Henn and Lindenberger (2002)[20]	Germany	0.64
		U.S. (1960-1993)	0.51
		Japan (1965-1992)	0.61
		U.S.-Total (1960-1993)	0.30
		Germany-Total (1960-1989)	0.44
Cointegration	Stressing, Kummel and Lindenberger (2008)	Germany (1960-1989)	0.517
		Japan (1965-1992)	0.350
		U.S. (1960-1978)	0.663

Table 4. OLS-AR(1) estimates-log linear specification.

Country	Constant	EP	K	L	R^2
U.S.	1.1678	0.4902	0.7826	0.1034	0.9990
(1958-1984)	(0.5342)	(3.169)	(0.9005)	(5.136)	$\rho = 0.688$
Germany	−0.2128	0.6124	0.5587	−0.1086	0.9494
(1963-1988)	(0.1961)	(3.710)	(0.5520)	(3.2171)	$\rho = 0.557$
Japan	−3.1852	0.6970	0.5175	0.3789	0.9818
(1965-1988)	(1.328)	(2.514)	(2.383)	(0.9804)	$\rho = 0.885$
Canada	−3.6435	0.2451	0.2655	1.2673	0.9844
(1962-1988)	(2.421)	(0.8631)	(1.216)	(3.070)	$\rho = 0.660$
Britain	1.2630	0.9141	−0.0972	−0.0870	0.9232
(1963-1988)	(0.936)	(5.762)	(4.000)	(0.7156)	$\rho = 0.502$
Finland	−0.4482	0.7081	0.3040	0.0583	0.9856
(1963-1988)	(0.6075)	(4.772)	(1.702)	(0.3133)	$\rho = 0.364$

Table 5. OLS-AR(1) estimates-linear specification.

Country	Constant	EP	K	L	R^2
U.S.	−64.7637	0.4554	0.0963	1.1141	0.9891
(1958-1984)	(3.186)	(4.009)	(1.084)	(5.417)	$\rho = 0.663$
Germany	−0.2128	0.6124	−0.1086	0.5587	0.9994

Continued

(1963-1988)	(0.1961)	(3.710)	(0.5222)	(3.217)	$\rho = 0.557$
Japan	−164.97	0.5618	0.2374	1.3221	0.9820
(1965-1988)	(1.814)	(2.983)	(3.683)	(1.643)	$\rho = 0.827$
Canada	−130.442	0.3426	0.1582	1.6709	0.9821
(1962-1988)	(2.347)	(1.210)	(6.2092)	(2.836)	$\rho = 0.651$
Britain	17.1535	0.8570	−0.0289	−0.0459	0.911
(1963-1988)	(0.3206)	(5.605)	(0.1008)	(0.1720)	$\rho = 0.583$
Finland	−17.9512	0.57475	0.3122	0.1854	0.9918
(1963-1988)	(0.8936)	(6.931)	(2.553)	(0.9723)	$\rho = 0.294$

Table 6. OLS-AR(1) estimates-log differences specification.

Country	Constant	EP	K	L	R^2
U.S.	0.0447	0.3824	0.9839	0.9646	0.9179
(1958-1984)	(3.168)	(2.498)	(2.9561)	(6.499)	
Germany	−0.0016	0.6093	0.0650	0.4675	0.6682
(1963-1988)	(0.1469)	(3.682)	(0.2197)	(1.872)	
Japan	0.0360	0.7176	0.3052	0.6291	0.6710
(1965-1988)	(1.930)	(2.942)	(1.128)	(1.228)	
Canada	0.0572	0.0528	−0.9138	1.4123	0.715
(1962-1988)	(2.391)	(0.2072)	(1.933)	(4.244)	
Britain	−0.0118	0.7898	−0.2098	0.0891	0.6432
(1963-1988)	(0.9165)	(5.122)	(0.4099)	(0.5597)	
Finland	0.0139	0.7066	−0.1171	−0.3518	0.48
(1963-1988)	(0.371)	(4.364)	(0.1352)	(0.8735)	

These results are consistent with the predictions of our model. More to the point, they are consistent with the predictions of mechanical and chemical kinetics. For the most part, the estimates of the energy output elasticity are greater than the theoretical value of 0.50. The difference, we believe, owes to, among other things, $\Gamma(t)$ which is country specific, continuous increases in energy efficiency, measurement errors, and the very nature of the estimates. Specifically, in addition to capturing kinetics (per unit of capital), they capture scale effects as the stock of capital was increasing over time. An attempt was made at eliminating these "scale" effects by regressing output per unit of capital on electric power per unit capital and labor per unit capital. The results were however not significantly different.[29]

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[29] One of the difficulties encountered was the fact that from 1973 onwards, capital literally exploded with massive investments in control technologies, which we believe thwarted our attempt at accounting for scale effects.

We then tested the model using 2-digit SIC data for U.S. manufacturing from 1947 to 1984.

The data in this case were taken from the *Annual Surveys of Manufactures* as well as the *Census of Manufactures.* The results are presented in **Table 7**, where three sets of electric power output elasticities are reported. Column 1 presents the relevant output elasticity when both electric power consumption (purchased and generated) and production workers were included as independent variables, while Column 2 presents the output elasticity when only electric power consumption was used as the independent variable. Column 3 presents the output elasticity when the dependent and independent variables were measured relative to the level of production workers, the idea being that this would eliminate cyclical biases/effects. As was the case with aggregate data, the output elasticities were centered around the predicted-by-the-law-of-kinetics value of 0.50. In fact, in the first case, the average output elasticity was 0.493.[30]

5.2. 2-Digit U.S. Manufacturing Sectoral Estimates of the Input Demand Elasticity for Supervision

In this section, we present estimates of two demand input elasticities for supervision, namely the demand input elasticity for supervision with regard to output (y(t)) and secondly, that with regard to the energy input—in this case, electric power consumption.[31] These are defined as the percentage increase in the demand for supervision (i.e. machine operatives) divided by either the percentage increase in the level of output or the percentage increase in the energy input at the 2-digit sectoral level (see **Table 8**). Given the persistence of energy deepening in the form of a rising electric power to machinery/equipment ratio throughout the period under study, it would stand to reason that the elasticity with regard to energy would be systematically less than that with regard to output. The estimates presented in **Table 6** confirm this. The demand for supervision per kwh was less than the demand for supervision per unit of output in virtually all industries.

What is interesting is the fact that in many industries, the input elasticities were negative, which confirms the well-documented decrease in supervisor demand per unit output in manufacturing (due to increased speed as well as AI-based automation of supervisory activity) as a whole in this period (Rifkin, 1995). In other words, supervisors/machine operatives were being called upon to oversee machines and processes that were turning out more and more output. Industries such as SIC 21 Tobacco Products and SIC 22 Textile Mill Products witnessed the lowest input elasticities, indicating that supervisory technology would have undergone important modifications/change. What is also interesting

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[30] Clearly, our analysis abstracts from a number of other variables and influences. For example, because data on capital stock are not available, we were unable to focus on the key theoretical construct in so far as kinetics is concerned, namely energy consumption per unit of capital. Increasing energy efficiency over time will bias the estimates upwards.

[31] Given the absence of annual, disaggregated data on the capital input, our analysis here will be limited to the demand for supervision.

Table 7. 2-Digit SIC industry electric power output Elasticities 1947-1984.

SIC	Industry	Elasticity-I (*t*-stat.)	Elasticity-II (*t*-stat.)	Elasticity-III (*t*-stat.)
20	Food and Kindred Products	0.610 (30.873)	0.552 (13.074)	0.586 (26.239)
21	Tobacco Products	0.386 (12.604)	0.399 (13.315)	0.870 (22.312)
22	Textile Mill Products	0.401 (5.243)	0.301 (5.154)	0.490 (11.897)
23	Apparel and Other Textile Products	0.142 (7.800)	0.200 (7.489)	0.164 (8.7221)
24	Lumber and Wood Products	0.518 (17.614)	0.474 (10.923)	0.493 (17.966)
25	Furniture and Fixtures	0.227 (5.785)	0.490 (13.566)	0.359 (11 .568)
26	Paper and Allied Products	0.5937 (17.558)	0.673 (32.139)	0.616 (28.6918)
27	Printing and Publishing	0.156 (3.3158)	0.458 (14.599)	0.341 (11.686)
28	Chemicals and Allied Products	0.519 (9.651)	0.595 (9.475)	0.560 (9.380)
29	Petroleum and Allied Products	1.153 (8.486)	0.658 (9.161)	0.733 (15.109)
30	Rubber and Misc. Products	0.247 (1 .822)	0.804 (24.828)	0.550 (9.437)
31	Leather and Leather Products	0.382 (7.373)	0.048 (0.8439)	0.323 (14.970)
32	Stone, Clay and Glass Products	0.627 (11.702)	0.769 (22.983)	0.728 (20.323)
33	Primary Metal Industries	0.607 (16.826)	0.552 (13.074)	0.0.571 (17.622)
34	Fabricated Metal Products	0.480 (11 .841)	0.603 (28.612)	0.0.489 (22.141)
35	Machinery, Except Electrical	0.624 (18.007)	0.624 (18.007)	0.622 (20.763)
36	Electric and Electronic Equipment	0.403 (6.740	0.744 (23.012)	0.583 (15.339)
37	Transportation Equipment	0.737 (20.826)	0.791 (19.149)	0.749 (19.692)
38	Instruments and Related Products	0.662 (15.220)	0.812 (37.508	0.725 (28.350)

Continued

39	Misc. Manufacturing Industries	0.400 (4.1755)	0.337 (3.134)	0.462 (6.542)
	Average	0.493	0.544	0.550

*RVA = Real Value Added; EP = Electric Power Consumption; PW = Production Workers. Model-I: $ln(RVA) = \alpha + \beta \ln(EP) + \gamma \ln(PW)$; Model-II: $\ln(RVA) = \alpha + \beta \ln(EP)$; Model-II: $ln(RVA/PW) = \alpha + \beta ln(EP/PW)$.

Table 8. 2-Digit SIC industry supervision input Elasticities 1947-1984.

SIC	Industry	Elasticity-EP (t-stat.)	Elasticity-RVA (t-stat.)	R^2
20	Food and Kindred Products	−0.049 (4.558)	−0.071 (3.368)	0.244
21	Tobacco Products	−0.700 (2.621)	−1.204 (2.883)	0.191
22	Textile Mill Products	−0.476 (7.796)	−0.336 (1.251)	0.042
23	Apparel and Other Textile Products	−0.025 (1.084)	0.065 (0.580)	0.010
24	Lumber and Wood Products	−0.043 (1.405)	0.027 (0.401)	0.004
25	Furniture and Fixtures	0.0186 (13.691)	0.153 (3.726)	0.284
26	Paper and Allied Products	0.085 (5.113)	0.134 (5.795)	0.489
27	Printing and Publishing	0.388 (35.772)	0.097 (6.846)	0.572
28	Chemicals and Allied Products	0.021 (1.103)	0.037 (1.519)	0.061
29	Petroleum and Allied Products	−0.387 (14.896)	−0.414 (5.164)	0.439
30	Rubber and Misc. Products	0.495 (30.930)	0.676 (43.024)	0.981
31	Leather and Leather Products	−0.444 (2.324)	1.478 (12.132)	0.807
32	Stone, Clay and Glass Products	0.0179 (0.605)	0.087 (2.166)	0.118
33	Primary Metal Industries	−0.254 (2.884)	0.307 (2.017)	0.104
34	Fabricated Metal Products	0.080 (4.075)	0.365 (15.894)	0.881
35	Machinery, Except Electrical	0.055 (2.147)	0.208 (4.763)	0.393
36	Electric and Electronic Equipment	0.286 (11.006)	0.406 (14.860)	0.863
37	Transportation Equipment	0.028 (0.839)	068 (1.633)	0.068
38	Instruments and Related Products	0.334 (19.402)	0.415 (22.355)	0.934
39	Misc. Manufacturing Industries	−0.204 (3.501)	0.549 (2.115)	0.122

*EP = Electric Power Consumption; PW = Production Workers; RVA = Real Value Added. Model-I: $ln(PW) = \alpha + \beta ln(EP)$; Model-II: $ln(PW) = \alpha + \gamma ln(RVA)$.

to note is the fact that the R^2’s are all considerably lower than those reported in Tier I output elasticities (Table 5). In other words, output varies more closely with energy use than with the demand for supervision, which is understandable given the indivisible nature of supervisory inputs (i.e. conventionally-defined workers).

6. Applications and Implications

In this section, we consider the various applications and implications of the kinetic-based theory of production presented here. It bears noting that unlike conventional production theory which consists largely of stylized correlations (Cobb & Douglas, 1928, CES, Trans-log), the model presented here is a bona fidel theory, grounded in translational, rotational and chemical kinetics—in short, in the laws of basic physics.

6.1. Factor Substitution: Separating Fact from Fiction

The conventional, mainstream view regarding factor substitution is founded on the (erroneous) view that all factor inputs are essentially alike, and hence substitutable (Solow, 1974). Put differently, it assumes that all factor inputs are physically productive (i.e. sources of energy), making substitution possible. For example, tools and energy are seen as substitutable, as are materials and energy, or labor and materials (Berndt & Wood, 1975).

It is our view that this somewhat simplistic (and erroneous) formalization had its roots in the 18th-century transition from an artisanal to an industrial economy, where brawn and muscles (e.g. human being-based energy) were replaced by steam power. Hence, human force/energy/work was replaced by *btus* and *hps* from Boulton-Watt steam engines (referred to as "capital."). While this form of substitution was (or can be viewed as) legitimate, substitution as found in the current context is not, owing in large measure to the very nature of the labor (and capital) input—that is, not being sources of energy.

Fast forward to the late 19th/early 20th century where labor had, as Marshall put it, become a supervisory input, overseeing machinery. Clearly, in this case the capital-labor substitution of the early 19th century was no longer physically possible, as was the labor-energy substitution. This follows from the fact that labor was no longer powering material processes, and capital was neither a source of energy, nor a source of supervision.

The tiered framework presented above puts these questions in what we feel is the proper perspective. Standard production analysis combines all three in a single, multivariate production function. Doing so connotes the notion that factor inputs are comparable and hence substitutable. The tiered approach, based on kinetics and supervisory technology, highlights the basic fundamental difference between the two universal factor inputs (Beaudreau, 1998), namely broadly-defined energy and broadly-defined organization. In so doing, statements like those of Robert Solow to the effect that "the world can get along without natural resources so exhaustion is just an event, not a catastrophe" would be dismissed outright as it confuses energy with organization. In fact, such statements would be dismissed as they would be seen as violating the basic laws of physics.

6.2. The End of Human Supervision and Not the "End of Work"

Our analysis provides important insights into the nature of material processes and the contribution of the various "factor inputs." One such insight has to do with Jeremy Rifkin's notion of the "end of work," according to which innovations in control technology have rendered and continue to render conventional labor redundant, thus the title of the book (Rifkin, 1995). Specifically, our results show that semantically, this is an inaccurate description of the underlying forces. According to basic physics, work is what is accomplished using force/energy. Moreover, as pointed out, conventionally-defined workers or labor have not "worked" in over two centuries. Rather, they have provided and continue to provide supervisory services, or supervision.

This leads us to argue that what Rifkin and others have been describing is not the end of work, but rather the end of human supervision. Work (i.e. the physical definition) in the economy has, since 1995, increased by a factor of two as evidenced by a doubling of GDP. The point is that this has been achieved with less human supervision. Again, this highlights the importance and relevance of having definitions and concepts in economics that are both internally and externally valid. Rifkin's prophecy of the "end of work" makes no sense to an engineer or to a physicist. In short, a more appropriate title for his book (although one that would be less catchy, marketing wise) would have been "The End of Human Supervision." Material processes will always be supervised, whether by man or machine. And they will always work.

6.3. The Labor PFI in the Post-WWII Era

The last application concerns what is typically referred to as labor productivity, but which we refer to as labor product per factor index, often times used as a basis for establishing remuneration—in short, it is often argued that wages should track labor "productivity." In this section, we maintain that the post-WWII labor PFI increased in two distinct phases, namely the speed phase and the automation phase. The former refers to the increase in labor PFI in the immediate post-WWII period owing to greater machine speeds, which increased the amount of product per labor or supervisory input. Again, it is imperative to point out that labor was not responsible for the increase, but rather was simply a witness to greater machine speeds.

The second phase, which began in the 1980s and continues to this day is the automation phase which witnessed the increasing use of inanimate supervision technologies, commonly referred to as factory automation. Here, product per factor input increased via a decrease in the denominator—as opposed to an increase in the numerator in the first phase. As the remaining supervisors (i.e. labor) were not responsible for the increase in the Labor PPFI, it stands to reason that their remuneration would not, in any noticable way, be affected. Perhaps this explains the wage-productivity gap that has been identified in the literature.

7. Summary and Conclusions

This paper set out to present an internally and externally-valid theory of wealth, one that is consistent with the basic laws of physics, and one that is consistent with both the goals and objectives of economics as the science of wealth. Finding most non-mainstream critiques of the standard neoiclassical model to be short on specifics, we developed a model that is dualistic in nature, focusing on the physical underpinnings of output (Tier I) as well as the supervisory and tool-related aspects (Tier II). Delineating the two was the physics-based construct of physical productivity. Supervisory activity was deemed to be a necessary part of production activity, without contributing physically to production.

Our model is the first ever to explicitly invoke the laws of kinetics in production theory, and the first ever to confirm empirically what is a key law of mechanics—and physics—in economics. Moreover, it provided a theoretical support for the observed 20th-century increase in productivity. Specifically, the productivity gains in the early 1900s identified by Alfred Chandler can be attributed in large measure to higher machine speeds/throughput rates and not to an increase in physical capacity.

It is our view that such models are not only a welcomed alternative to what are archaic approaches to understanding material processes, they are necessary to resolving a number of the puzzles and paradoxes in economics. For example, there is the question of the "information paradox" according to which "we see computers everywhere except in the productivity data." The kinetics-based approach points to the fact that it is not a paradox at all, given that information is not physically productive, and can only contribute marginally—if at all—to productivity via second-law efficiency. As the latter is bounded from above and highly stable, it stands to reason that ICT has not, cannot, and will not increase productivity. This stands in contrast to the two other GPTs, namely the steam engine and the electric motor, both of which resulted in greater energy consumption per machine, and hence, greater productivity and output.

Lastly, they provide a long, overdue bridge between classical mechanics, basic physics, process engineering and economics. While the economics profession has paid and continues to pay lip service to the fact that its formalizations of production are grounded in engineering and applied physics, the resulting models have been and continue to be orthogonal to material processes as seen in the physical sciences. It was shown that this bridge provides valuable insights into such things as productivity and product indexes, the most telling example being the theoretically correct measure of Labor's Product Per Factor Input, which measures output per unit labor, without connoting of physical productivity. Such insights are immensely important in moving the debate over output, wages and profits (i.e. the debate instigated by Thomas Piketty's Capital in the 21st Century) along.

Conflicts of Interest

The corresponding author states that there is no conflict of interest.

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