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Multiple working hypotheses for technology analysis

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Abstract. Technology analysis focuses on technology that is a complex system formed by different elements given by incremental and radical innovations to satisfy needs, achieve goals and/or solve problems of users to take advantage of important opportunities or to cope with consequential environmental threats. This study suggests a methods of inquiry, called multiple working hypotheses (MWHs), for technology analysis that consider the development, prior to research, of different hypotheses concerning the origin and evolution of technology, which are likely due to several causes, not just one. The MWHs presented here are categorized in traditional hypotheses, such as demand for technology hypothesis, Induced-innovation hypothesis, learning by doing hypothesis, learning via diffusion hypothesis, specialization via scale hypothesis, disadvantage of beginning hypothesis, path-dependence hypothesis, competitive substitution hypothesis, predator-prey hypothesis, and modern hypotheses such as killer technology hypothesis, parasite technologies hypothesis. Scholars of technology studies should consider all suggested hypotheses for technology analysis, also considering the possibility that none of them are correct and that some new explanations may emerge in more and more complex and turbulent environment.

Keywords. Technology, Technological innovation, Technology analysis, Induced innovation, Learning by doing, Technological evolution, Nature of technology, Path dependence, Technological change, Technological progress, Technological parasitism, Technological advances, Killer technology, Evolution of technology, Multiple working hypotheses.

JEL. O30, O31, O33.

1. Introduction

Technology plays an important role forcompetitive advantage of firms and nations, economic and social change of societies (Arthur, 2009;Coccia, 2018, 2019; Hosler, 1994; Sahal, 1981). *Technology*can be defined as a complex system, composed of more than one entity or sub-system and a relationship that holds between each entity and at least one other entity in the system (Coccia, 2019). Technology is selected considering practical, technical, social and/or economic characteristics to satisfy needs, achieve goals and/or solve problems of users to take advantage of important opportunities or to cope with consequential environmental threats for supporting adaptation and/or survival in a highly differentiated and volatile environment (Coccia, 2019a, b). Technology is driven by *inventions* of new things, new ways of doing things, and transformation of

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inventions into usable *innovations* in markets, and the subsequent adoption, diffusion and evolution of such innovations in society (Coccia, 2019b, c). Technology, as a complex system, develops with different typologies of innovation, generating technological change, given by (Coccia, 2005, 2006, 2016a): *incremental innovation* (progressive modifications of existing products and/or processes); *radical innovation* (a drastic change of existing products/processes, or new products to satisfy needs or solve problems in society); *technological systems* (a cluster of innovations that are technically and economically inter-related, e.g., nanotechnology; cf., Coccia & Wang, 2015); *technological revolution* (pervasive changes in technology affecting many branches of the economy, such as general purpose technologies given by Information and Communication Technologies having a technological dynamism and a pervasive use in wide range of sectors; cf., Coccia, 2017, 2020)[1].

Technology analysis focuses on sources, evolution and diffusion of technologies that can be investigated with "multi working hypotheses" (Chamberlin, 1897) to provide theoretical, empirical and policy implications. The method of multiple working hypotheses (MWHs) involves the development, prior to research, of several hypotheses that might explain the phenomenon under study, which is likely due to several causes, not just one (Chamberlin, 1897). All suggested hypotheses are considered, including the possibility that none of them are correct and that some new explanations may emerge (Coccia & Benati, 2018; Heidelberger & Schiemann, 2009).

MWHs for technology analysis can be systematized as follows (Figure 1):

- ☐ MWHs of the traditional approach are:demand of technology, induced innovation, learning processes, specialization *via*scale, disadvantage of beginning, path-dependence processes, competitive substitution between technologies,and predator-prey relationships.
- ☐ MWHs of the modern approach are based on multi-mode relationships between technologies, such as the hypothesis of killer technologies and parasitic technologies.

[1] For other studies about the interaction between science, technology and innovation, their sources, evolution, diffusion and impact on socioeconomic systems, see: Calabrese *et al.*, 2005; Chagpar & Coccia, 2019; Coccia, 1999, 2003, 2004, 2005, 2005a,b,c,d, 2006, 2006a, 2007, 2008, 2008a, 2009, 200a, b, 2010, 2010a, b, 2011, 2012, 2012a, b, c, 2013, 2014, 2014a, b, c, d, e, f, g, 2015, 2015a, b, c, d, 2016, 2016a, b, 2017, 2017a, b, c, d, e, f, g, 2018, 2018a, b, c, d, e, f, g, h, i, l, m, n, 2019, 2019a, b, c, d, e, f, g, h, i, l, m, n, o, Coccia, 2020; Coccia & Benati, 2018; Coccia & Cadario, 2014; Coccia & Finardi, 2012; Coccia & Rolfo, 2002, 2008, 2009, 2013; Coccia & Wang, 2015, 2016; Coccia & Watts, 2020.

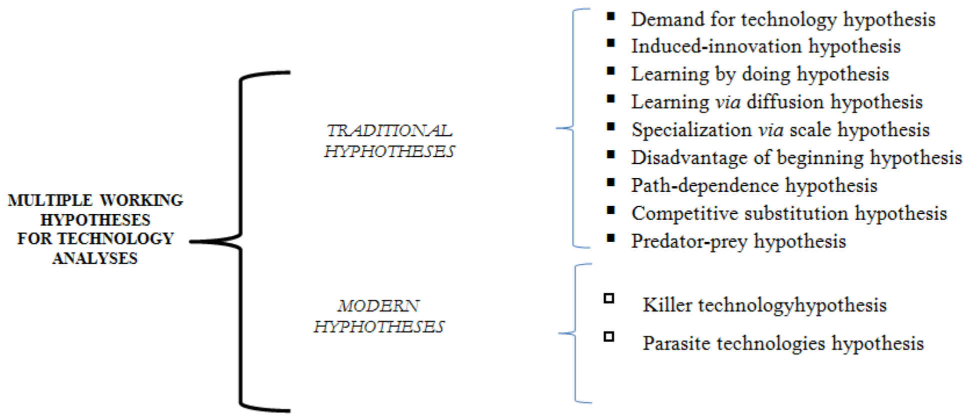

Figure 1. *Multiple Working Hypotheses (MWHs) for technological analyses*

2. Multiple working hypotheses for technological analyses

The hypotheses that are describedhere play a vital role to explain *how* technology evolves in the industrial dynamics of markets. Approaches can be categorized in tradition and modernmultiple working hypotheses (MWHs)to explain technical progress in society (cf., Figure 1).

2.1. Traditionalmultiple working hypotheses for technology analysis

- *Demand for technology hypothesis*

This hypothesis suggests that the inventive output of an industry varies in a direct relation to the volume of its sales. Schmookler & Brownlee (1962) argue that the relationship between technological innovation and demand is postulated to hold in both the long run and short run. The demand-pull hypothesis has received convincing evidence with the work by Griliches and Schmookler in support of the importance of change in market demand on the supply of knowledge and technology. In particular, Griliches (1957) in the study of the invention and diffusion of hybrid maize demonstrates the role of demand in determining the timing and location of invention and innovation. Schmookler (1962, 1966), using patentstatistics on inventions in industries (railroads, agricultural equipment,paper, and petroleum),shows that demand was more important instimulating inventive activity than advances in the state of knowledge.

A simple model to analyze this hypothesis of demand for technology, considering for instance farm tractor technology, is given by:

$$\log Y_t = a + \beta_1 \log X^{\#}_t + \beta_2 \log Y_{t-1}$$

Y is a measure of efficiency of technology under study; $X^{\#}$ is gross investment in tractors, i.e., the number of tractors sold each year (in hundreds)

- *Induced-innovation hypothesis*

Hicks argues that: "a change in the relative prices of factors of production is itself a spur to innovation and to inventions of a particular kind directed at economizing the use of a factor which has become relatively expensive" (Hicks, 1932, pp.124-125). Hicks' suggestion initially received little attention by scholars. The microeconomic version of induced innovation was advanced again by Ahmad (1966) and elaborated by Binswanger (1974). In the 1970s and 1980s there was a substantial body of theoretical and empirical studies, particularly by agricultural economists, whichexplains source and evolution of technology with induced-innovation hypothesis (Hayami & Ruttan, 1970; Binswanger & Ruttan, 1978). Olmstead and& Rhode (1993, p.102) argue that Hayami and Ruttan's induced-innovation hypothesis reveals two distinct variants. The first is *change variant*, associated with the argument by John Hicks: a rise in the relative price in one factor leads to technological innovations sparing that factor. The second is *level variant*that even at constant relative factor price levels, new technologies are developed and adopted to save relatively expensive factors.

- *Learning by doing hypothesis*

This hypothesis of technological innovation suggests that technical progress depends on acquisition of practical experience over the course of time about a given technology. This experience is driven by solution of consequential problems during the utilization of technology in practical contexts (Coccia, 2015, 2016, 2016a). In particular, learning by doing hypothesis argues that the evolution of technology is governed by a process of cumulative change, rather than by a set of replicative events at work (Coccia, 2014, 2014a, 2015, 2016a). The operationalization of this hypothesis requires a suitable measure of the experience that can be acquired, for instance, when the process takes place over time (cf., Sahal, 1981, p.112). In particular, considering the temporal aspects of technology, experience can be measured in terms of cumulated production quantities or cumulated years of production. A relationship, which investigates the learning by doing hypothesis of technological innovation, is given by:

$$\log Y_t = a + \beta_1 \log X_t + \beta_2 \log Y_{t-1}$$

Y is a measure of the efficiency of technology under study; X is given by cumulated production quantities.

- *Learning via diffusion hypothesis*

This perspective suggests that the increased adoption of a technology paves the way for improvement of its characteristics. In this context, the relevant variable in the explanation of innovation process is the cumulated utilization of technology (i.e., capital stock) rather than cumulated production volume. For instance, the successful development of a transport technology depends on how well it dovetails with the larger system of its use and main improvements in the communications network (cf., Sahal, 1981, p.117).

A relationship that analyzes the learning *via* diffusion hypothesis of technological innovation is given by:

$$\log Y_t = a + \beta_1 \log X^*_t + \beta_2 \log Y_{t-1}$$

Y is a measure of the efficiency of technology; X* is the stock of technology under study.

- *Disadvantage of beginning hypothesis*

In contrast to learning hypotheses, technical change is not always a matter of learning or accumulation of experience because in some cases technological development can suffer a disadvantage relative to newcomers, the *hypothesis of disadvantage of beginning*. The factors of this hypothesis can be resistance to change, the effect of sunk costs (costs that have been incurrent and cannot be recovered), as well as new technology cannot be conform to specification of existing plant, infrastructure and/or equipment (Frankel, 1955; Sahal, 1981, p.115). The operational form of this hypothesis can imply that the younger the age of capital stock, the better are the prospects for technical progress. To put it differently, technological innovation can be limited as capital stock grows older. The age variable (i.e., oldness) can be measured as a ratio of capital stock to gross investment. A relationship that explains this hypothesis of technological innovation in the case study of farm tractor technology, is given by:

$$\log Y_t = a + \beta_1 \log X''_t + \beta_2 \log Y_{t-1}$$

Y is a measure of efficiency of technology under study; X'' is the ratio of the number of tractors on farms to number of tractors sold.

- *Specialization via scale hypothesis*

The specialization *via scale* hypothesis is based on the observation that technology depends on the scale of its utilization because of economic reasons that are associated with factors of a physical nature of technology itself. For instance,the technological advances in electricity generation have been made possible by an increase in the scale of the electricity transmission network: the reason is that capacity increases with the square of the voltage (Meek, 1972, p.74). Of course, the advances of technology do not necessary depend on big or small size of the system scale. According to this hypothesis, variations of scale affect the course of innovative activity. In particular, this approach considersthat the relevance of scale to innovation processes is based on systemic nature of technological progress (Sahal, 1981, p.119). In this context, a basic variable is the scale of input utilization. A relationship to test this hypothesis in the case study of farm tractor is given by:

$$\log Y_t = a + \beta_1 \log X'_t + \beta_2 \log Y_{t-1}$$

Y is a measure of efficiency of technology under study; X′ is the average acreage per farm, which is a main indicator of the scale of input utilization.

- *Path-dependenceof technology hypothesis*

The approach of*path-dependence of technological innovation* was advanced by Arthur (1989, 1994). David (1985, 1993) provides evidence of the path-dependence perspective with historical studies, such as typewriter keyboard, electric light, power supply industries, etc. In particular, David (1985) shows path-dependence approach with the example of QWERTY typewriter keyboard, explaining why an inefficient structure of keyboard, according to nowadays perspective, persisted because of lock-ineffects (i.e., adopters of technology depend on a vendor for products and services, unable to use another vendor without substantial switching costs and barriers). The strength of the path-dependence model is due to a basic sequence of micro-level historical events and current choices of techniques that may influence the future pathways of technology and knowledge. However, the concept of technology lock-infor path dependence seems to workonly for network information and communication technologies characterized by increasing returns to scale. Instead, industries with constant or decreasing returns to scale, historical lock-in effect does not apply. In short, technical change in this perspectiveis path dependent in the sense that it evolves from earlier technological development.

- *Competitive substitution of technology hypothesis*

The evolution of technology is a process of actual substitution of new technology for the old one. Fisher & Pry (1971, p.75) show that technological evolution consists of substituting a new technology for the old one, such as the substitution of coal for wood, hydrocarbons for coal, etc. Fisher & Pry (1971) modeled the evolution of a new product or process (*emerging technologies)*becoming a substitute for a prior one (*mature technology*) in the form of $f / (1-f)$ as a function of time on semilog paper, fitting a straight line through resulting points (f is the market share of the emerging product or process versus time). 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".

- *Predator-Prey hypothesis*

Technologies can generate a predator-prey relationship, where one technology enhances the growth rate of the other but the second inhibits the growth rate of the first (Pistorius & Utterback, 1997, p.74). In fact, a predator-prey relationship can exist between an emerging technology and a mature technology, in particular, when emerging technology enters a niche market that is not served by mature technology. In this case, emerging technology may reduce the market share of mature technology. Farrell (1993) used a model based on Lotka-Volterra equations to examine a predator-prey relationshipbetween technologies, such as nylon *versus* rayon tire cords, telephone *versus* telegraph usage, etc. Overall, then, a predator-prey interaction has an emerging technology in the role of predator and the mature technology as prey. However, one can also visualize a situation where a mature technology is predator and emerging technology is prey (Pistorius & Utterback, 1997, p.78). Utterback *et al.*, (2019) show this type of predator-prey relationship between plywood and Oriented Strand Board technology in a specific period (OSB is a composite of oriented and layered strands, peeled from widely available smaller trees).

2.1. New multiple working hypothesesfor technology analysis

- *Hypothesis of killertechnologies*

Killer technology is a radical innovation, based on new products and/or processes, which with high technical and/or economic performance destroys the usage value of established techniques previously sold and used in markets (Coccia, 2019c). Killer technology can explain and generalize the behavior and characteristics of innovations that generate a destructive creation for technical and industrial changein markets (Coccia, 2019c). Sahal (1981, p. 79ff) describes the competition between steamship and sailing ship generates in the long run a dominance of steamships (a killer technology) as means of transportation of goods and people (cf., Rosenberg, 1976). Another main example of killer technology is the diffusion of Solvay process that in the 1900s destroys the Leblanc process in the manufacturing sector of the production of soda (Freeman, 1974). To explore the behavior of killer technologies, a simple *log-log* model shows*how killer technologies destroys* established technologies, generating technological change in markets. In particular, let a killer technology = *Kl* (a new radical technology), let a victim technology = *V* (established technology), the model is given by (Coccia, 2019c):

$$\log Kl = \log A + B \ \log V$$

B is the coefficient of growth that measures the evolution of killer technology *Kl* in relation to victim technology *V*. This model of the evolution of killer technology has linear parameters that are estimated with the Ordinary Least-Squares Method. The value of *B* in the model measures the relative growth of *Kl* in relation to the growth of *V* and it indicates different patterns of technological evolution in markets. In particular,

- *B*<1, whether new technology *Kl* destroys at a lower relative rate of change old victim technology
- *B*=1, then the killer technology *Kl* substitutes victim technology at a proportional rate of change
- *B*>1, whether killer technology *Kl* destroys victim technology at greater relative rate of change

- *Hypothesis of technological parasitism*

Utterback *et al.*, (2019) suggest to abandon the idea that technology and innovation originate only in pure competition between new and established artifacts. These scholars argue that the growth of one technology will often stimulate the growth of othertechnologies, calling this interaction as *symbiotic competition* (Utterback *et al.*, 2019). In this context, Coccia (2019, 2019a, 2019b; Coccia & Watts, 2020) proposes a new theory to explain the evolution of technology in society considering aparasite-host relationship between technologies that generatesthe coevolution of overall complex system of technology: *technological parasitism*. The theoretical background of this theory is a "Generalized Darwinism" (Hodgson & Knudsen, 2006) for framing a broad analogy between evolution of technology and evolutionary ecology of parasites that provides a logical structure of scientific inquiry (cf., Coccia, 2019; Coccia & Watts, 2020). In particular, Coccia (2019, 2018) argues that technologies have a behavior similar to parasites because technologies cannot survive and develop as independent systems *per se*, but they can function and evolve in markets if and only if they are associated with other technologies, such as audio headphones, wireless speakers, software apps, etc. that function *if and only if*they are associated with host or master electronic devices, such as smartphone, radio receiver, television, etc.In fact, a parasitic technology Pin a host or master technology$H$ is atechnologythat during its life cycle is able to interact and adapt into the complex system of H, generating coevolutionary processes to satisfy human needs and/or solve problems in society. A technology Pcan be a parasite of different host *or* master technologies, as well as a technology Hcan be a host or master of different parasitic technologies(e.g., mobile devices are host of software applications, headphones, Bluetooth technology,etc.; *cf.*, Coccia, 2018). In general, many technologies*de facto* depend, as parasites, on other (hosts *or* masters) technologies to form a complex system of parts that interact in a non-simple way. This behavior of technologies can be generalized with the *theorem of not independence of any technology*by Coccia (2018): the long-run behavior and evolution of any technological innovation Ti is not independent from the behavior and evolution of the other technological innovations Tj, $\forall i = 1, \ldots, n$ and $j = 1, \ldots, m$

Hence, many technologies can be considered specifically as *parasitictechnologies* because they have the characteristics of obliged parasites, as they depend on a host *or* master for most of their technological functions and developmental processes. Some parasitic technologies are able to function only within specific hosts (e.g., diesel fuel as parasitic technology can be used only in compression-ignition engines as host technologies), while others are able to function on many host technologies (e.g., electrical energy as parasitic technology can be used for many appliances of different scale).

This theory of technological parasitism by Coccia (2019) also proposes a model to explain the relationship between a host *or* master technology (*H*system) and a parasitictechnology (*P*subsystem).

The logarithmic form of the model (Coccia, 2019) is a simple linear relationship:

$$\log P = \log a + B \ \log H + u_t$$

For instance, variables in the case study of farm tractor technology are:

- *P*= evolutionary advances of parasitic technology, e.g., fuel-consumption efficiency in horsepower-hours indicates the technological advances of engine for farm tractor
- log*a*=constant
- *H*=evolutionary advances of host *or* master technology, e.g., total mechanical efficiencyofoverall farm tractor
- u_t = error term

B is the evolutionary coefficient of growth that measures the evolution of parasitic technology *P* in relation to host *or* master technology *H*. This theory of technological parasitism suggeststheoretical and empirical predictionsfor the evolution of technology (Coccia, 2019, 2019a, 2019b):

1. The long-run behavior and evolution of any technology depend on behavior and evolution of inter-related technologies; in particular, the long-run behavior and evolution of any technology are driven by interactions with other technologies (Coccia, 2019, 2019a, 2019b).
2. The long-run evolution of an established technology is due to interaction with *new*parasitic or host technologies.
3. Technological host *or* master with many parasitic technologies generates a rapid stepwise evolution of technological host-parasite system. Technological systems with fewer parasitic technologies and a low level of interaction with other technologies improve slowly (Coccia & Watts, 2020).
4. *Property of mutual benefaction between interactive technologies*by Coccia (2018) argues that the interaction between technologies reduces negative effects and favors positive effects directed to an evolution of reciprocal adaptations of technologies in complex systems of technology over time and space.

3. Conclusion

Determinants of technology and technological evolution are due to manifold factors, such as R&D investments, appropriate social structures with consolidated democracy, good economic governance, widespread higher education system, skilled human capital,moderate growth rates of population, purposeful socioeconomic systems with high economic-war potential, etc. (Coccia, 2010, 2014, 2015). These different factors play a vital role for technology analysis. Hence, technology as a complex concept in science, affected by manifold endogenous and exogenous factors, needs a method of inquiry based on multi working hypotheses for a comprehensive technology analysis, rather than apply a single hypothesis in isolation.In fact, Wright (1997, p.1562) properly claims that: “In the world of technological change, bounded rationality is the rule.”

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