

Measurement and assessment of the evolution of technology with a simple biological model

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Abstract. A simple model of the development of technology is presented. This model, in a broad analogy with evolutionary ecology of parasites, within a theoretical framework of Generalized Darwinism, can explain vital characteristics of technological advances and technological evolution. In particular, the evolution of technology is modelled here in terms of morphological changes between a host technology and a main subsystem of technology. The coefficient of evolutionary growth of this simple model here indicates the grade and type of the evolution of technology. This coefficient is quantified in real cases study using historical data of farm tractor, freight locomotive and electricity generation technology in steam-powered plants and internal-combustion plants. The approach of measurement and assessment of technological evolution proposed here seems to be appropriate in grasping the dynamics of technological evolution to predict which technologies are likeliest to evolve rapidly.

Keywords. Measurement of technology, Technometrics, Technological evolution, Technological change, Technological forecasting, Technology assessment, Technological progress, Innovation, Technology studies, Public decision making.

JEL. O30, O31, O32, O33, O38.

1. Introduction

The measurement of technology and innovation is an increasing challenge faced by agencies, scholars, public research labs and governments for supporting technological forecasting in society (cf., [Daim et al., 2018](#); [Hall & Jaffe, 2018](#); [Linstone, 2004](#))¹. Patterns of technological innovation have been analyzed using many analogies with biological phenomena ([Basalla, 1988](#); [Farrell, 1993](#); [Nelson & Winter, 1982](#); [Sahal, 1981](#); [Solé et al., 2013](#); [Wagner, 2011](#); [Ziman, 2000](#)). [Wagner & Rosen \(2014\)](#) argue that the application of evolutionary biology to different research fields has reduced the distance between life sciences and social sciences, generating new approaches, such as the evolutionary theory of economic change ([Nelson & Winter, 1982](#); cf., [Dosi, 1988](#)). In the research field of technical change and technological forecasting, the measurement of technological advances is a central and enduring research theme to explain the dynamics of the evolution of technology and technological progress ([Coccia, 2005, 2005a](#)). Scholars in these research topics endeavour of measuring technological advances, the level of technological development and changes in technology with different approaches directed to technological forecasting and assessing the impact of new technology on socioeconomic systems ([Coccia, 2005](#); [Daim et al., 2018](#); [Dodson, 1985](#); [Faust, 1990](#); [Fisher & Pry, 1971](#); [Farrell, 1993](#); [Knight, 1985](#); [Martino, 1985](#); [Sahal, 1981](#); [Wang et al., 2016](#)). However, a technometrics that measures and assesses the comprehensive evolution of

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technology as a complex system of technologies is, at author's knowledge, unknown.

This study confronts this problem by proposing a theory of measurement of the evolution of technology based on interaction between technologies that may be useful for bringing a new perspective to explain and predict, whenever possible, the long-run coevolution between technologies. In order to position this paper in existing frameworks, the study here starts by establishing a theoretical framework of different approaches for measuring technological advances. Moreover, in broad analogy with biology, a conceptual framework of technological evolution, based on the approach of technological parasitism, is suggested (cf., [Coccia & Watts, 2018](#)). Then, the evolution of technology is modelled in simple way in terms of morphological changes between a host technology and its technological subsystems. The coefficient of evolutionary growth of the proposed model is quantified in real technologies using historical data. Overall, then, the technometrics here seems to be appropriate in grasping the typology and grade of the evolution of technology. This approach also provides fruitful information to predict which technologies are likeliest to evolve rapidly and lays a foundation for the development of more sophisticated concepts to measure and explain the general properties of the evolution of new technology in society.

2. Theoretical framework of the measurement of technological advances (Technometrics)

Measurement assigns mathematical characteristics to conceptual entities. Stevens (1959, p.19) claims that the measurement is: "the assignment of numeral² to objects or events". The central issue for a theory of measurement is the status of the two basic problems: the first is the justification of the assignment of the numbers to objects or phenomena (called the representational theorem); the second is the specification of the degree to which this assignment is unique (the uniqueness theorem; cf., [Suppes & Zinnes, 1963](#); [Luce et al., 1963](#)). In the research field of technology, technometrics refers to a theoretical framework for the measurement of technology, technological advances and technological change with policy implications ([Sahal, 1981](#)). The measurement of technological advances has been performed with different approaches in engineering, scientometrics, technometrics, economics and related disciplines. This section presents some of the most important methods of technometrics, without pretending to be comprehensive ([Coccia, 2005, 2005a](#), p. 948 ff).

2.1. Hedonic approach to the measurement of technology

The assumption of this approach is a positive relationship between market price of a good or service and its quality. In particular, it is assumed that a particular product can be represented by a set of characteristics and by their value; hence, the quality of the product Q is given by:

$$Q_j = f(a_1, \dots, a_n, X_{1j}, \dots, X_{2j}, \dots, X_{kj})$$

where a_i is the relative importance of the i -th characteristics and X_{ij} is the qualitative level of the same characteristics in product j . Technological progress can be defined here as the change in quality during a given period of time:

$$TC_j = \frac{\Delta Q_j}{\Delta t}$$

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The observed changes in the price of a product can be decomposed into a “quality/technological change” effect and “pure price effect” (cf., Coccia, 2005a, pp.948-949; Saviotti, 1985).

2.2. RAND³ approach to the measurement of technology

A technological device has many technical parameters that measure its characteristics and characterize the state-of-the-art (SOA). Many approaches measure the SOA and advances in SOA. Dodson (1985) considers the SOA as a convex surface in an N -dimensional space, where N is the number of essential characteristics of a technology. He proposes the use of either a planar or an ellipsoidal surface:

$$\begin{array}{ll} \textit{Planar} & \textit{Ellipsoidal} \\ \sum_{i=1}^n \left(\frac{x_i}{a_i} \right) = 1 & \sum_{i=1}^n \left(\frac{x_i}{a_i} \right)^2 = 1 \end{array}$$

Where x_i is the i -th technological characteristic and a_i is the i -th parameter (a constant). Alexander & Nelson (1973) developed an alternative procedure, using hyperplanes instead of ellipses. Overall, then, the hedonic and the RAND techniques for measuring technological advances are very similar and differ only in their choice of the dependent variable, which is price in the former and calendar year in the latter (Coccia, 2005a, pp.949-952).

2.3. Functional and structural measurement of technology

The technique by Knight (1985) is based on a functional and a structural description of a given technology over time to detect its evolution. The structural model was originated by Burks *et al.*, (1946) that describe the computing system by outlining the pieces of equipment the computer must have, the purpose of devices, and the way the items interact with one another to perform as a computer. The functional description of a new computer over an earlier one indicates that technological advancement has taken place, but it does not specify the details of new development. In order to explain the technological advances, it is also necessary to use the structural description by comparing the structure of new systems with that of earlier computers (cf., Coccia, 2005a, pp.955-957).

2.4. Wholistic and holistic approaches to the measurement of technology

Sahal (1981) suggests two ideas of technometrics. In the first approach (called *Wholistic*), the state-of-the-art (SOA) is specified in terms of a surface of constant probability density given the distribution of technological characteristics. The SOA at any given point in time is represented by a probability mountain, rising above the plane. The level of technological capability is given by the height of the mountain. Instead, the magnitude of technological change can be estimated by the difference in the heights of successive mountains. In the second approach (called *Holistic*), a technological characteristic is specified as a vector in an N -dimensional space generated by a set of N linearly independent elements, such as mass, length, and time. The length of the vector represents the magnitude of a technological characteristic, while the kind of the characteristic is represented by the direction. In this case, the SOA reduces to a point. The successive points at various times constitute a general pattern of technological evolution that evinces a series of S-shaped curves. These two approaches are distinct but related (Coccia, 2005a, p.955).

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2.5. Seismic approach to the measurement of technology

This approach, elaborated by Coccia (2005), categorizes effects of technological change through a scale similar to that used in seismology by Mercalli. In particular, according to the seismic approach, innovations of higher intensity generate a series of effects on subjects and objects within and between geoeconomic systems. The intensity of innovation on socioeconomic systems is measured with an indicator called Magnitude of Technological Change, which is similar to the magnitude of the Richter scale that measures the energy of earthquakes (cf., Coccia, 2005a, pp.967-969).

2.6. Technological advances measured with patent data

These studies are aimed to investigate technological evolution considering the patent data. Faust (1990, p.473) argues that patent indicators allow for a differentiated observation of technological advances before the actual emergence of an innovation, such as technological development in the scientific field of superconductivity. Wang *et al.* (2016, p.537ff) investigate technological evolution using US Patent Classification (USPC) reclassification. Results suggest that: “patents with Inter-field Mobilized Codes, related to the topics of ‘Data processing: measuring, calibrating, or testing’ and ‘Optical communications’, involved broader technology topics but had a low speed of innovation. Patents with Intra-field Mobilized Codes, mostly in the Computers & Communications and Drugs & Medical fields, tended to have little novelty and a small innovative scope” (Wang *et al.*, 2016, p.537, original emphasis). Future research in this research field should extend the patent sample to subclasses or reclassified secondary USPCs in order to explain the in-depth technological evolution within a specific scientific field.

2.7. Measuring technological evolution using a model of technological substitution

In the context of the measurement of technological advances, Fisher & Pry (1971, p.75) argue that technological evolution consists of substituting a new technology for the old one, such as the substitution of coal for wood, hydrocarbons for coal, robotics technologies for humans (see Daim *et al.*, 2018), etc. They suggest a simple model of technological substitution that contains only two parameters. Technological advances are here represented by competitive substitutions of one method of satisfying a need for another. Fisher & Pry (1971, p.88) state that: “The speed with which a substitution takes place is not a simple measure of the pace of technical advance... it is, rather a measure of the unbalance in these factors between the competitive elements of the substitution”.

New approaches of technological assessment apply technology development envelope to detect multiple pathways for technological evolution and construct strategic roadmapping as illustrated by Daim *et al.*, (2018, p. 49ff) for robotics technologies.

Overall, then, although different approaches of the measurement of technological advances are suggested (Arthur & Polak, 2006; Sahal, 1981; Daim *et al.*, 2018), a technometrics that measures the evolution of technology considering how subsystems of technology interact with a host technology in a complex system of technology is, at author’s knowledge, unknown. To reiterate, this study endeavours to measure the evolution of technology with a new perspective based on coevolution between technologies to predict the long-term development of the whole complex system of technology.

Next section presents the conceptual framework of the technometrics here, which is based on the theory of technological parasitism (Coccia & Watts, 2018).

3. A proposed technometrics for the evolution of technology in complex systems

Hodgson & Knudsen (2006) suggest a generalization of the Darwinian concepts of selection, variation and retention to explain how a complex system evolves (Hodgson 2002, p.260; cf., Levit *et al.*, 2011; Schubert, 2014, p.486ff). In economics of technical change, it is become commonplace to argue that the generalization of Darwinian principles (“Generalized Darwinism”) can assist in explaining the nature of innovation processes (cf., Basalla, 1988). Sahal (1981) argues that: “evolution...pertains to the very structure and function of the object (p. 64) ...involves a process of equilibrium governed by the internal dynamics of the object system (p. 69)”. The process of development of technology generates the formation of a complex system (cf., Sahal, 1981, p.33). Evolution of a technology concerns a process governed by the interaction between a complex system of technology and its inter-related systems and subsystems (Coccia & Watts, 2018). An important step towards the measurement and assessment of technological progress is to first clarify the concept of complex system. Simon (1962, p.468) states that: “a complex system [is]... one made up of a large number of parts that interact in a nonsimple way... complexity frequently takes the form of hierarchy, and... a hierarchic system... is composed of interrelated subsystems, each of the latter being, in turn, hierarchic in structure until we reach some lowest level of elementary subsystem.” McNerney *et al.*, (2011, p.9008) argue that: “The technology can be decomposed into n components, each of which interacts with a cluster of $d-1$ other components” (cf., Andriani & Cohen, 2013; Angus & Newnham, 2013; Arthur & Polak, 2006, Barton, 2014; Gherardi & Rotondo, 2016; Kauffman & Macready, 1995; Kyriazis, 2015; McNerney *et al.*, 2011; Solé *et al.*, 2013). Arthur (2009, pp.18-19) claims that the evolution of technology is due to combinatorial evolution: “Technologies somehow must come into being as fresh combinations of what already exists”. This combination of components and assemblies is organized into systems to some human purpose and has a hierarchical and recursive structure. This study here endeavours, starting from concepts just mentioned, to measure technological advances in a framework of host-parasite technological systems, in a broad analogy with ecology (Coccia & Watts, 2018). Basic concepts of this conceptual framework are by Coccia & Watts (2018).

Technology is defined as a complex system that is composed of more than one component and a relationship that holds between each component and at least one other element in the system. The technology is selected and adapted in the Environment E to satisfy needs and human desires, solve problems in human society and support human control of nature.

Interaction between technologies in complex system is a reciprocal adaptation between technologies with interrelationship of information/resources/energy and other physical phenomena to satisfy needs and human wants.

Coevolution of technologies is the evolution of reciprocal adaptations in a complex system that generates innovation—i.e., a modification and/or improvement of technologies that interact and adapt in a complex system to expand content of the human life-interests whose increasing realization constitutes progress.

In general, host technologies form a complex system of parts and subsystems that interact in a non-simple way (e.g., batteries and antennas in mobile devices; cf., Coccia & Watts, 2018; Coccia, 2017). In this context, Coccia (2017a) states the *theorem of impossible independence* of any technology that: in the long run, the behaviour and evolution of any technology is not independent from the behaviour and evolution of the other technologies. In fact, Sahal (1981, p.71) argues that: “the evolution of a system is subject to limits only insofar as it remains an isolated system.”

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Overall, then, the theory of technological parasitism (Coccia & Watts, 2018), shortly described here, proposes that the interaction between technologies in a complex system tends to generate stepwise coevolutionary processes of a whole system of technology within the “space of the possible” (Wagner & Rosen, 2014, *passim*).

In order to operationalize the approach of technological parasitism to measure and predict the evolution of technology, this study proposes a simple model of technological interaction between a host technology H and an interrelated subsystem P . This model focuses on morphological changes in subsystems of technology in relation to proportional changes in the overall host system of technology. This model, based on the biological principle of allometry, was originally developed by biologists to study the differential growth rates of the parts of a living organism’s body in relation to the whole body during evolution processes (Reeve & Huxley, 1945; Sahal, 1981).

3.1. A model of technological evolution

Let $P(t)$ be the extent of technological advances of a technology P at the time t and $H(t)$ be the extent of technological advances of a technology H that is a master or host system that interacts with P , at the same time (cf., Sahal, 1981, pp.79-89). Suppose that both P and H evolve according to some S -shaped pattern of technological growth, such a pattern can be represented analytically in terms of the differential equation of the logistic function:

$$\frac{1}{H} \frac{dH}{dt} = \frac{b_1}{K_1} (K_1 - H)$$

We can rewrite the equation as:

$$\frac{K_1}{H} \frac{1}{(K_1 - H)} dH = b_1 dt$$

The integral of this equation is:

$$\begin{aligned} \log H - \log(K_1 - H) &= A + b_1 t \\ \log \frac{K_1 - H}{H} &= a_1 - b_1 t \\ H &= \frac{K_1}{1 + \exp(a_1 - b_1 t)} \end{aligned}$$

$a_1 = b_1 t$ and $t =$ abscissa of the point of inflection.

The growth of H can be described respectively as:

$$\log \frac{K_1 - H}{H} = a_1 - b_1 t \tag{1}$$

Mutatis mutandis, for $P(t)$ in similar way of $H(t)$, the equation is:

$$\log \frac{K_2 - P}{P} = a_2 - b_2 t \tag{2}$$

The logistic curve here is a symmetrical S -shaped curve with a point of inflection at $0.5K$ with $a_1 =$ constant depending on the initial conditions, $K_1 =$ equilibrium level of growth, and $b_1 =$ rate-of-growth parameter.

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Solving equations [1] and [2] for t , the result is:

$$t = \frac{a_1}{b_1} - \frac{1}{b_1} \log \frac{K_1 - H}{H} = \frac{a_2}{b_2} - \frac{1}{b_2} \log \frac{K_2 - P}{P}$$

The expression generated is:

$$\frac{H}{K_1 - H} = C_1 \left(\frac{P}{K_2 - P} \right)^{\frac{b_1}{b_2}} \quad (3)$$

$C_1 = \exp[b_1(t_2 - t_1)]$ (for t_2 and t_1 , cf., eqs. [1] and [2]); when P and H are small in comparison with their final value, the simple model of technological evolution is given by:

$$P = A_1 (H)^{B_1} \quad (4)$$

$$\text{where } A_1 = \frac{K_2}{(K_1)^{\frac{b_2}{b_1}}} C_1 \text{ and } B_1 = \frac{b_2}{b_1}$$

The logarithmic form of the equation [4] is a simple linear relationship:

$$\ln P = \ln A_1 + B_1 \ln H \quad (5)$$

B_1 is the evolutionary coefficient of growth that measures the evolution of technology and is quantified in real instances in the next section.

This model of the evolution of technology [5] has linear parameters that are estimated with the Ordinary Least-Squares Method. The value of B_1 in the model [5] measures the relative growth of P in relation to the growth of H and indicates different patterns of technological evolution: $B_1 < 1$ (underdevelopment), $B_1 \geq 1$ (growth or development of technology). In particular,

$B_1 < 1$, whether technology P (a subsystem of H) evolves at a lower relative rate of change than technology H ; the whole host technology H has a slowed evolution (underdevelopment) over the course of time.

B_1 has a unit value: $B_1 = 1$, then the two technologies P and H have proportional change during their evolution: i.e., a coevolution between a whole system of technology (H) and its interacting subsystem P . This case of the proportional change generates a technological evolution of isometry between elements of a complex system. In short, when $B_1 = 1$, the whole system of technology H here has a proportional evolution of its component technologies (growth) over the course of time.

$B_1 > 1$, whether P evolves at greater relative rate of change than H ; this pattern denotes disproportionate technological advances in the structure of a subsystem P as a consequence of change in the overall structure of a host technological system H . The whole system of technology H has an accelerated evolution (development) over the course of time.

This technometrics justifies the representational and uniqueness theorem in the measurement of the evolution of technology. Moreover, results of model [5], represented by the coefficient of evolutionary growth of technology, can be systematized in an ordinal scale that indicates the grade and type of the evolution of technology (table 1).

Table 1. *Scale of the evolution of technology in complex systems*

<i>Grade of evolution</i>	<i>Coefficient of evolutionary growth</i>	<i>Type of the evolution of technology</i>	<i>Associated Evolutionary stages of the evolution of technology</i>	<i>Predictions</i>
1 Low	$B < 1$	Slowed	Underdevelopment	Technology evolves slowly over the course of time
2 Average	$B = 1$	Proportional	Growth	Technology has a steady-state path of evolution
3 High	$B > 1$	Accelerated	Development	Technology is likeliest to evolve rapidly

Properties of the scale of the evolution of technology (Table 1) are:

Technology of higher rank-order (grade) on the scale has higher technological advances of lower rank-order (grade) technologies.

If a technology has the highest ranking on the scale (i.e., three), it evolves rapidly (development) over the course of time. Vice versa, if a technology has the lowest ranking on the scale (i.e., one), it evolves slowly (underdevelopment).

Evolution of technology of higher rank order on the scale has accumulated all previous stages of low rank order and generates a fruitful symbiotic growth between a whole system of technology H and its interacting subsystem-components $P_i (i=1, \dots, n)$.

4. Materials and method

4.1. Data and their sources

The evolution of technology is illustrated here using historical data of four example technologies: farm tractor technology, freight locomotive technology, generation of electricity technology in steam-powered and internal-combustion plants in the USA. Sources of data are tables published by Sahal (1981, pp.319-350, originally sourced from trade literature; cf., also Coccia, 2018). Note that data from the earliest years and also the war years are sparse for some technologies.

4.2. Measures

Technological parameters that measure the evolution of technology are given by Functional Measures of Technology (FMT) over the course of time to take into account both major and minor innovations (cf., Sahal, 1981, pp. 27-29).

FMTs for farm tractor are:

fuel-consumption efficiency in horsepower-hours over 1920-1968 CE indicates the technological advances of engines (a subsystem) of farm tractors. This FMT represents the dependent variable P in the model [5].

mechanical efficiency (ratio of drawbar horsepower to belt or power take-off – PTO- horsepower) over 1920-1968 CE is a proxy of the technological advances of farm tractor. This FMT represents the explanatory variable H in the model [5].

For freight locomotive, FMTs are:

Tractive efforts in pound over 1904-1932 CE indicate the technological advances of locomotive. This FMT represents the dependent variable P in the model [5].

Total railroad mileage over 1904-1932 CE indicates the evolution of the infrastructure system of railroad. This FMT represents the explanatory variable in the model [5].

For steam-powered electricity-generating technology, FMTs are:

Average fuel-consumption efficiency in kilowatt-hours per pound of coal over 1920-1970 CE indicates the technological advances of boiler, turbines and electrical generator (subsystems of steam-powered plant). This FMT represents the dependent variable P in the model [5].

Average scale of plant utilization (the ratio of net production of steam-powered electrical energy in millions of kilowatt-hours to number of steam

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powered plants) over 1920-1970 CE indicates a proxy of the technological advances of the overall electricity-generating plants. This FMT represents the explanatory variable in the model [5].

For internal-combustion type electric power technology, FMTs are:

Average fuel-consumption efficiency in kilowatt-hours per cubic foot of gas 1920-1970 CE indicates the technological advances of boiler, turbines and electrical generator (subsystems of internal combustion plant). This FMT represents the dependent variable P in the model [5].

Average scale of plant utilization (the ratio of net production of electrical energy by internal-combustion type plants in millions of kilowatt-hours to total number of these plants) over 1920-1970 CE indicates a proxy of the technological advances of the overall electricity-generating plants with this internal-combustion technology. This FMT represents the explanatory variable in the model [5].

4.3. Model and data analysis procedure

Model [5] of the technological evolution implemented in real instances here is:

$$\ln P_t = \ln a + B \ln H_t + u_t \quad (\text{with } u_t = \text{error term}) \quad (6)$$

a is a constant

P_t will be the extent of technological advances of technology P that represents a subsystem of the Host technology H at time t

H_t will be the extent of technological advances of technology H that represents the host technology of an interacting subsystem technology P at time t ; H technology is the driving force of the evolutionary growth of overall interrelated subsystems of technology.

The equation of simple regression [6] is estimated using the Ordinary Least Squares method. Statistical analyses are performed with the Statistics Software SPSS® version 24.

5. Case studies of the evolution of technology in the agriculture, rail transport and electricity generation

The evolution of technology modelled here is illustrated with realistic examples using historical data of farm tractor, freight locomotive, steam-powered electricity-generating technology and internal-combustion type electric power technology in the USA. Table 2 shows the descriptive statistics of the study.

Table 2. Descriptive statistics (logarithmic scale)

	LN Fuel consumption efficiency in horse power hours (Engine of Tractor)	LN Mechanical efficiency ratio of drawbar horsepower to belt (Tractor efficiency)	LN Tractive efforts in pound (Locomotive power)	LN Total railroad Mileage (Infrastructure for locomotive)
Years	44	44	29	29
Mean	2.13	4.19	10.43	12.86
Std. Deviation	0.27	0.146	0.22	0.11
Skewness	-0.76	-0.68	-0.21	-1.04
Kurtosis	-0.83	-0.56	-1.19	-0.06
	LN Average fuel consumption efficiency in kwh per pound of coal (turbine and various equipment in steam- powered plants)	LN Average scale of steam- powered plants	LN Average fuel consumption efficiency in kwh per cubic feet of gas (turbine and various equipment in internal- combustion plants)	LN Average scale of internal-combustion plants
Years	51	51	51	51
Mean	-0.25	4.85	-2.75	0.51
Std. Deviation	0.34	1.43	0.33	0.85
Skewness	-0.67	-0.17	-0.67	0.02
Kurtosis	-0.09	-1.26	0.04	-1.64

5.1. Results of the evolution of farm tractor technology (1920-1968)

Table 3 shows the evolutionary coefficient of growth of farm tractor technology, from model [6], is $B = 1.74$, i.e., $B > 1$: the subsystem component technology of engine (P) has a disproportionate technological growth in comparison with overall farm tractor (H). This coefficient indicates a high grade of the evolution of technology (three) and a development of the whole system of farm tractor technology (cf., Figure 1).

Table 3. Estimated relationship for farm tractor technology

Dependent variable: LN fuel consumption efficiency in horsepower hours (technological advances of engine for tractor at $t=1920, \dots, 1968$)

	Constant α (St. Err.)	Evolutionary coefficient $\beta=B$ (St. Err.)	R^2 adj. (St. Err. of the Estimate)	F (sign.)
Farm tractor	-5.14*** (0.45)	1.74*** (0.11)	0.85 (0.10)	256.44 (0.001)

Note: ***Coefficient β is significant at 1%; Explanatory variable is LN mechanical efficiency ratio of drawbar horsepower to belt (technological advances of farm tractor –Host technology), $t = (1920-1968)$.

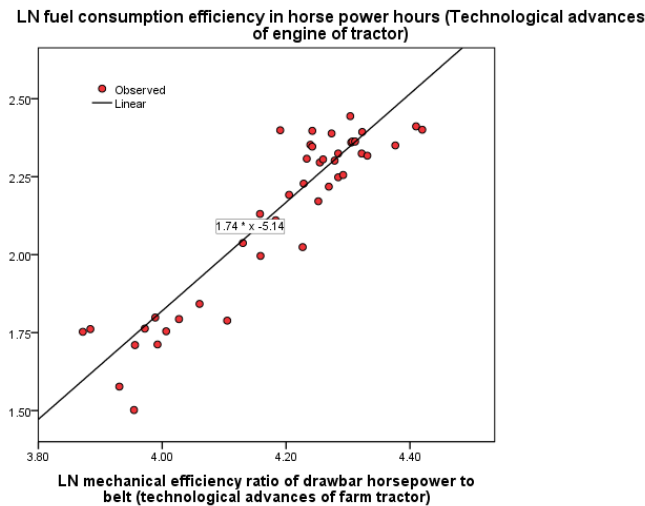


Figure 1.

Trend and estimated relationship of the evolution of farm tractor technology

This result confirms the study by Sahal (1981) that the rapid evolution of farm tractor technology is due to numerous advances and radical innovations over time, such as the diesel-powered track-type tractor in 1931, low-pressure rubber tires in 1934 and the introduction of remote control in 1947 that made possible improved control of large drawn implements. The development of the continuous running power takeoff (PTO) also in 1947 allowed the tractor’s clutch to be disengaged without impeding power to the implements. Moreover, it introduced, in 1950, the 1000-rpm PTO for transmission of higher power, whereas in 1953 power steering was applied in new generations of tractor. In addition, the PTO horsepower of the tractor has more than doubled from about 27hp to 69hp over 1948-1968; finally, dual rear wheels in 1965, auxiliary front-wheel drive and four-wheel drive in 1967 have improved the overall technological performance of the tractor (Sahal, 1981, p.132ff). These radical and incremental innovations have supported the accelerated evolution of the farm tractor technology over time as confirmed by the statistical evidence here with the coefficient of evolutionary growth $B > 1$.

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5.2. Results of the evolution of freight locomotive technology (1904–1932)

Table 4 shows that the evolutionary coefficient of freight locomotive technology is $B = 1.89$, i.e., $B > 1$: this coefficient of growth indicates a stage of development of freight locomotive technology in the complex system of rail transportation (see, Figure 2).

Table 4. *Estimated relationship for freight locomotive technology*

<i>Dependent variable: LN Tractive efforts in pound of locomotive (technological advances), $t = (1904-1932)$</i>				
	<i>Constant</i>	<i>Evolutionary coefficient</i>	<i>R² adj.</i>	<i>F</i>
	α	$\beta=B$	(<i>St. Err. of the Estimate</i>)	(<i>sign.</i>)
	(<i>St. Err.</i>)	(<i>St. Err.</i>)		
Farm tractor	-13.87***	1.89***	0.91	270.15
	(1.48)	(0.12)	(0.07)	(0.001)

Note: ***Coefficient β is significant at 1%; Explanatory variable is LN Total railroad mileage (technological advances of the infrastructure –Host technology) at $t=1904, \dots, 1932$

This development of freight locomotive technology can be explained with a number of technological improvements, such as the introduction of the compound engine in 1906 that improved the tractive effort (Sahal, 1981). In 1912 the first mechanical stoker to use the steam-jet overfeed system of coal distribution and the substitution of pneumatically operated power reverse gear for the hand lever have improved locomotive power. In 1916, it is introduced the unit drawbar and radial buffer that eliminated the need for a safety chain in coupling the engine and tender together. Further technological advances are due to the adoption of cast-steel frames integral with the cylinder, the chemical treatment of the locomotive boiler water supply and the introduction of roller bearings over 1930s. In particular, these technical developments reduced the frequency of maintenance work in locomotives. Subsequently, the continuous modification of the steam locomotive with reciprocating engine has led to diesel-electric locomotive by the mid-1940s (Sahal, 1981, p.154ff). These technological developments have supported the accelerated evolution of freight locomotive technology over time as confirmed by the coefficient of evolutionary growth $B > 1$ calculated above.

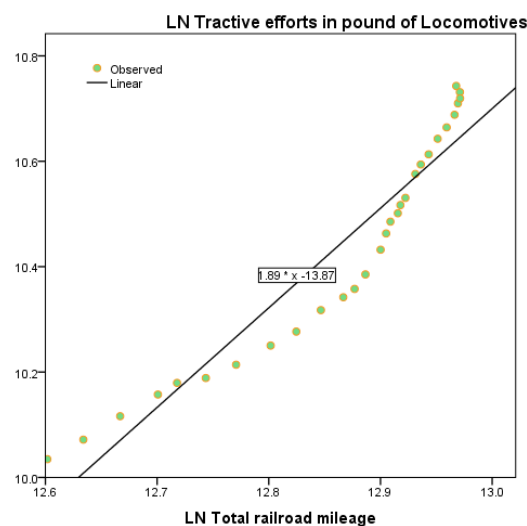


Figure 2.

Trend and estimated relationship of the evolution of freight locomotive technology

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5.3. Results of the evolution of electricity generation technology (1920-1970)

Table 5 shows that steam-powered electricity-generating technology is $B = 0.23$, i.e., $B < 1$ (see also Figure 3).

Table 5. *Estimated relationship for the steam-powered electricity-generating technology (1920-1970)*

<i>Dependent variable: LN Average fuel consumption efficiency in kwh per pound of coal (technological advances of turbine and various equipment)</i>				
	<i>Constant</i>	<i>Evolutionary Coefficient $\beta=B$</i>	<i>R² adj. (St. Err. of the Estimate)</i>	<i>F (sign.)</i>
	α (<i>St. Err.</i>)	<i>(St. Err.)</i>		
Turbine and various equipment	-1.35*** (0.04)	0.23*** (0.01)	0.93 (0.09)	675.12 (0.001)

Note: ***Coefficient β is significant at 1%; Explanatory variable is Average scale of steam-powered plants (Host technology) at $t=1920, \dots, 1970$

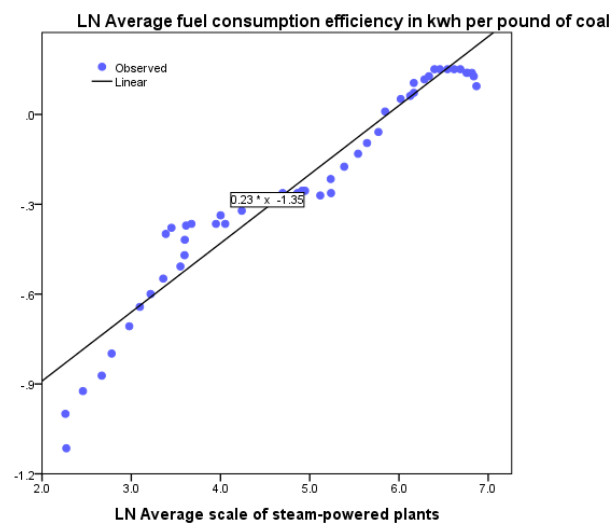


Figure 3.

Trend and estimated relationship of the evolution of steam-powered electricity-generating technology (1920-1970)

Table 6 shows for internal-combustion type electric power technology similar results to steam-powered electricity-generating technology: coefficient of evolutionary growth of this technology is $B = 0.35$, i.e., $B < 1$. In short, evolution of technology in the generation of electricity both in steam-powered plants and internal-combustion plants is low and driven by an evolutionary route of underdevelopment over the course of time (see, Figure 3 and 4). This evolution of technology in the generation of electricity is associated with available natural resources, the increase in steam pressure and temperature made possible by advances in metallurgy, the use of double reheat units and improvements in the integrated system man-machine interactions to optimize the operation of overall plants (Sahal, 1981, pp.183ff). In general, the rate of technological evolution in the generation of technology has slowed down (underdevelopment) because of: “the deterioration in the quality of fuel and of constraints imposed by environmental conditions....other main reasons: First, increased steam temperature requires the use of more costly alloys, which in turn entail maintenance problems of their own.... Thus there has been a decrease in the maximum throttle temperature from 1200 °F in 1962, to about 1000 °F in 1970. Second, there has been lack of motivation to increase the efficiency in the use of gas in both steam-powered and internal-combustion plants because of the artificially low price of fuel due to Federal Power Commission’s wellhead gas

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price regulation. Finally, ... there has been a slowdown in generation efficiency due to heavy use of low-efficiency gas turbines necessitated by delays in the construction of nuclear power plant” (Sahal, 1981, p.184).

Table 6. *Estimated relationship for internal-combustion type electric power technology (1920-1970)*

	<i>Dependent variable:</i> LN Average fuel consumption efficiency in kwh per cubic feet of gas (technological advances of turbine and various equipment)			
	<i>Constant</i> α (<i>St. Err.</i>)	<i>Evolutionary coefficient</i> $\beta=B$ (<i>St. Err.</i>)	<i>R² adj.</i> (<i>St. Err.</i> of the Estimate)	<i>F</i> (<i>sign.</i>)
Turbine and various equipment	-2.93*** (0.02)	0.35*** (0.02)	0.81 (0.14)	213.63 (0.001)

Note: ***Coefficient β is significant at 1%; Explanatory variable is LN Average scale of internal-combustion plants (Host technology) at $t=1920, \dots, 1970$

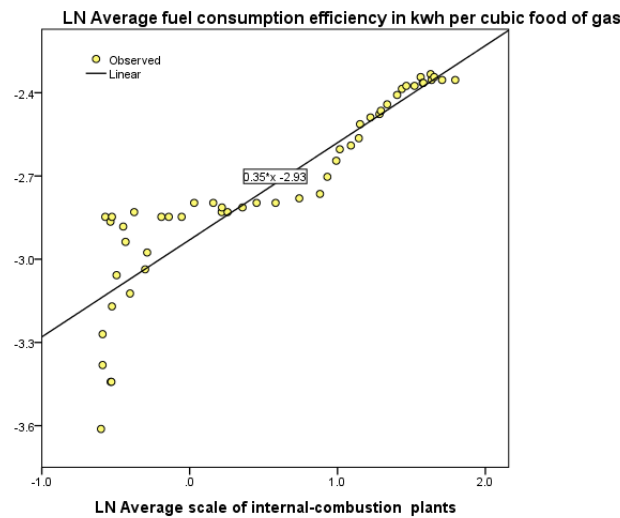


Figure 4.

Trend and estimated relationship of the evolution of internal-combustion type electric power technology (1920-1970)

6. Discussion

The measurement of technological advances needs a unifying perspective to explain and predict the evolution of technology, which has more and more complexity in markets with rapid changes. This article proposes a new perspective for the measurement of the evolution of technology that is adapted from ecology and is modelled with a simple model of morphological change that assesses and predicts the technological development driven by interaction between a host technology and its parasitic-subsystems of technology over the long run. As a matter of fact, some scholars argue that technologies and technological progress display numerous life-like features, suggesting a deep connection with biological evolution (Basalla, 1988; Erwin & Krakauer, 2004; Solé *et al.*, 2011; Wagner & Rosen, 2014). In general, biological evolution seems to support possible explanations of technology evolution (Basalla, 1988). In this context, this study extends the broad analogy between technological and biological evolution to more specifically focus on the potential of a technometrics based on interaction between technologies in complex systems, but fully acknowledge that interaction between technologies is not a perfect analogy of biological/ecological interaction; of course, there are differences (Ziman, 2000; Jacob, 1977; Solé *et al.*, 2013). For studying technical progress, though, the analogy with biology and ecology is a source of ideas because biological

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evolution has been studied in-depth and provides a logical structure of scientific inquiry in research fields concerning technology.

The study here suggests a theoretical framework that seems to be appropriate to measure the evolution of technology and predict possible evolutionary pathways of the complex systems of technology. In particular, the evolution of technology here is based on a simple assumption that technologies are complex systems that interact in a nonsimple way with other technologies and its interrelated subsystems of technology. The dynamics of the evolution of technology here is based on a S-shaped growth curve of technological advances both for the whole system of technology and for its interrelated subsystem components. The approach here is formalized with a simple model that contains only two parameters and provides the coefficient of evolutionary growth, which is useful to measure the typology of evolution of technology and predict which technologies are likeliest to evolve rapidly. In particular, the technometrics here provides three simple grades of the evolution of technology according to the coefficient of evolutionary growth: $B < 1$ (underdevelopment), $B = 1$ (growth) and $B > 1$ indicates the development of the whole system of technology. Hence, the evolution of technology is a multidimensional process of interaction within and between technologies, such that a technology, which remains an isolated system and does not interact with other technologies, can slow down technological advances over the course of time (Coccia, 2017a; Sahal, 1981). The technometrics proposed here, illustrated in four example technologies, provides consistent patterns of the evolution of technology supported by the history of technology.

One of the most important findings of the proposed theoretical framework here is two general properties of the accelerated evolution of technology as a complex system: (1) disproportionate growth of its subsystems and (2) increase in the complexity of the structure of technology during the rapid evolutionary growth of its interacting subsystem-component technologies.

The quantification of the coefficient of evolutionary growth of the model [6], called B , can also suggest reliable predictions of the long-term development of technology, given by:

Evolution of technology in the form of development of the whole system is governed by a process of disproportionate growth in its subsystems ($B > 1$) as a consequence of change in the overall system of the host technology (e.g., technological development of farm tractor and freight locomotive technologies described here).

Evolution of technology reduces speed when its component subsystems have low changes as a consequence of changes of the whole system of host technology ($B < 1$), generating underdevelopment of the whole system of technology over the course of time (e.g., the electricity generation technology).

The long-run evolution of a technology depends on the behaviour and evolution of associated technologies (interacting systems and subsystems). To put it differently, long-run evolution of a specific technology is enhanced by the integration of two or more technologies that generate co-evolution of system innovations.

Technologies having an accelerated symbiotic growth of its interacting subsystem technologies ($B > 1$) advance rapidly, whereas technologies with low growth of its interacting parts ($B < 1$) improve slowly.

Isolated system of technology, with low interaction between systems and among the parts of its system, is subject to limits of long-run evolution.

In general, this study shows that the technology is a complex system driven by manifold factors. Sahal (1981, p.69) argues that the dynamics of a system is affected by its history and associated processes of self-generating and self-constraining of its growth. Moreover, the evolution of technological system is also due to processes of learning, based on interaction processes between different technological devices and its subsystems that determine the scope for

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the utilization of a technology and the directions of technological guideposts and innovation avenues over time (cf., Sahal, 1981; Nelson & Winter, 1982). In fact, Sahal (1981, p.82, original italics) argues that: “the role of learning in the *evolution* of a technique has profound implications for its *diffusion* as well”. In addition, findings here show that the evolution of technologies is affected by scientific and technological advances of the whole system and its subsystems (e.g., for farm tractor and freight locomotive technologies) but it is also affected by socio-institutional environment that can slowdown technological progress (e.g., low technological advances in steam-powered electricity-generating technology and internal-combustion type electric power technology).

The finding of this study could aid technology policy and management of technology to design best practices for supporting development of new technology, and as a consequence, industrial and economic change in human society. Proposed theory here has also a number of implications for the analysis of nature, sources and evolution of technology. One of the most important implications is the interaction between technology and its subsystem components in complex systems that drive the evolutionary pathways of complex systems of technology and technological diversification over time and space. This suggested approach of technometrics here is consistent with the well-established literature by Arthur (2009) as well as with studies that consider structural innovations and systems innovations based on integration of two or more symbiotic technologies (Sahal, 1981).

The main limitation of this approach is in the lack of useful data in sufficient quality for different technologies. Future efforts in this research field require a substantial amount of data of technological parameters to provide additional empirical evidence of the different pathways of technological evolution over time and space.

To conclude, the proposed approach here based on the ecology-like interaction between technologies—may lay the foundation for development of more sophisticated concepts and theoretical frameworks in technometrics and technological forecasting. In particular, this study constitutes an initial significant step in measuring the evolution of technology considering the interaction between technologies in complex systems to predict the long-run behaviour and evolution of fruitful technological trajectories in society. Nevertheless, identifying comprehensive technometrics in different domains of technology, affected by manifold and complex factors, is a non-trivial exercise. Wright (1997, p. 1562) properly claims that: “In the world of technological change, bounded rationality is the rule.”

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Notes

¹Cf. for study of the sources of technological innovation in a context of complexity and national system of innovation: Anadon *et al.*, 2016; Andriani & Cohen, 2013; Angus & Newnham, 2013; Barabási *et al.*, 2001; Barton, 2014; Coccia, 2005, 2005a, 2005b, 2006, 2009, 2010, 2010a, 2012, 2013, 2013a, 2014, 2014a, 2014b, 2015, 2015a, 2016, 2016a, 2017, 2017a, 2017b, 2017c, 2018, 2018a, 2018b, 2018c, 2018e, 2018f; Coccia & Bellitto, 2018; Coccia & Bozeman, 2016; Coccia & Cadario, 2014; Coccia *et al.*, 2015; Coccia & Rolfo, 2009, 2010, 2013; Dawkins, 1983; Farmer & Lafond, 2016; Grodal *et al.*, 2015; Hodgson, 2002; Hodgson & Knudsen, 2006, 2008; Kauffman & Macready, 1995; Kreindler & Peyton Young, 2014; Kyriazis, 2015; Levit *et al.*, 2011; Nagy *et al.*, 2013; Nelson, 2006; Nordhaus, 1997; Oswald, 1976; Rosenberg, 1969; Schubert, 2014; Schuster, 2016; Valverde, 2016; Valverde *et al.*, 2007; Watanabe *et al.*, 2012.

² The term “numeral” according to Stevens (1959, p. 19) refers to an element in a formal model, not to a particular mark on a particular piece of paper.

³ RAND Corporation (“Research AND Development”) is an U.S. research organization to develop research and analysis that support US public policy for increasing the security, health and economic growth of the USA, allied countries and in general the world.

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