Mario Coccia

New patterns of technological evolution

Theory and practice

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ISBN: 978-605-7602-88-6 (e-Book)
KSP Books 2019

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Preface

In 2009, Brian Arthur claimed that one of the most important problems to understand regarding technology is to explain how it evolves (p.15ff). In fact, the evolution of technology plays an important role in the economic and social change of human societies (Basalla, 1988; Coccia, 2018, 2019; Hosler, 1994; Sahal, 1981). Technological evolution as a main process of technical change has been compared to biological evolution by many scholars (Arthur, 2009; Basalla, 1988; Coccia, 2018, 2019; Solé *et al.,* 2013; Wagner, 2011). The similarities between biological and technological evolution have generated a considerable literature (Coccia, 2018, 2019). Wagner & Rosen (2014) argued that biological thinking has reduced the distance between life sciences and social sciences (cf., Solé *et al.,* 2013). Basalla (1988) suggested that the history of technology can profitably be seen as analogous to biological evolution. Technological evolution, alongside biological evolution, displays radiations, stasis, extinctions, and novelty (Valverde *et al.,* 2007). In general, patterns of technological innovation emerge and evolve with technological paradigms and trajectories in specific economic, institutional and social environments (Dosi, 1988). Hosler (1994, p.3, original italics) argues that the development of technology is, at least to some extent, influenced by "technical *choices*", which express social and political factors, and "technical *requirements*", imposed by material properties. Arthur & Polak (2006, p.23) claim that: "Technology … evolves by constructing new devices and methods from ones that previously exist, and in turn offering these as possible components—building blocks—for the construction of further new devices and elements". In particular, Arthur (2009, pp.18-19) argues 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 or modules to some human purpose and has a hierarchical and recursive structure. Other scholars suggest that technological evolution is driven by solving consequential problems during the engineering process (Coccia, 2017; cf., Dosi, 1988) and by supporting leadership of distinct purposeful organizations —for instance firms— to achieve the prospect of a (temporary) profit monopoly and/or competitive advantage (Coccia, 2017a).

In this context, the main goal of this book is to explain some characteristics of the evolution of technology in society. In particular, this book focuses on new studies that can clarify how new technology evolve, how to measure new directions of technological trajectories, how to classify the evolution of technology, which are the main sources of the evolution of innovation in socioeconomic systems to suggest general properties that can explain technical change in industrial completion.

This book is designed for students, undergraduate, graduate or managers in business and public administration that wish to understand critical aspects of the evolution of technology and that wish to expand their knowledge on these research fields.

I have attempted to apply simple theories and approaches for explaining theoretical and empirical patterns of technological evolution in socioeconomic systems. Moreover, the studies here are integrated with examples and actual applications in economic and social settings that can help policymakers and manager to design best practices for achieving and sustaining competitive advantage. In order to attain a reasonable depth, this book concentrates on selected topics of particular relevance to the evolution of technology, and which meet the needs of the intended audience.

The book is divided in six interrelated chapters.

- First of all, the chapter 1 of the book explains the concept and characteristics of revolution and evolution to underpin the theoretical frameworks, techniques and sources of the evolution of technologies explained later.
- The chapter 2 of this book proposes a general theorem that explains how technology evolve over time and space, suggesting main theoretical predictions.
- The chapter 3 contains a technometrics to measure and assess technological evolution, as well as to classify technological pathways considering the interaction between technologies.
- Chapter 4 of the book concentrates on development of product innovation, suggesting a hedonic price method to analyze critical technical characteristics and technological trajectories that support the evolution of smartphone technology, a critical radical innovation in society.
- Chapter 5 of the book focuses on sources of technological evolution, explain the vital role of disruptive firms that introduce radical innovation and perform technical that generate, industrial, economic and social change.
- The final chapter 6 of the book explains how superpowers (nations with a high economic-war potential) achieve/sustain global leadership to take advantage of important opportunities, generating at the same time new technology for a technological change that supports in the long run economic growth and social change worldwide.

However, no single book could hope to cover adequately all aspects of what is wide and essentially multi-disciplinary field of inquiry, and it is not the intention to attempt to cover all aspects and topics of the evolution of technology and technological change. It is regrettable but inevitable therefore that some topics are excluded or given only limited coverage and it is not possible to meet fully the preferences of all readers. I hope that readers dealing with technological evolution, such as students and managers, policymakers, etc. are able to see this text as a starting point to understand the complex processes and characteristics of the evolution of technology and technological change in society.

This book's strengths and weaknesses are the responsibility of author.

M. Coccia
June 20, 2019

Further details of the topics covered in this book can be found in the following suggested readings.

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Contents

1 Definition and characteristics of the concepts of evolution and revolution

Introduction of the concept of revolution

Revolution is one of the most important events in the history of human society (Amman, 1962; Pettee, 1938). Revolutioncan be defined as: “change, effected by the use of violence, in government, and/or regime, and/or society. By society is meant the consciousness and the mechanics of communal solidarity, which may be tribal, peasant, kinship, national, and so on; by regime is meant the constitutional structure-democracy, oligarchy, monarchy; and by government is meant specific political and administrative institutions” (Stone, 1966, p.159). This definition allows to distinguish between the seizure of power that leads to a major restructuring of government or society and the replacement of the former elite by a new one, and the coup d’état involving no more than a change of ruling personnel by violence or threat of violence. In the 1960s, social scientists at Princeton University have changed the word "revolution" with the concept of "internal war": any attempt to alter state policy, rulers, or institutions by the use of violence in society, where violent competition is not the norm and where well-defined institutional patterns exist (Paret, 1961, cf., Rosenau, 1964). In philosophy, Hegel suggests that revolution is equated with irresistible change represented by a manifestation of the world spirit in an unceasing quest for its own fulfillment (Benhabib & Marcuse, 1987). Marx

(1976, 1978, 1981) argues that revolution is a struggle between the bourgeoisie and the proletariat. Arendt (1958, 1963) interprets the revolutionary experience as a kind of restoration, whereby insurgents attempt to restore liberties and privileges, which were lost as the result of government's temporary lapse into despotism. Instead, de Tocqueville (1955, p.8) has defined revolution as an overthrow of the legally constituted elite, which initiated a period of intense social, political, and economic change.

The main characteristics of revolution according to Deutsch (1964, pp.102-104) are:

a) degree of mass participation
b) duration
c) number of persons killed both during and after the revolution (a measure of intensity)
d) intentions of the insurgents

A prime factor of revolution is the emergence of an obsessive revolutionary mentality. In the behaviorist approach, the causes of alienation of revolutionaries and of the weakness of incumbent elite are economic factors. Parsons (1951) treats disaffection or "alienation" as a generalized phenomenon that may manifest itself in crime, alcoholism, drug addiction, daytime fantasies, religious enthusiasm, or serious political agitation (cf., Coccia, 2014, 2014d). Marx (1976, 1978, 1981) states that popular revolution is a product of increasing misery, whereas de Tocqueville (1955) claims that revolution is a product of increasing prosperity. Olson (1963) and Lewis (1963) argue that revolutionaries are the product of rapid economic growth, which creates both *nouveaux riches* and *nouveaux pauvres* The initial growth phase may cause a decline in the standard of living of the majority of people because of enormous forced savings for reinvestment. Revolution can increase the gap between expectations (social and political for the new rich, economic for the new poor) and the realities of everyday life (cf., Gottschalk, 1944). In short, revolution creates new expectations by economic improvement, followed by economic recession and governmental reaction, which widen the gap between expectations and reality (Davies, 1962).

Davies (1962) argues that the fundamental impetus toward a revolutionary situation is generated by rapid economic growth associated with a rising of the standard of living and a long-term phase of growth followed by a short-term phase of economic stagnation. In this context, Coccia (2018) seems to reveal a sequential historical process that runs from wars between great powers occurring in phases of instability of long waves (peak and/or trough) to clusters of innovation (in the trough of long waves), which trigger the upward phase of new long waves[1].

Revolution can generate a variety of typologies in different societies. Brinton (1938, pp.3-4) suggests a differentiation between coup d'état that is a simple replacement of one elite by another, and major revolutions that are associated with social, political, and economic change. Huntington (1962, pp.23-24) presents a further refinement in the classification of revolution using four categories: the internal war, the revolutionary coup, the reform coup, and the palace revolution.

Finally, Chalmers (1964) categorizes revolution in six typologies as follows:

1. the Jacquerie is a spontaneous mass peasant rising.
2. the Millenarian Rebellion is similar to the first but with the added feature of a utopian dream, inspired by a living messiah.
3. the Anarchistic Rebellion is the nostalgic reaction to progressive change.
4. the Jacobin Communist Revolution is: "a sweeping fundamental change in political organization, social structure, economic property control and the predominant myth of a social order, thus indicating a major break in the continuity of development" (Sigmund Neumann as quoted in Chalmers, 1964).
5. the Conspiratorial coup d'état is the planned work of a tiny elite fired by an oligarchic ideology.
6. the Militarized Mass Insurrection is a phenomenon of the twentieth century based on a deliberately planned mass revolutionary war guided bydedicated elite.

Coccia (2018c, 2018d) argues that terrorism (a distinct form of political violence with some characteristics similar to revolution) thrives in specific regions with high growth rates of population that may generate income inequality and relative deprivation of

[1]cf., Coccia, 2005a, 2015b, 2016, 2017b, 2018e, 2018f

people. Overall, then, revolutions are a systematic processdue to manifold economic, social, psychological, anthropological, and perhaps biological factors. Of course, these factors can change over time and space in society.

The concept of evolution

The concept 'evolution' is associated with a specific directional activity. Theword 'evolution' was first applied to natural phenomena by the German biologist Albrecht von Haller in 1744 (cf., Richards, 1992). Darwin (1859) preferred phrases like 'descent with modification'and only once wrote 'evolved'. Spencer (1957) did much more than Darwin (1859, 1871) to popularize the term 'evolution' that can be associated with different types of phenomena, including all feasible manifestations of development and change (Hodgson & Knudsen, 2006). In general, under some conditions, evolution must involve Darwin's principles of variation, inheritance and selection (Hodgson & Knudsen, 2006). Bagehot (1872), Ritchie (1896) and Veblen (1899) argued that the principle of selection could explain survival and evolution not only of individuals, but also of groups, customs, nations, business firms and social institutions. The principle of selection provides the means for explaining adaptedness, survival and evolution in society. In the evolution of complex systems, some scholars point out self-organization or spontaneous order as an alternative concept to Darwinian selection (Ashby, 1947; Von Foerster, 1960). Others scientists consider social evolution as a Lamarckism process rather than Darwinian one. In fact, the Lamarckian inheritance of acquired characters may occur in social evolution. These mechanisms of change supporting evolution are often very different, within and between systems in nature and society (Hodgson & Knudsen, 2006). Socioeconomic evolution is due to successful rules, habits or behavior spread by imitation and learning. Socioeconomic evolution is also based on characteristics acquired or learned by individuals that are more adapted to their environment.

Individuals and human society sometimes give up resources to benefit their neighbors, to the extent that this helping lowers the entity's reproductive fitness (Wenseleers *et al.*, 2010; Wenseleers, 2006). These altruistic traits pose a difficulty for Darwin's theory of natural selection, which emphasizes the spread of individually advantageous traits (Darwin 1859; Pennisi, 2005). This altruism, generating cooperation between potentially competing individuals, and as a consequence co-evolution, abounds in natural and social systems (Gintis *et al.,* 2005). Szathmáry (2011) argues thatthe benefits of cooperation can drive the social evolutionbecause it must pay off, even if it is immediately costly to cooperators (cf., Bourke, 2011; Queller, 1997; Maynard, Smith & Szathmáry, 1995).

The concept of evolution in society isassociated with the idea of human progress. Spencer (1902, p.253) suggests that social evolution is: "the full happiness of each, and therefore to the greatest happiness of all". In particular, the idea of evolution in society is based on: "progressive satisfaction of human wants in all their ramifications and complexities. It is this inner kernel of human satisfactions which gives character to the whole account of social evolution; which is interpreted, not in terms of mechanism, … but of purpose" (Woods, 1907, p.816). The fundamental elements of social evolution are health, wealth, sociability, knowledge, beauty, etc. (cf., Small, 1905, p.682). These elements support the acquisition by humanity of better and more complex forms of life. Social evolutionis associated with new technologies that yield greater satisfaction of human wants (cf., Coccia, 2010, 2014, 2015). Moreover, evolution is achieved in appropriate structures with strong democracy, good governance, higher education,and higher innovative outputs (Coccia, 2010, 2014, 2018). In fact, Woods (1907, p.817) points out that: "Progress in an individual or in a community is thus a function of all the various qualities and aspects of life which are there realized. Not physical well-being alone, nor the abundance of wealth, nor even the moral advance which has been attained, may serve as the measure of progress; all of the interests are required because all are phases of normal human life." Hence, the determinants of socioeconomic evolution and, as a consequence, ofhuman progress are human wants and human control of nature through science advances and new technology (cf., Woods, 1907)[2].

Finally, evolution can be categorized in two types:

- *growth* is a proportionate change in a system
- *development* denotes a disproportionate change in the size of a sub-system as a consequence of change in the overall size of a system (economic, biologic, social, etc.).

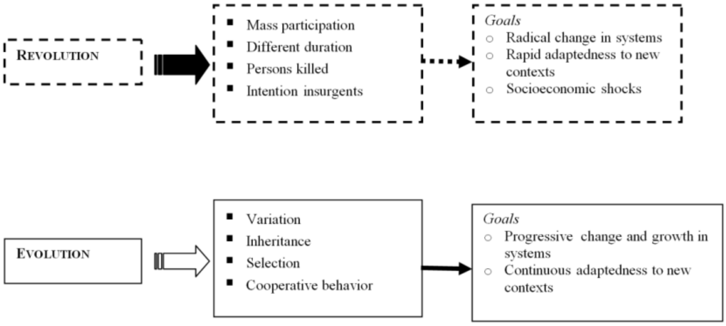

Figure 1. *General characteristics and goals of revolutions and evolutions*

Conclusion

Krader (1976, pp.109-110) argues that: "The concept of advancing society through the combined agencies of evolution and revolution was at one time related in a single overarching theory. The opposition of evolution and revolution, on the contrary, stands to us not as a dialectical relation whose contradictions are to be resolved, but as an unresolved tension…. The theory underlying social evolution is doubly linked to biology". Overall, then, evolution and revolution are a cyclical process in human society affected by manifold factors that can change over time and space (Figure 1). A comprehensive analysis of these phenomena in nature and society, affected by economic, social, psychological, anthropological, and biological factors of the entities under study,

[2] Cf. also studies by Coccia, 2005, 2009, 2010, 2010a, 2010b, 2010c, 2011, 2012, 2014, 2014a, 2014b, 2014c, 2014d, 2015, 2015a, 2017, 2017a, 2018, 2018a, 2018b, Coccia & Benati, 2018; Coccia & Bellitto, 2018; Coccia & Cadario, 2014; Coccia & Rolfo, 2010; Coccia *et al.*, 2015.

is a non-trivial exercise. To conclude, revolutions and evolutions are a result of human activity in society to satisfy specific needs to cope with and/or adapt in the presence of environmental threats and changing contexts.

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2 How technologies evolve: General theorem of not independence of any technology

Introduction

In analogy with some concepts from systems science (Ackoff, 1971, p. 661ff; *cf.*, Churchman & Ackoff, 1950; Oppenheimer, 1958; Rosenblueth *et al.*, 1943), suppose that: Technological innovation[i] is defined an entity (system) that is composed of at least two components and a relation that holds between each of its components and at least one other element in the set. Each of a technological innovation's components is connected to every other component, directly or indirectly. No subset of components in a technology is unrelated to any other subset.

Remark: a component of technology is an element of its system that can be abstract or concrete. Abstract components of technology are concepts, such as in computer programming, a string. Concrete (tangible) components of technology are objects, such as electronic and/or mechanical parts of artifacts (cf., Ackoff, 1971).

In this context, the technology has fundamental interactions between components (sub-systems) and other associated systems (technological innovations) in a complex system; these fundamental interactions are reciprocal movement of information/resources/energy and other physical phenomena directed to satisfy needs, achieve goals and/or solve problems of human society. The fundamental interaction in technological domains is strong between intra-component linkages (sub-systems) and weak between inter-component linkages of one or more technological innovations (Simon, 1962). The environment of a technological innovation is a set of elements and factors that can affect its state. The state of a technological innovation "at a moment of time is the set of relevant properties which that system has at that time" (Ackoff, 1971). For instance, environments of technology are the markets (competition, oligopoly, monopolistic competition, contestable, etc.) that can drive technological advances with a reciprocal influence between innovations in order to achieve and/or support goals and competitive advantage of subjects (competition-driven innovation).

Some characteristics of technological innovations are:

1. A technological innovation can be a state-maintaining system: "is one that (1) can react in only one way to any one external or internal event but (2) it reacts differently to different external or internal events, and (3) these different reactions produce the same external or internal state (outcome). Such a system …must be able to *discriminate* between different internal or external states to changes in which it reacts". These technological innovations: "are not capable of learning because they cannot choose their behavior. They cannot improve with experience." (e.g., compass; Ackoff, 1971, p.665, original italics).
2. A goal-seeking technological innovation is a system:"that can respond differently to one or more different external or internal events in one or more different external or internal states and that can respond differently to a particular event in an unchanging environment until it produces a particular state (outcome)…Thus such a system has a *choice* of behavior… Under constant conditions a goal-seeking system may be able to accomplish the same thing in different ways and it may be able to do so under different conditions. If it has memory, it can increase its efficiency over time in producing the outcome that is its goal ...for example, an electronic maze-solving rat.... Systems with automatic 'pilots' are goal-seeking." (Ackoff, 1971, pp.665-666, original emphasis).
3. A multi-goal-seeking technological innovation isa system: "that is goal-seeking in each of two or more different (initial) external

or internal states, and which seeks different goals in at least two different states, the goal being determined by the initial state" (Ackoff, 1971, pp.666).

4. A purposive technological innovation: "is a multi-goal-seeking system the different goals of which have a common property. These types of system can pursue different goals but they do not select the goal to be pursued.... A computer which is programmed to play more than one game ...is multi-goal-seeking. What game it plays is not a matter of its choice, however; it is usually determined by an instruction from an external source. Such a system is also purposive because 'game winning' is a common property of the different goals which it seeks" (Ackoff, 1971, pp.666). In short, by combining two or more goal-seeking components, it is possible to construct a multi-goal-seeking (and hence a purposive) system.

5. A purposeful system, instead, is: "one which can produce the same outcome in different ways in the same (internal or external) state and can produce different outcomes in the same and different states. Thus a purposeful system is one which can change its goals under constant conditions; it selects ends as well as means and thus displays *will*. Human beings are the most familiar examples of such systems …The goal of a purposeful system in a particular situation is a preferred outcome that can be obtained within a specified time period. The objective of a purposeful system in a particular situation is a preferred outcome that... can be obtained over a longer time period." (Ackoff, 1971, pp.666-667, original italics).

6. A technological innovation can be state-maintaining, goal-seeking, multi-goal-seeking, or purposive; but not a purposeful system.

Theorem of *Not* independence of *Any* technological innovation

In the long run, the behavior and evolution of *any* technological innovation φ_i is *not* independent from the behavior and evolution of the other technological innovations $\lambda_j \forall i = 1, \dots, n \text{ and } j = 1, \dots, m$

Proof

Assume the statement of the theorem above (called P) to be false.

Suppose that $\neg P$ (the negation of the theorem) is true: ∃ a technological innovation φ_i such that (s.t.) φ_i is independent from the other technological innovations λ_j

⇒∃a technological innovation φ_i s.t. it is a purposeful system that can change its goals, select ends as well as means and displays will.

However, *any* technological innovation cannot be a purposeful system per definition.

The statement $\neg P$ implies a contradictory assertion (an *argumentum ad absurdum*: reduction to absurdity).

Therefore, ∴ the statement P (theorem) is true (QED).

Corollary

- ∄*any* technological innovation φ_I that has a long-run behavior and evolution independent from the other technological innovations λ_j.
- The theoretical implications of this theorem are fundamental interactions between systems of technologies that generate dependence and interdependence between two or more associated technologies in human society.

Theoretical and practical implications of the theorem

The concept system, applied here, plays a critical role in science and technology (Ackoff, 1971). The systems approach focuses on systems taken as a whole, not on their parts taken separately and is an appropriate theoretical framework to analyze the patterns and evolution of technological innovation. The theoretical implication of this theorem is that:

1. in the long run, the behavior and evolution of any one of the technological innovations interact and depend on the behavior and evolution of the other technological innovations;
2. in the short-run, the behavior and evolution of technological innovations may be approximately independent of the short-run behavior and evolution of the other technological innovations (cf., Simon, 1962).

The theorem here can explain and generalize, whenever possible the existence of fundamental interactions, between *any* technological innovations and at least one other technological innovations in complex and inter-related systems. The not independence of any technology is an important property of the evolution of technology inhuman societies.

Overall, then, this theory here suggests that in the long run, *any* technological innovation does not function as independent system *per se*, but technological innovations depend on the other technological innovations to form elements of complex systems that interact and coevolve in a non-simple way. Technology has an intrinsic nature to progress with fundamental interactions with the other technological innovations and human societies (human-technology interactions) to satisfy needs, achieve goals and/or solve problems. Future technological and scientific progress may generate, with the artificial intelligence (AI), new technology similar to purposeful systems, but the similarity will not be an identity and a completely independence of AI technology is hard to be conceived.

To conclude, the proposed theorem here may form a groundwork for development of more sophisticated theoretical framework sto explain the evolution of technology in the long run. However, we know that other things are often not equal over time and space in the domain of technology. There is need for much more detailed research to shed further theoretical and empirical light on patterns of technological innovation to explain evolution of technology, technological and economic change in human society.

Notes

[i] For studies about technological innovation see Coccia, 2001, 2003, 2004, 2005, 2005a, 2005b, 2005c, 2006, 2006a, 2007, 2008, 2008a, 2008b, 2009, 2009a, 2010, 2010a, 2010b, 2010c, 2010d, 2010e, 2011, 2012, 2012a, 2012b, 2012c, 2012d, 2013, 2013a, 2014, 2014a, 2014b, 2014c, 2014d, 2014e, 2014f, 2014g, 2015, 2015a, 2015b, 2015c, 2015d, 2016, 2016a, 2016b, 2016c, 2017, 2017a, 2017b, 2017c, 2017d, 2018, Coccia & Bozeman, 2016; Coccia & Finardi, 2012, 2013; Coccia & Wang, 2015, 2016.

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3 Measurement and taxonomy of the evolution of technology

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)[ii]. 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 endeavourof 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 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 modelledin simple way in terms of morphological changes between a host technology and its technological subsystems. Thecoefficient 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 oftechnology. 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.

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 numeral [iii] 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*).

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_j is given by:

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

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:

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

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).

RAND[iv] 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:

Planar *Ellipsoidal*

$$\sum_{i=1}^{n}\left(\frac{x_i}{a_i}\right)=1 \qquad \sum_{i=1}^{n}\left(\frac{x_i}{a_i}\right)^2=1$$

Where x_i is the *i*-th technological characteristic and $a_i$is the *i*-thparameter (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).

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 detectits 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 descriptionby comparing the structure of new systems with that of earlier computers (cf., Coccia, 2005a, pp.955-957).

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).

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 generatea series of effectson 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).

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.

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 technologywith 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).

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 acomplex systemof 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 studyhere 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 technologiesin 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.”

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).

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 atechnology*H* that is a master or host systemthat interacts with *P*, at the same time (cf., Sahal, 1981, pp.79-89). Suppose that both *P* and *H*e volve 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:

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

We can rewrite the equation as:

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

The integral of this equation is:

$$\log H - \log\left(K_1 - H\right) = A \;\; + b_1 t$$

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

$$H = \frac{K_1}{1 + \exp\left(a_1 - b_1 t\right)}$$

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

The growth of *H* can be described respectively as:

$$\log\frac{K_1 - H}{H} = a_1 - b_1 t \qquad (1)$$

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

$$\log\frac{K_2 - P}{P} = a_2 - b_2 t \qquad (2)$$

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.

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:

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

$C_1=exp[b_1(t_2-t_1)]$ (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:

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

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

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

$$LnP = LnA_1 + B_1 LnH \quad (5)$$

B_1 is the evolutionary coefficient of growththat 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 andindicates 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 hosttechnology 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., acoevolution 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, 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*

Grade of evolution	*Coefficient of evolutionary growth*	*Type of the evolution of technology*	*Associated Evolutionary stages of the evolution of technology*	*Predictions*
1 Low	B<1	Slowed	Underdevelopment	Technologyevolves slowly over the course of time
2 Average	B=1	Proportional	Growth	Technologyhas a steady-state path of evolution
3 High	B>1	Accelerated	Development	Technologyis 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 evolvesslowly (underdevelopment).

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

Materials and method

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.

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 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].

Model and data analysis procedure

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

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

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.

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

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

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

Table 3 shows theevolutionary 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) anda 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, …, 1968)

	Constant α *(St. Err.)*	*Evolutionary coefficient* β=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).

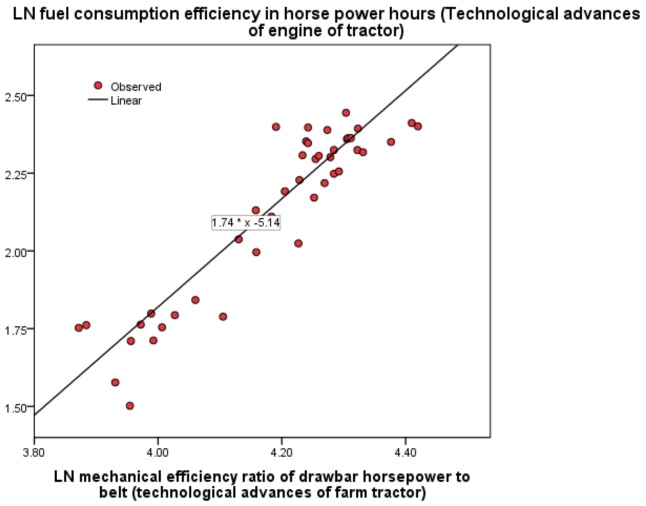

Figure 1. *Trend and estimated relationship of the evolution of farm tractor technology*

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, itis 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.

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*

Dependent variable: LN Tractive efforts in pound of locomotive (technological advances), t = (1904–1932)

	Constant α *(St. Err.)*	*Evolutionary coefficient* β=B *(St. Err.)*	R^2 *adj. (St. Err. of the Estimate)*	*F (sign.)*
Farm tractor	–13.87*** (1.48)	1.89*** (0.12)	0.91 (0.07)	270.15 (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, …, 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 leverhave 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.154*ff*). 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.

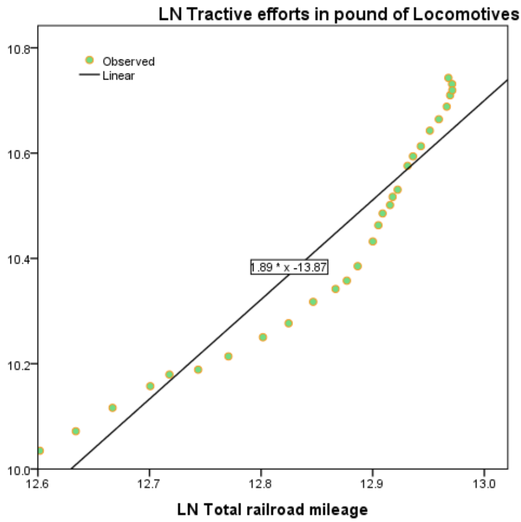

Figure 2. *Trend and estimated relationship of the evolution of freight locomotive technology*

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 alsoFigure 3).

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

Dependent variable: LN Average fuel consumption efficiency in kwh per pound of coal (technological advances of turbine and various equipment)				
	Constant α *(St. Err.)*	*Evolutionary Coefficient* β*=B (St. Err.)*	R^2 *adj. (St. Err. of the Estimate)*	*F (sign.)*
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, …, 1970

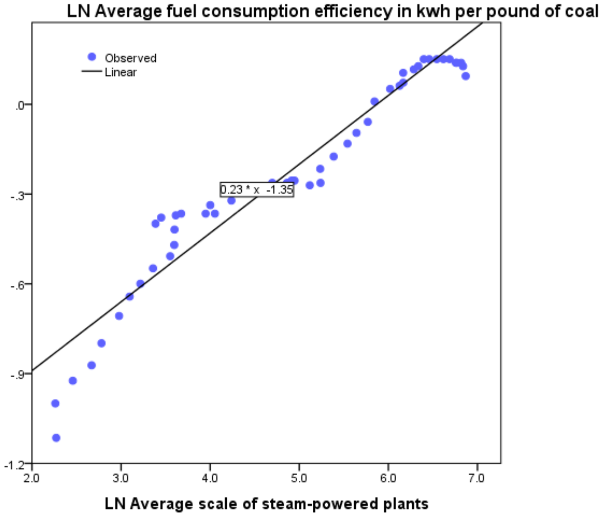

Figure 3. *Trend and estimated relationship of the evolution of steam-powered electricity-generating technology (1920-1970)*

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 evolutionin 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 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)*

Dependent variable: LN Average fuel consumption efficiency in kwh per cubic feet of gas (technological advances of turbine and various equipment)				
	Constant α *(St. Err.)*	*Evolutionary coefficient* β=B *(St. Err.)*	R^2 *adj. (St. Err. of the Estimate)*	*F (sign.)*
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, …, 1970

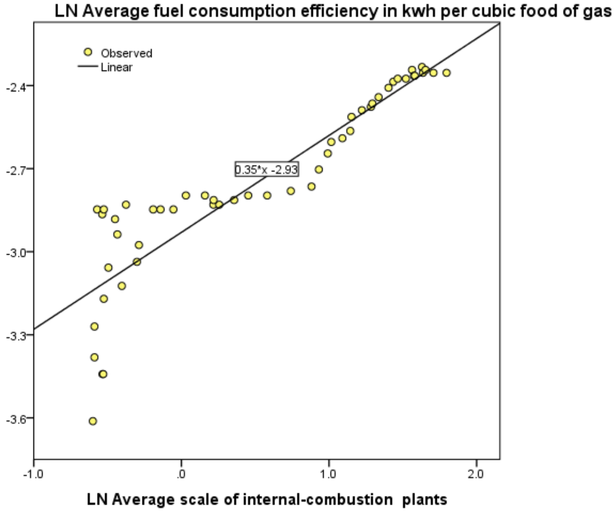

Figure 4. *Trend and estimated relationship of the evolution of internal-combustion type electric power technology (1920-1970)*

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 modelof morphological change thatassessesand predicts the technological development driven by interaction between a host technology and its parasitic-subsystems of technologyover 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 evolution has been studied in-depth and provides a logical structure of scientific inquiry in research fields concerning technology.

The study here suggestsa 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. Thedynamics of the evolution of technology here is based on a S-shaped growth curve of technological advances both forthe whole system of technology and for its interrelated subsystem components. The approach here is formalized with a simple model that contains only two parametersand 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 infour example technologies, provides consistent patterns of the evolution of technologiessupported 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.

Thequantification 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 locomotivetechnologies 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 underdevelopmentof 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 itsinteracting 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 the utilization of a technology andthe 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 forsupporting development of new technology, and as a consequence, industrial and economic change in human society. Proposed theory here hasalso a number of implications for the analysis of nature, sources and evolution of technology. One of the most important implications is theinteraction between technologyand its subsystem components in complex systems that drivethe 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 fieldrequire a substantial amount of data of technological parameters to provide additionalempirical evidence of the different pathways of technological evolutionover 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 comprehensivetechnometrics 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.”

Acknowledgement

I gratefully acknowledge financial support from National Endowment for the Humanities and National Research Council of Italy–Direzione Generale Relazioni Internazionali (Research Grant n. 0072373-2014 and n. 0003005-2016) for my visiting at Arizona State University where this research started in 2014. I thank the Library of Arizona State University for scientific material provided on these topics. I am grateful to Trang T. Thai (Intel Corporation) and participants at seminars held in the USA and Italy for fruitful suggestions and comments concerning these scientific topics.

Notes

[ii]Cf. 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; Oswalt, 1976; Rosenberg, 1969; Schubert, 2014; Schuster, 2016; Valverde, 2016; Valverde *et al.*, 2007; Watanabe *et al.*, 2012.

[iii] 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.

[iv] 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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4 Development of product innovation: a case study

Introduction

In the research field of technical change and technological forecasting, the analysis of technological advances is a central and enduring research theme to explain the evolution of technology and technological progress in society (Coccia, 2005, 2005a; Saviotti, 1985)[v]. In particular, the technology analysis of nature and evolution of innovation is important research field for predicting evolutionary pathways and critical characteristics of new technologies (cf., Arthur, 2009; Arthur & Polak, 2006; Hall & Jaffe, 2018; Linstone, 2004; Coccia, 2017). Scholars in these research topics endeavor of measuring technological advances, the level of technological development and changes in technology with different approaches directed to technological forecasting of emerging trajectories (Coccia, 2005; Daim *et al.*, 2018; Faust, 1990; Farrell, 1993; Sahal, 1981; Tran & Daim, 2008; Wang *et al.*, 2016). However, studies about methods for detecting the technical characteristics supporting the evolution of specific technologies are rather elusive. In this context, the study of technological advances in smartphone technology plays a vital role to explain general properties of the evolution of technology because this device is one of the most important Information and Communication Technologies (ICTs) used by people in society (Lee & Lim, 2014; Coccia, 2017a; cf., Teece *et al.*, 1997). The goal of this study is to suggest a method for technology analysis to detect and forecast the most important technical characteristics that support greater functionality development of smartphone technology in markets. Especially, the evolution of smartphone technology is modeled here in simple way with a linear function of hedonic pricing to detect technical characteristics of these ICTs that matter most. This approach can be generalized to analyze and explain evolutionary pathways of new technology in society. In addition, results can support best practices of management of technology for guiding funding for R&D and forecasting critical technologies and/or technical characteristics of products that are likeliest to evolve rapidly in society. Before presenting the method and results of this study, next section introduces the theoretical framework.

Theoretical framework

A smartphone or pocket-sized computer for voice, message and data communication is among the most important ICTs used by people worldwide in current society (Woods, 2018). The diffusion of mobile phones and smartphones, measured with subscribers, has growth rates higher than fixed phone (Watanabe *et al.*, 2012). Lee & Lim (2014, pp.808-809) argue that the main characteristics of mobile phones are: the mass in grams, physical dimensions in terms of length, width and thickness in mm, the measured dominant frequency of vibration in Hz, the peak acceleration measured in m/s^2 and peak inertia force measured in kg m/s^2, etc.

The evolution of smartphone technology is associated with stepwise functionality development ("the ability to dramatically improve performance of production processes, goods and services by means of innovation", Watanabe *et al.*, 2009, p.738). Watanabe *et al.* (2009, p.738) also argue that: "functionality development stimulates customer's demand leading to rapid increase in number of subscribers. This increase leads to dramatic decline in handsets prices as a result of both effects of learning and economies of scale. Balance between prices increase by functionality development and their decrease by effects of learning and economies of scale has been the driving force behind the growth in mobile phones" (cf., Lacohée *et al.*, 2003). In economics of innovation and industrial organization, scholars have investigated specific technologies, such as digital camera considering a relation between sales and characteristics of all camera models (Carranza, 2010). In particular, Carranza (2010, p. 605) argues that the functionality development of the quality of cameras is due to increasing resolution from around 0.5 in 1998 to more than 1.5 megapixels in 2001, whereas the average optical zoom of sold cameras has decreased slightly during the same period of time. This technological trade-off is explained as follows: increased resolution, which facilitates the use of a digital zoom, is a good and cheaper substitute for the optical zoom, especially among lower-quality cameras. In this context, Watanabe *et al.*, (2012) argue that learning effects in ICTs can be the sources of its self-propagating development of technology, acquiring new functionality from digital industry.

Stimulated by these studies, a fundamental problem in economics of innovation is which technological characteristics matter most in evolutionary pathways of new technology to predict fruitful technological trajectories (Coccia, 2005, 2005a, 2017). The literature of appropriate methods to explain this technological problem is rather scarce. The study confronts this question here by developing a theoretical framework based on technology as a complex systems and a hedonic pricing method, which endeavor to analyze smartphone technology to detect the most important technical characteristics driving evolutionary pathways over time.

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., Gherardi & Rotondo, 2016). Technology here 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. Sahal (1981) points out that systems innovations are due to integration of two or more symbiotic technologies.

The analysis of technological advances has been performed with different approaches in engineering, scientometrics, technometrics, economics of innovation and related disciplines (Coccia, 2005, 2005a, p.948ff). One of these methods is the hedonic approach applied to technology analysis. Hedonic methods consider both economic and technical information (Saviotti, 1985). In economics, this approach is motivated by economic goals (e.g., sources of the competitive advantage of firms), whereas in engineering focuses on specific technical changes to improve performance of new products (Triplett, 1985, 2006). The assumption of this approach is a positive relationship between market price of a good and its quality. In particular, a product can be represented by a set of characteristics and by their value. The quality of the product Q_j is assumed to be a function of the defining characteristics as follows:

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

a_i = relative importance of the *i*-th characteristics (*i*=1, …, n)

X_{ij} =the qualitative level of the same characteristics in product *j*

Technological progress or technological evolution of the product *j* is given by the change in quality during a period of time:

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

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, p.309ff). In general, Saviotti (1985, p.315, original emphasis) argues that: "hedonic price method has been applied mostly to products. In order to apply the method to process technology, one must be able to represent individual elements of the process and the process as a whole as sets of characteristics, and cost/prices must be known for individual elements of the process. Furthermore, a sufficiently large number of 'process models' should be available to obtain statistically significant results".

The hedonic pricing method is based on specific steps to assess the evolution of technology.

Firstly, in order to analyze technological evolution of a product, it is important to detect the product characteristics (X_{ij}) and their relative importance (a_i). Product characteristics can be found in the technical literature that provides the technical characteristics of products (i.e., those characteristics describing internal aspects of technology). Technical characteristics are manipulated by engineers in order to support innovative devices over time. Saviotti (1985, p.310) shows the example of the bore, stroke, number of revolutions per minute (RPM) of a motor car engine that are manipulated to supply the required engine power, fuel consumption, etc. Carranza (2010) has showed with a hedonic price model that camera prices decreased over time, controlling for the improving quality, measured with technical characteristics of resolution and digital zoom. This approach is important in markets because adopters of a technology are interested to technical characteristics supplied by a product to fulfil their needs.

Secondly, method of hedonic pricing requires the selection of a set of variables given by technical characteristics of a product.

Thirdly, the evolution of technology, after the identification of technical characteristics of a given product, is analyzed with a functional form for the relationship between quality and product characteristics. This functional form has to show that positive increments in technical characteristics levels must lead to an increase in quality. The simplest form of functional relationships between quality and product characteristics is a linear combination. However, the relationship between price and technical characteristics of a product is not necessarily linear, it can be semilog or log-log function (cf., Triplett, 1985). The choice between different functional forms of the hedonic pricing relationship is essentially an empirical problem (cf., Saviotti, 1985). In a log-log model of hedonic pricing, product prices are regressed with respect to technical characteristics, according to following equation:

$$logP_j = \alpha_0 + \alpha_1 logX_{1t} + \cdots + \alpha_i logX_{it} + \cdots + \alpha_n logX_{nt}$$

where

P_j= price of a product over time. It represents the value that firm has given to a specific product

X_i=explanatory variables are given by technical characteristics of product over time, such as weight, efficiency, velocity, etc.

a_0= constant

a_i= coefficient of regression (i=1, …, n)

This approach can explain the functionality development dynamism of technology for detecting technological trajectories directed to achieve and sustain competitive advantage of firms in markets with rapid change and fulfill needs of adopters. Next section presents the methods and materials applied here to analyze the evolution of smartphone technology.

Materials and method

This study focuses on functionality development of smartphone technology. The crux of the study here is the measurement of the evolution of technology. A brief background of the concept of evolution is useful to clarify this study. Evolution is the stepwise and comprehensive development [it derives from Latin *evolution –onis,* der. of *evolvĕre* = act of carrying out (the papyrus)]. In particular, the evolution of technology is due to major innovations, made possible by numerous minor innovations (Sahal, 1981, p.37). The process of development of technology generates the formation of a complex system (cf., Sahal, 1981, p.33). Sahal (1981) argues that: "evolution…pertains to the verystructure and function of the object (p.64)….involves a process of equilibrium governed by the internal dynamics of the object system (p.69)". Moreover, the short-term evolution of technology is due to changes within the system, whereas the long-term evolution is possible by forming an integrated system, the formation of increasingly comprehensive systems (Sahal, 1981, pp.73-74). In general, "the evolution of a technology often proceeds along more than one pathway so as to meet the requirements of its task environment" (Sahal, 1981, p.116). In short, evolution of technology is a constant process based on different technical and socioeconomic factors that generate a stepwise transition of technology from simple to a complex system. Using a Generalized Darwinism perspective (Hodgson &

Knudsen, 2006, 2008), the evolution of technology, with the principle of selection of fruitful technical and economic characteristics, ensures diffusion and survival of successful technologies in markets (environment of technology).

The approach is modelled with a function of hedonic pricing to detect technical characteristics that matter most in evolutionary pathways over time.

Data and their sources

Smartphone is one of the most important ICTs used by people worldwide. The market of smartphone is concentrated at the brand level, with a small number of firms having a disproportionately large market share, creating an oligopoly (Lee & Lim, 2014). Sources of data here are originally sourced from trade literature (Punto & Cellulare, 2018). In particular, this study considers a sample of *N*=738 models of smartphone from 2008 to 2018 sold in Italy during the years 2012 and 2018 by famous brands: Apple. ASUS, HTC, Huawei, LG Electronics, Motorola, Nokia, Samsung, Sony, ZTE. Table 1 shows, in detail, the composition of the sample per brands of smartphone under study.

Table 1. *Sample of this study*

Brand of smartphone	N
APPLE	16
ASUS	46
HTC	81
Huawei	121
LG	64
MOTOROLA	61
NOOKIA	112
SAMSUNG	105
SONY	80
ZTE	52
Total cases (sample)	738

Measures

Firstly, this approach considers the monetary value of smartphones, which is expressed with the utilitarian unit of price in markets:

– Price *P* of smartphones (current Euros) sold in Italy during the years 2012 and 2018, though some models are launched in previous years.

Secondly, the evolution of technology here is measured with Functional Measures of Technological characteristics (FMT) in smartphone technology over 2008-2018 period to take into account both major and minor innovations (cf., Sahal, 1981, pp.27-29). FMTs in smartphone used here are given by:

– Display in inches
– Display resolution in total pixels [vi]= display size row × display size column
– Main Camera (megapixel, Mpx)
– Second Camera (megapixel, Mpx)
– Processor GHz (Giga Hertz, GHz)
– Memory Gb (Giga byte, Gb)
– RAM Gb
– Battery (milliampere hour, mAh).

Models and data analysis procedure

The technical characteristics of smartphone have accelerated from 2006 in line with the market of ICTs (cf., Lee & Lim, 2014). In order to detect the technological trajectories of the evolution of smartphone, a preliminary analysis is performed with the arithmetic, geometric and exponential rates of growth per each vital characteristic *i* under study (*i*=1, …, *n*).

Let

FMT*i, 2018*= level of technical characteristic *i* in 2018

FMT*i, 2008*= level of technical characteristic *i* in 2008

 If the development of technical characteristic *i* (*i*=1, …, *n*) in smartphone is assumed to be of *arithmetic type*, the rate of growth is given by:

$$FMT_{i,2018} = FMT_{i,2008} + FMT_{i,2008}(r_{art} \cdot t)$$
$$FMT_{i,2018} - FMT_{i,2008} = FMT_{i,2008}(r_{art} \cdot t)$$
$$r_{art} = \frac{FMT_{i,2018} - FMT_{i,2008}}{FMT_{i,2008} \cdot t}$$

- If the development of technical characteristic *i*(*i*=1, …, *n*) in smartphone is assumed to be of *geometric type*, the rate of growth is given by:

$$FMT_{i,2018} = FMT_{i,2008} \cdot (1 + r_{geom})^t$$

$$Log\left(\frac{FMT_{i,2018}}{FMT_{i,2008}}\right) = t \cdot Log \cdot (1 + r_{geom})$$

$$Log\frac{\left(\frac{FMT_{i,2018}}{FMT_{i,2008}}\right)}{t} = Log \cdot (1 + r_{geom})$$

$$r_{geom} = \frac{\left(\frac{FMT_{i,2018}}{FMT_{i,2008}}\right)}{t} - 1 \cdot$$

- If the development of technical characteristic i (i=1, …, n) in smartphone is of *exponential type*, the exponential rate of growth is given by:

$$FMT_{i,2018} = FMT_{i,2008}\, e^{rexp_i t}$$

$$\frac{FMT_{i,2018}}{FMT_{i,2008}} = e^{r exp_i \; t}$$

$$log\left(\frac{FMT_{i,2018}}{FMT_{i,2008}}\right) = r_{exp_i} t$$

$r_{exp_i} = \frac{log\left(\frac{FMT_{i,2018}}{FMT_{i,2008}}\right)}{t}$ = rate of exponential growth of technological characteristic *i*. In order to operationalize the approach of hedonic pricing to analyze the drivers of the evolution of smartphone technology, this study considers a log-log model of hedonic pricing, in which smartphone prices are regressed with respect to technological characteristics. The specification of *log-log* model (considering data in natural logarithms) is the following equation:

$$log\ P_{smartphone} = \alpha_0 + \alpha_1 log\ Display\ in\ inch + \dots + \alpha_i log\ Camera\ (megapixel) + \dots + \alpha_n log RAM\ Gb \qquad (1)$$

a_0= constant

a_i= coefficient of regression (*i*=1, …, *n*)

A *t*-test is performed for each coefficient in the hedonic price equation. Standardized values of the coefficients of regression a_i provide information about the most important technological trajectories driving the technological progress of a given product over time. This study also applies the multiple regression analysis of model (1) using the stepwise method (Criteria: Probability-of-*F*-to-enter <= .050, Probability-of-*F*-to-remove >= .100). Moreover, in order to check the generalizability of results, the study applies the hierarchical regression, considering a linear model similar to Eq. [1], to show if additional variables of interest explain a statistically significant amount of variance in dependent variable (Price of smartphone), after accounting for all other variables. This technique determines whether added variables show a significant improvement in R^2 (the proportion of explained variance in dependent variable by the model).

Logical models of hierarchical regression here are:

- Model 1 includes as explanatory variables, technical characteristics of smartphone that interact with visual perception of adopters, such as display resolution in pixels and camera in megapixels.
- Model 2 includes, in addition to model 1, a variable measuring the technical characteristic of storage and functionality of smartphone: RAM in Gb
- Model 3 includes, in addition to model 2, a variable about the long life of battery in mAh that allows a longer temporal utilization of smartphones for fulfil needs of adopters.

Hierarchical regression calculates ΔR^2 and ΔF to determine if model 2 and model 3 are better than model 1. The equations of regression analyses here are estimated using the Ordinary Least Squares method. Statistical analyses are performed with the Software IBM SPSS Statistics version 21.

Results

Table 2 shows descriptive statistics, using a natural logarithmic scale. In general, variables in natural logarithm have normal distribution, except technical characteristics of Display in inches, 1st Camera Mpx, Processor and Memory. For these variables, if values not transformed in natural logarithmic scale have normal distribution, they are used in statistical analyses, otherwise variables not having normal distribution are not considered in statistical analyses. The normality of distribution of FMT is important to apply correct parametric analyses and reduce distortions and misleading results. Table 3 shows bivariate correlation between variables having normal distribution.

Table 2. *Descriptive statistics of technical characteristics of smartphone*

		log Price in Euros	*log* Display in inches	*log* Resolution display pixels	*log* 1st Camera megapixel	*log* 2nd Camera megapixel	*log* Processor GHz	*log* Memory Gb	*log* RAM Gb	*log* Battery mAh
N	Valid	735	733	733	724	624	673	716	656	727
	Missing	0	2	2	11	111	62	19	79	8
Mean		5.206	1.551	13.735	2.303	1.416	0.414	2.710	0.717	7.792
Std. Deviation		0.647	0.260	1.157	0.786	1.073	0.438	1.443	0.742	0.381
Skewness		-.034	-2.018	-1.094	-1.528	-1.111	-2.597	-1.669	-.750	-.783
Std. Error of Skewness		.090	.090	.090	.091	.098	.094	.091	.095	.091
Kurtosis		.379	4.125	1.174	4.507	.780	12.780	4.083	2.346	.092
Std. Error of Kurtosis		.180	.180	.180	.181	.195	.188	.182	.191	.181
Minimum		3.07	.372	9.704	-1.204	-1.204	-2.283	-5.298	-3.219	6.620
Maximum		7.44	1.917	15.931	4.220	3.332	1.030	5.545	3.466	8.517

Table 3 shows that the highest bivariate correlation is given by: *log* price and *log* resolution display in px (r=0.66, p-value=0.01), *log* price and processor GHz (r=0.61, p-value=0.01), *log* price and *log* RAM Gb (r=0.58, p-value=0.01), *log* price and display in inches (r=0.56, p-value=0.01). Coefficient of correlation is lower between *log* price and *log* battery MAh (r=0.51, p-value=0.01), *log* price and *log* 2nd Camera Mpx (r=0.41, p-value=0.01).

Table 3. *Correlations*

		log Price Euro	*log* Resolution display pixels	*log* 2nd Camera megapixel	*log* RAM Gb	*log* Battery mAh	Display in inches	Processor in Ghz
log Price Euro	Pearson Correlation	1						
	Sig. (2-tailed)							
	N	735						
log Resolution Display pixels	Pearson Correlation	.655**	1					
	Sig. (2-tailed)	.001						
	N	733	733					
log 2nd Camera megapixels	Pearson Correlation	.408**	.673**	1				
	Sig. (2-tailed)	.001	.001					
	N	624	624	624				
log RAM Gb	Pearson Correlation	.575**	.714**	.736**	1			
	Sig. (2-tailed)	.001	.001	.001				
	N	656	656	617	656			
log Battery MAh	Pearson Correlation	.509**	.849**	.689**	.683**	1		
	Sig. (2-tailed)	.001	.001	.001	.001			
	N	727	727	624	654	727		
Display in inches	Pearson Correlation	.564**	.905**	.697**	.643**	.914**	1	
	Sig. (2-tailed)	.001	.001	.001	.001	.001		
	N	733	733	624	656	727	733	
Processor GHz	Pearson Correlation	.609**	.838**	.562**	.781**	.669**	.711**	1
	Sig. (2-tailed)	.001	.001	.001	.001	.001	.001	
	N	673	673	609	638	670	673	673

Note: ** Correlation is significant at the 0.01 level (2-tailed).

Table 4 shows the arithmetic, geometric and exponential rates of growth of the technical characteristics of smartphone technology. Although differences of magnitude between these types of growth, the ranking of important technical characteristics having higher evolution is similar from the highest to lowest value between these different models. Table 4 shows, in decreasing order, that the technical characteristics in smartphone technology that have had the highest exponential growth r_{exp} from 2008 to 2018 are respectively: Gb of memory=1.02; Gb of RAM=0.67, resolution display in px=0.62; Mpx of main camera= 0.54, Mpx of second camera=0.45. The lowest rates are for mAh of battery=0.19 and inches of display=0.16.

The first technical characteristic that, according to these rates in table 4, has had higher growth is memory Gb and RAM because of increasing needof smartphone to have large memory and RAM for allowing continuous updates of software applications and greater functionality (in fact, apps are more and more symbiotic technologies within complex systems of smartphones; Coccia, 2018h). The accelerated improvement of other technical characteristics (i.e., higher resolution of display and Mpx of cameras) is associated with visual perception of adopters that increase their satisfaction with better displays, images and videos (cf., Bhalla & Proffitt, 1999; Iriki *et al.*, 1996; Leutgeb *et al.*, 2005).

Table 4. *Rates of exponential, geometric and arithmetic growth in technical characteristics of smartphone technology from 2008 to 2018*

Rates of growth	Memory Gb	RAM Gb	Resolution Display Pixels	1st Camera Megapixels	2nd Camera Megapixels	Processor GHz	Battery mAh	Display in inches
r exponential	1.015	0.668	0.623	0.542	0.454	0.331	0.190	0.155
r geometric	1.759	0.951	0.864	0.720	0.574	0.393	0.209	0.167
r arithmetic	2559.900	79.900	50.525	22.567	9.233	2.645	0.567	0.369

Table 5 suggests some symbols to indicate the intensity of growth of technological trajectories, measured with exponential rates of growth as illustrated in table 4. Hence, for instance, the evolutionary pathways of display in inches is \ = steady-state growth, main camera=+ (growth), and memory in Gb= ! (high development).

Table 5. *Scale for rating the acceleration of technological trajectories within complex systems of technology*

Symbol	Description	Measure of the growth of technical characteristics with r_{exp}
!	High development of technological trajectory	$r_{exp}>1$
+	Growth of technological trajectory	$0.5 \leq r_{exp} \leq 1$
/	Steady-state technological trajectory	$r_{exp} < 0.5$

Table 6. *Estimated relationship for the evolution of smartphone technology (log-log model)*

Dependent variable: *log* Price			
Smartphone	*Unstandardized Coefficient*	*Standardized Coefficient*	*t-test*
Constant. α	1.41		1.77
(St. Err.)	(0.80)		
Coefficient *log* Resolution Display in pixels	0.44***	0.58	11.62
(St. Err.)	(0.04)		
Coefficient *log* 2nd Camera megapixel	–0.05*	–0.1	–2.06
(St. Err.)	(0.03)		
Coefficient *log* RAM Gb	0.27***	0.30	2.50
(St. Err.)	(0.05)		
Coefficient *log* Battery mAh	–0.32***	–0.15	–3.23
(St. Err.)	(0.1)		
R^2 adj. adj.	0.44		
(St. Err. of the Estimate)	(0.43)		
F	124.16		
(sign.)	(0.001)		

Note: *** *p-value*< .001 ** *p-value*< .010 * *p-value*< .050

Table 6 shows that the evolutionary pathways of smartphone technology is, in average, driven by resolution of display in pixels and performance of RAM in Gb as suggested by standardized coefficients of regression. Moreover, the OLS estimation of model in table 6 indicates that a 1% higher level of quality in Display resolution increases the expected price of smartphone by about 0.44% (*p*-value<.001), whereas a 1% higher level of Gb in RAM increases the expected price of smartphone by about 0.27% (*p*-value<.001). Using the multiple regression analysis with stepwise method (Criteria: Probability-of-*F*-to-enter <= .050, Probability-of-*F*-to-remove >= .100), R^2 adjusted of the model indicates that about 42% of the variation in price can be attributed (linearly) to the resolution of display in px as predictor. Table 7 shows that models with other variables entered increase the goodness of fit of about 2%, achieving 44% with four predictors (cf., model 4d. in Tab. 7).

Table 7. *Model summary with stepwise method*

Model	*Adjusted R Square (std. error of the estimate)*	*F*	*Sign.*
1 a.	0.415 (0.438)	436.27	0.001
2 b.	0.427 (0.433)	230.86	0.001
3 c.	0.441 (0.428)	163.27	0.001
4 d.	0.444 (0.427)	124.16	0.001

Note: Dependent variable is *log* price in euros.
a. Predictors: (Constant), *log* resolution display in px
b. Predictors: (Constant), *log* resolution display in px, *log* RAM in Gb
c. Predictors: (Constant), *log* resolution display in px, *log* RAM in Gb, *log* Battery in mAh
d. Predictors: (Constant), *log* resolution display in px, *log* RAM in Gb, *log* Battery in mAh, *log* second camera in Mpx

Table 8. *Hierarchical regression analysis of predictors of smartphone prices*

	Model 1	*Model 2*	*Model 3*
Constant λ_0	–1.94***	–0.61	1.41
(St. Err.)	(0.43)	(0.50)	(0.80)
log (Resolution Display in Pixels)			
Coefficient λ_1	0.52***	0.41***	0.44***
(St. Err.)	(0.03)	(0.04)	(0.04)
log 2nd camera in Megapixels			
Coefficient λ_2	–0.02	–0.08***	–0.05*
(St. Err.)	(0.02)	(0.03)	(0.03)
log RAM Gb			
Coefficient λ_3		0.24***	0.27***
(St. Err.)		(0.05)	(0.05)
log Battery mAh			
Coefficient λ_4			–0.32***
(St. Err.)			(0.10
F	218.56	159.61	124.16
Sig.	0.001	0.001	0.001
R^2 *adj.*	0.41	0.436	0.444
(St. Err. of the Estimate)	(0.44)	(0.43)	(0.43)
ΔR^2	0.41	0.023	0.009
ΔF	218.56***	24.78***	10.43***

Note: Dependent variable: *Log* Price. *** = *p-value*< .001 ** = *p-value*< .010 * = *p-value*< .050

Models of hierarchical regression in table 8 show that Model 1 of the hierarchical ordering including technical characteristics of smartphone that interact with visual perception of adopters (resolution display in pixels and second camera in Mpx), entered together, contribute significantly: R^2 adjusted of the model indicates that about 41% of the variation in price can be attributed (linearly) to these technical characteristics. Other variables, such as main camera, are not included because they have not normal distribution. At next stage, in model 2, the technical characteristic of storage and functionality of smartphones given by RAM in Gb explains about 2.3% of the variance accuracy scores over and above the technical characteristics associated with visual perception of adopters, which is a significant amount (p-value<0.001). At the next stage, in model 3, the long life of battery in mAh explains about 1% of the variance accuracy scores over and above the technical characteristics associated with visual perception of adopters and the technical characteristic of storage and functionality of smartphones given by RAM in Gb (p-value<0.001).

Table 9 shows descriptive statistics of the evolutionary improvements of technical characteristics in smartphone technology from 2008 to 2018. The maximum value indicates the highest level achieved by technical characteristics in 2018.

Table 9. *Descriptive statistics of the evolutionary stepwise improvements of technical characteristics in smartphone technology from 2008 to 2018*

Technical characteristics	N	Minimum	Maximum	Mean	Std. Deviation
Display in inches	55	1.45	6.80	4.44	1.49
Resolution Display total pixels	33	16384.00	8294400.00	1411271.03	1845077.45
1st Camera megapixels	38	0.30	68.00	18.50	13.72
2nd Camera megapixels	25	0.30	28.00	7.85	8.25
Processor GHz	29	0.10	2.80	1.45	0.81
Memory Gb	30	0.01	256.00	17.25	52.02
RAM Gb	15	0.04	32.00	4.96	8.39
Battery MAh	123	750.00	5000.00	2411.87	931.22

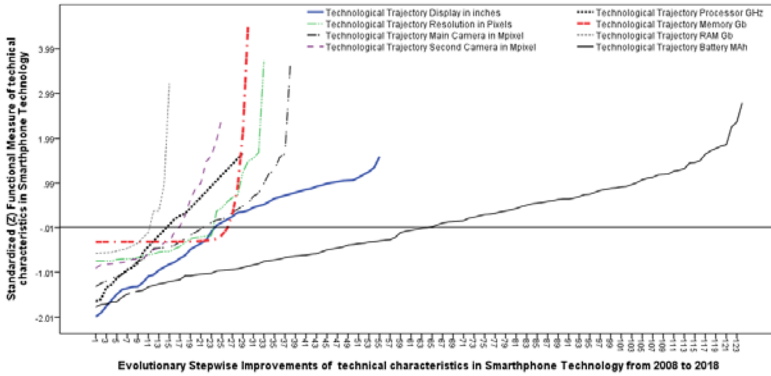

Figure 1. *Technological trajectories of the evolution of smartphone technology from 2008 to 2018*

Figure 1 shows the representation of technological trajectories of the evolutionary improvements of technical characteristics in smartphone technology from 2008 to 2018. Figure 1 reveals two patterns of technological evolution of these characteristics in smartphone technology:

- *Arithmetic* growth of technological trajectories is for the technological characteristics of battery in mAh, display in inches, and processor in GHz.
- *Exponential* growth of technological trajectories is for the technological characteristics of RAM in Gb, 1st and 2nd camera in Mpx, memory in Gb and resolution in total pixels.

Therefore, representation of the evolution of technological trajectories from 2008 to 2018 in Figure 1 suggests that smartphone technology is driven mainly by technological characteristics associate with visual perception of adopters (high definition of display and camera), storage (memory) and functionality with RAM in Gb.

Table 10. *Estimated relationships of evolutionary improvements of technical characteristics in smartphone technology*

Models	*Mod. 1 linear*	*Mod. 2 linear*	*Mod. 3 linear*	*Mod. 4 Exp*	*Mod. 5 Exp*	*Mod. 6 Exp*	*Mod. 7 linear*	*Mod.8 linear*
Constant β_0	1.88***	792.52***	0.02	2.35***	0.48***	10.27***	–4.33***	–3.04***
(St. Err.)	(0.08)	(26.95)	(0.01)	(0.37)	(0.04)	(0.14)	(0.36)	(0.14)
Display in inches	0.09***							
Coefficient β_1								
(St. Err.)	(0.002)							
Battery mAh		25.73***						
Coefficient β_2								
(St. Err.)		(0.37)						
Processor Ghz			0.10***					
Coefficient β_3								
(St. Err.)			(0.001)					
1st Camera Mpx				0.09***				
Coefficient β_4								
(St. Err.)				(0.007)				
2nd Camera Mpx					0.17***			
Coefficient β_5								
(St. Err.)					(0.005)			
*log*Resolution px						0.014***		
Coefficient β_6								
(St. Err.)						(0.001)		
*log*Memory Gb							0.26***	
Coefficient β_7								
(St. Err.)							(0.02)	
*log*RAM Gb								0.42***
Coefficient β_8								
(St. Err.)								(0.02)
F	1420.28	4766.17	14001.71	149.99	1176.20	391.32	159.38	772.84
Sig.	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
R^2 *adj.*	0.96	0.98	0.998	0.80	0.98	0.92	0.85	0.98
(St. Err. of the Estimate)	(0.29)	(147.13)	(0.04)	(0.48)	(0.18)	(0.04)	(0.97)	(0.25)

Note: Dependent variable: temporal steps from 2008 to 2018; px is acronyms of pixel. *** = *p-value*< .001 ** = *p-value*< .010 * = *p-value*< .050

Table 10 shows the parametric estimates of linear or exponential models of the technological evolution of technical characteristics in smartphone technology. Results are consistent with previous statistical analyses. The R^2 values are nevertheless very high. Thus in majority of cases models explain more than 90% variance in the data.

Discussionand concluding observations

This article proposes a hedonic price method for the analysis of the most important technical characteristics supporting the evolution of smartphone technology. In particular, the approach here is based on a simple assumption that technologies are complex systems based on interrelated sub-systems of technologies. The approach is formalized with a simple *log-log model of hedonic pricing*, which is useful to be generalized in order to predict which technical characteristics within complex systems of technology (e.g., smartphone) are likeliest to evolve rapidly. This approach seems also to be appropriate to detect evolutionary pathways of new technology that may sustain competitive advantage of firms and fulfil needs of adopters in markets.

The results here are that evolutionary pathways of smartphone technology are, in average, driven by display resolution in pixel and performance of RAM in Gb as suggested by standardized coefficients of regression.

In particular, hierarchical regression suggests that technical characteristics of smartphone that interact with visual perception of adopters (resolution display in pixels and second camera in Mpx) contribute significantly to technological evolution of this ICT. This result is represented in figure 1 that shows *exponentialgrowth* of the technological characteristics of RAM in Gb, 1^{st} and 2^{nd} camera in Mpx, memory in Gb and resolution in total pixels, whereas other technical characteristics have arithmetic pathways of growth.

This result of smartphone technology is consistent with the market of digital cameras that shows how the evolutionary pathway of resolution from 1998 to 2001 is increased from around 0.5 to more than 1.5 megapixels (Carranza, 2010). This finding indicates that the long-run evolution of smartphone technology depends on the behavior and evolution of associated technologies (cf., Sahal, 1981, Coccia, 2017b). In fact, the evolution of smartphone technology, as a complex system, is driven by a coevolution of innovations in digital cameras and other technologies, such as resolution HD, full HD, Quad HD or 2K, 4K or Ultra HD as well as new technology for displays, e.g., LCD, OLED, AMOLED, Super AMOLED, TFT-LCD, Retina, etc. As a matter of fact, evolutionary pathways of smartphone technology are due to the effects of cumulative learning from digital technology (cf., Watanabe *et al.,* 2012). In particular, learning effects, based on learning by doing and learning by using, are fostering the assimilation of new technology in smartphone devices (Cohen & Levinthal, 1990). 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”. Williams *et al.*, (2000) suggest: “a concept of domestication which tames assimilated spillover technology for a whole institutional system in a co-evolutionary way” (as quoted by Watanabe *et al.*, 2012, p.1293). Watanabe *et al.*, (2012, pp.1293-1294) claim that mobile phones can attract a vast spectrum of adopters by incorporating “super-functionality, and…. users are transformed into explorers in search of further exciting stories based on their own initiative and this then thrills them with gratification of such exploration”.In general, this study shows that the evolution of technology is driven by the interaction between smartphone technology and its subsystem components, e.g., displays, camera, etc. that drive the evolutionary pathways of these complex systems of technology and technological diversification over time and space (cf., Coccia, 2017b). The finding of this study could aid technology policy and management of technology to design best practices for supporting the development of technological trajectories with faster rates of growth. The hedonic price method applied here for assessing technological evolution is useful for: “products that can be represented as sets of characteristics and for which both characteristics values and corresponding prices are known for a sufficiently large number of models” (Saviotti, 1985, p.314-315). In addition, within competitive markets, well informed adopters are available to pay a given price for a product only if the levels of characteristics supplied satisfy their requirements. The analysis of the evolution of technological characteristics and pricing behavior of different products within smartphone industry can therefore serve to compare the performance of different technologies and provide information of its technical progress and evolutionary pathways.

However, drawbacks of the approach here to analysis of the evolution of technology are that hedonic pricing function cannot, in general, be rigorously derived from theories of consumer demand or from the production function. Its theoretical status is still not clear (cf., Saviotti, 1985, Triplett, 1985). In short, hedonic pricing applied to technological evolution needs improvements in the theoretical framework and its empirical evidence. Some of the methodological issues (e.g., choice of variables, data collection, etc.) are common to all methods of technology analysis, while others are specific to the hedonic price method. For instance, a price-technological characteristics relationship should only be applicable to a homogeneous market (Muellbauer, 1974, p.988). Saviotti (1985, p.334, original emphasis) also argues that: "the hedonic price method cannot be used in an 'unskilled' way to measure changes in technology". Of course, this approach requires an accurate knowledge of the technology under study.

To conclude, the proposed approach here keeps its validity in explaining specific technological characteristics supporting the evolutionary pathways of a given technology, such as smartphone. In particular, this study constitutes an initial significant step in the application of hedonic pricing method to study the evolution of technology considering the interaction between technologies in complex systems to predict fruitful technological trajectories. Hence, this study may lay the foundation for development of more sophisticated theoretical frameworks in technology analysis and technological forecasting, using hedonic pricing, to detect and forecast the evolutionary technological trajectories of a given complex system of technology. Nevertheless, the identification of a comprehensive method for detecting critical pathways of the evolution of technology that depends on the behavior of the other technologies is a non-trivial exercise, because manifold factors are not equal over time and space as well as between different technologies. Wright (1997, p.1562) properly claims that: "In the world of technological change, bounded rationality is the rule."

Acknowledgement

I gratefully acknowledge financial support from National Endowment for the Humanities and National Research Council of Italy–Direzione Generale Relazioni Internazionali (Research Grant n. 0072373-2014 and n. 0003005-2016) for my visiting at Arizona State University where this research started in 2014. I am grateful to Trang T. Thai (Intel Corporation) and seminar participants at the Beyond-Center for Fundamental Concepts in Science at Arizona State University for helpful comments and suggestions (Tempe, USA).

Notes

[v] For studies about the role of science, technology, sources of innovation and knowledge in society, see also, Calabrese *et al.,* 2005; Cariola & Coccia, 2004; Cavallo *et al.,* 2014, 2014a, 2015; Coccia, 2001, 2003, 2004, 2005, 2005a, 2005b, 2005c, 2006, 2006a, 2007, 2008, 2008a, 2008b, 2009, 2009a, 2010, 2010a, 2010b, 2010c, 2010d, 2010e, 2011, 2012, 2012a, 2012b, 2012c, 2012d, 2013, 2013a, 2014, 2014a, 2014b, 2014c, 2014d, 2014e, 2014f, 2014g, 2015, 2015a, 2015b, 2015c, 2015d, 2016, 2016a, 2016b, 2016c, 2017, 2017a, 2017b, 2017c, 2017d, 2018, Coccia & Bozeman, 2016; Coccia & Finardi, 2012, 2013; Coccia & Wang, 2015, 2016; Coccia & Cadario, 2014; Coccia *et al.,* 2015, 2012, Coccia & Rolfo, 2000, 2002, 2009, 2012, 2007, 2010, 2010, 2013; Coccia & Wang, 2015, 2016; Rolfo & Coccia, 2005.

[vi] The display resolution is usually quoted as width × height, with the units in pixels: for example, "1024 × 768" means the width is 1024 pixels and the height is 768 pixels. Total pixels= 1024 × 768=786,432 pixels.

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5 Disruptive firms and technological evolution for corporate and industrial change

Introduction

Current economies show the advent of many technological advances in information technology, biotechnology, nanotechnology, etc. that generate corporate, industrial and economic change (Arora *et al.*, 2001; Henderson & Clark, 1990; Nicholson *et al.*, 1990; Teece *et al.*, 1997; Van de Ven *at al.*, 2008; von Hippel, 1988). The literature in these research fields has suggested several approaches to explain the technological and industrial change, such as the theory by Christensen (1997, 2006) that introduces the concept of disruptive technologies of new entrants that disrupt the competitive advantage of incumbents in the presence market dynamisms. This theory explains the industrial change with the interplay between incumbent and entrant firms that can generate path-breaking Technologies (Ansari *et al.*, 2016; King & Baatartogtokh, 2015; Chesbrough & Rosenbloom, 2002; Christensen, 1997, 2006; Christensen *et al.*, 2015; Danneels, 2004, 2006; Gilbert & Bower, 2002; Hill & Rothaermel, 2003; Jenkins, 2010; King *et al.*, 2015; Ryan & Tipu, 2013; Tellis, 2006; Wessel &

Christensen, 2012). While the validity of certain of these studies may be debated, it is clear that there are at least some facts about industrial change that theory of disruptive technologies has trouble explaining. As a matter of fact, current dynamics of industries shows that new entrants can generate disruptive technologies but their development and diffusion between markets have more and more economic barriers (Coccia, 2016; 2017).

This paper suggests that industrial change is driven by specific subjects -disruptive firms, rather than disruptive technologies per se. This study can be useful for bringing a new perspective to explain and generalize one of the sources of technological change that is represented by specific firms that have the potential to generate and/or to develop radical innovations that disrupt current products in markets and support industrial, economic and social change.

In order to position this study in existing approaches, the paper develops the theoretical framework in next section.

Theoretical framework

Many industries are characterized by incumbents that focus mainly on improving their products and services (usually most profitable), and entrants that endeavor to develop new technologies in market segments, delivering market performance that incumbents' mainstream customers require (Christensen *et al.*, 2015; Christensen, 1997). In this context, Christensen (1997) argues that disruptive innovations generate significant shifts in markets (cf., Henderson, 2006). In particular, disruptive innovations are generated by small firms with fewer resources that successfully challenge established incumbent businesses (Christensen *et al.*, 2015). New firms can generate competence-destroying discontinuities that increase the environmental turbulence, whereas incumbents focus mainly on competence-enhancing discontinuities that decrease the turbulence in markets (cf., Tushman & Anderson, 1986). Scholars also argue that the ability of incumbents to develop and to market disruptive innovations is due to their specific ambidexterity: competence-destroying and competence-enhancing based on simultaneous exploratory and exploitative activities to support both incremental and radical innovations (Danneels, 2006; Durisin & Todorova, 2012; Lin & McDonough III, 2014; O'Reilly III & Tushman, 2004, 2008; cf., Henderson, 2006; Madsen & Leiblein, 2015) [3]. Disruptive innovations generate main effects both for consumers and producers in markets and society (Markides, 2006, pp. 22-23; Markides & Geroski, 2005). In general, disruptive innovations change habits of consumers in markets and undermine the competences and complementary assets of existing producers. Calvano (2007) argues that: "we highlight the role of destruction rather than creation in driving innovative activity. The formal analysis shows that destructive creation unambiguously leads to higher profits whatever the innovation cost". In particular, disruptive innovations disturb the business models of incumbents that have to counter mobilize resources to sustain their competitive advantage in the presence of market change (Garud *et al.,* 2002; Markman & Waldron, 2014). In fact, new radical technologies in markets require that incumbents undertake specific R&D investments and strategic change to support competitive advantage (Christensen & Raynor, 2003; cf., Gioia & Chittipeddi, 1991; Teece *et al.,* 1997). Current R&D management of incumbents, to support innovation processes, is more and more based on network organizations to build research alliances and strategic partnerships for increasing the access to external knowledge from new firms and/or research organizations (cf., Coccia, 2016b; Nicholls-Nixon & Woo, 2003). Kapoor & Klueter (2015) argue that incumbents tend to not invest in disruptive technological regimes and maintain a competence-enhancing approach. In some industries, such as biopharmaceutical sector, current wave of research alliances and acquisitions may help incumbents to overcome this "inertia" both in the initial stage of research and in the later stage of development. Other studies show that R&D investments of innovative enterprises in pharmaceutical industry are directed towards both internal research units and strategic alliances to accelerate the drug discovery process (Coccia, 2014).

3 For studies on science, new technology and economic growth see also Cavallo *et al.,* 2014, 2014a, 2015; Coccia 2006, 2009, 2012, 2012a, 2012b, 2015a; Coccia & Finardi, 2012, 2013; Coccia & Rolfo, 2000; Coccia & Wang, 2015, 2016.

However, theoretical framework of disruptive technologies suffers of some limitations, such as the ambiguity in the definition of disruptive innovations that considers technologies but also products and business models (cf., Christensen & Raynor, 2003; Tellis, 2006). Strictly speaking, a disruptive technological innovation is fundamentally a different phenomenon from a disruptive business-model innovation. Disruptive innovations arise in different ways, have different competitive effects, and require different responses into the organizational behaviour of incumbents and entrants (Markides, 2006, p. 19). This diversity can be due to a variation in the sources of innovation, such as in some industries, users develop innovation, in other sectors, innovations are due to suppliers of related components and product manufactures (von Hippel, 1988). A vital factor in the development of innovations is also played by the coevolution of technical and institutional events (Van de Ven & Garud, 1994). The theory of disruptive technologies also seems to show some inconsistencies in many markets because new small entrants can generate new technology and innovations but their development and diffusion in markets present many economic barriers, such as within biopharmaceutical industry (Coccia, 2014; 2016). In short, the theory of disruptive technologies presents some difficulties to explain the general drivers of technological and economic change.

This study here suggests the vital role of specific firms, called disruptive firms that in the ecosystems can generate and spread new technologies with market shifts within and between industries. The study proposes some characteristics of these disruptive firms that can clarify, as far as possible, a main source of innovation to explain drivers of technological change and, as a consequence, industrial, economic and social change.

The model of this study is in Figure 1. Unlike theoretical framework of disruptive innovation (Christensen, 1997), the theoretical framework here suggests that, leading firms -called disruptive firms-support the emergence and diffusion of new technology and radical innovations that generate market shifts, technological and economic change.

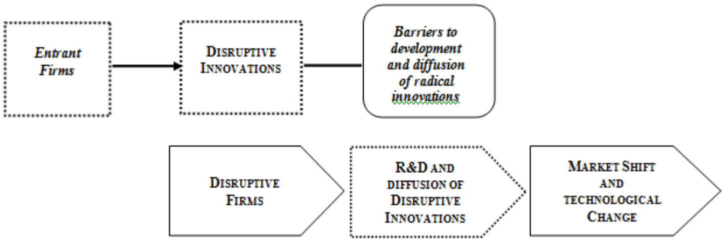

Figure 1. *Disruptive firms sustain technological and economic change with the introduction and diffusion of technical breakthroughs.*

The purpose of the present study is to see whether case study research supports the hypothesis that one of the general sources of technological change is due to disruptive firms (subjects) that generate market shifts, rather than disruptive technologies (objects) per se.

Methods: case study research

The methodology is based on an inductive analysis of case study research (Eisenhardt, 1989; Eisenhardt & Graebner, 2007).

The study analyzes the managerial and organizational behavior of specific leading enterprises (disruptive firms) to explain one of the general sources of technological and economic change. The firms under study are:

* Apple Inc. for Information and Communication Technologies (ICTs)

* AstraZeneca for biopharmaceutical industry

In particular, the hypothesis of this study is that specific and distinct firms, called disruptive firms, are the driving force of market shift in industries by introducing new products, standard and/or components in markets with new technology and innovation, generating technological and socioeconomic change. Of course, the emergence of a disruptive technology is a necessary but not sufficient condition for the development and diffusion of new technology in markets that generate industrial change. Manifold factors also create important conditions for supporting technical breakthroughs. This study here focuses on specific subjects, the disruptive firms that play a vital role in competitive markets. In order to support the theoretical framework, firstly, the study analyzes shortly these firms and then we contextualized the theory with some examples of new technology and the organizational and managerial behavior of disruptive firms that generate market shift, technological and economic change.

Inductive analysis

Apple Inc. is an American multinational technology company headquartered in California (USA) that designs, develops, and sells consumer electronics, computer software, and online services. Apple was founded in 1976 to develop and sell personal computers. It was incorporated as Apple Computer Inc. in 1977, and was renamed as Apple Inc. in 2007 to reflect its shifted focus toward consumer electronics (Wozniak, 2007). Number of employees as of October 2016 is about 116,000 units.

Apple Inc. is a disruptive firm of storage devices. A simple storage device was the floppy disk: a disk storage medium composed of a disk of thin and flexible magnetic storage medium encased in a rectangular plastic carrier. In 1983 Sony introduced 90 mm micro diskettes (better known as 3.5-inch -89 mm- floppy disks), which it had developed at a time when there were 4" floppy disks, and a lot of variations from different companies, to replace on-going 5.25" floppy disks. Apple Computer, a market leader in ICTs, decided to use in 1984 the 3½-inch drives produced by Sony in the Macintosh 128K model. This firm strategy effectively makes the 3½-inch drive a de-facto standard in markets. This Apples' decision generated a main market shift and the format 3.5" floppy disks became dominant. Floppy disks 3.5" remained a popular medium for nearly 40 years, but their use was declining by the mid-1990s (Mee & Daniel, 1996). In 1998, Apple Inc. released the iMac G3 with a new store device, called USB because it considered the floppy disk an old technology. USB—or Universal Serial Bus—is a protocol for connecting peripherals to a computer. The development of the first USB technology began in 1994 by Intel and the USB-IF (USB Implementers Forum, Inc., formed with industry leaders like Intel, Microsoft, Compaq, LSI, Apple and Hewlett-Packard). USB was designed to standardize the connection of computer peripherals (Cunningham, 2014). The USB 1.0 debuted in late 1995 and transferred data at a rate of 12 megabits per second. This parasitic technology is associated to other host technologies, such as PCs. Interaction between these high-tech devices and a host computer without the need to disconnect or restart the computer also enables USB technology to render more efficient operation. As just mentioned, in 1998, the iMac G3 was the first consumer computer to discontinue legacy ports (serial and parallel) in favor of USB. This implementation helped to pave the way for a market of solely USB peripherals rather than those using other ports for devices. The combination of the ease of use, self-powering capabilities and technical specifications offered by USB technology and related devices helped this new technology to triumph over other port options (Au Yong, 2006; Tham, 2011). This decision of Apple generated a market shift and industrial change. In the presence of this technological change generated by a market leader, the ICT industry's reaction is to follow Apple's technological pathway, such as Dell, Hewlett-Packard, etc. that dumped the floppy drivers from their standard PCs. Trek Technology and IBM began selling the first USB flash drives commercially in 2000. IBM's USB flash drive had a storage capacity of 8 MB, more than five times the capacity of the then-common 3½-inch floppy disks (of 1440 KB). Similar pathway is with the Compact Disc (CD), a digital optical disc data storage format released in 1982 and co-developed by Philips and Sony (BBC News, 2007). The format was originally developed to store and play only sound recordings but was later adapted for storage of data (CD-ROM). Apple Inc. released the third generation of MacBook Pro in 2012 with a 15-inch screen that was a quarter thinner than its predecessor and the Retina Display with a much higher screen resolution. The MacBook Pro with Retina Display does not have an optical drive and to play discs, it is necessary to have an external Super Drive. This decision of a market leader generated a further market shift and industrial change towards new storage devices with the USB port, micro-USB or USBType-C (Hruska, 2015; Mee & Daniel, 1996; Goda & Kitsuregawa, 2012, USB, 2005).

Apple Inc. is also a disruptive firm of wired headphones. Headphones are pair of small listening devices that are electroacoustic transducers, which convert an electrical signal to a corresponding sound in the user's ear. They are designed to allow a single user to listen to an audio source privately. Firstly, the headphone with jack was created in the period 1890-1910 and with several generations is still used in many electronic devices. The study here focuses on a critical period associated to Bluetooth technology (a wireless technology standard for exchanging data over short distances from fixed and mobile devices, and building personal area networks-PANs). In fact, the revolution of ICT has generated several innovations such as the Bluetooth technology in 1999 (Bluetooth, 2017). The evolution of this technology has generated in 2004 the Bluetooth 2.0 with an Enhanced Data Rate for faster data transfer, in 2010 Bluetooth 4.0 with low energy and so on (Bluetooth, 2017). The interaction between Bluetooth and mobile phone has generated in 2002 the first mobile phone with integrated Bluetooth by Nokia, whereas the interaction between Bluetooth and headphones has also generated in 2003 the first Nokia headset, which was sold to end-users (Windows, 2012). The 29 June, 2007 Apple Inc. launched the 1st generation of iPhone with Bluetooth 2.0; the diffusion of the iPhone worldwide plays a main role in the evolution of several ICTs, driven by Apple Inc., which is one of the market leaders in smartphones and other mobile devices. In 2011, Apple Inc. has announced that new iPhone 4S supports Bluetooth 4.0 with low energy phone. In September 2016, the iPhone 7 of Generation 10th is launched without headphone jack 3.5mm. This strategic decision by Apple Inc. has a main impact for the evolution of new generations of headphones that will be more and more wireless to function, interact and survive with mobile devices (Coccia, 2017a). This decision of Apple Inc. to produce a new iPhone 7 without jack 3.5mm for headphone generates a selection pressure on manufacturers of these technologies that are focusing on new technological directions of headphones with Bluetooth™ technology (wireless) generating an on-going technological substitution and "Destructive creation" (Calvano, 2007) of current headphones with wire. In short, this case study seems to confirm that new technologies and technological trajectories are driven by specific firms that play a role of destruction of current technologies in favor of the creation of new technology and technological standards. Other examples of the organizational behavior of Apple Inc. as disruptive firm, are the destruction of the physical keyboard in smartphones with the creation of virtual keyboards in the iPhone of 1st generation in 2007. In general, disruptive firms have the market power to support new technological trajectories and industrial change. In short, the innovative behavior of market leaders can be a main driving force of technological, industrial and economic change. Moreover, market shifts are due to leader firms of host technologies, such as PC or smartphones, rather than leader firms of parasitic technologies, such as headphones, storage devices, etc. (cf., Coccia, 2017a).

AstraZeneca (AZ) is a British–Swedish research-based biopharmaceutical company. It is originated by a merger in 1999 of the Astra AB company formed in 1913 (Sweden) and British Zeneca Group formed in 1993. AstraZeneca (AZ) is a large corporation that has a net income of US$3.406 billion (AstraZeneca, 2016), total assets for US$60.12 billion (Forbes, 2016) and total number of employees for about 50,000 (AstraZeneca, 2015). The human and economic resources invested in R&D by AstraZeneca are about 15,000 units of personnel and over US$4 billion in eight countries (AstraZeneca, 2015). One of the research fields of AZ is anticancer treatments, such as for lung cancer. The current therapeutic treatments (technology) for advanced non-small cell lung cancer (NSCLC) are again mainly based on chemotherapy agents. However, this technology has low efficacy for lung cancer treatment since the mortality rate is still high (Coccia, 2014). AstraZeneca as incumbent firm in drug discovery industry has generated a main radical innovation to treat lung cancer: the target therapy Iressa® that is based on the blocking agent Gefitinib. These path-breaking anticancer drugs are generating a revolution in therapeutic treatments of lung cancer with mutation Epidermal Growth Factor Receptor (EGFR) because they block specific enzymes and growth factor receptors involved in cancer cell proliferation (Coccia, 2012, 2014, 2016). Studies in the biology show that lung cancer can become resistant to these new drugs because of a secondary mutation (T790M) that generates a progression of the cancer with several metastases and, as a consequence, high mortality within five years (Coccia, 2012). Clovis Oncology is a small pharmaceutical company, which is generating innovative products for new treatments in oncology. Clovis was founded in 2009 and is headquartered in Boulder, Colorado. This small pharmaceutical firm, Clovis oncology, has generated a new technology to treat lung cancer with mutation T790M: a new target therapy for EGFR-mutant lung cancer (Clovis Oncology, 2015). However, this small firm has difficulties in the development of this radical innovation in a sector with high capital intensity for R&D. This problem has induced Clovis oncology to enter in the stock exchange to gather financial resources directed to support R&D of several innovative products in its pipeline. The structure of the sector based on larger corporation has induced the biopharmaceutical company AstraZeneca (2015) to introduce a similar innovation for mutant lung cancers, called Tagrisso™ (AZD9291), that it was approved by US Food and Drug Administration in 2015 (AstraZeneca, 2016). This case study also confirms the vital role of large and leader firms, in competitive markets based on high intensity of R&D, that have the power to generate and/or to spread path-breaking innovations in order to achieve and sustain competitive advantage, as well as the goal of a (temporary) profit monopoly to support their market shares and industrial leadership.

Next section endeavors to detect the general characteristics of these disruptive firms that generate technological, industrial and economic change.

Discussion

A main goal of this study is the concept of disruptive firms: they are firms with market leadership that deliberate introduce new and improved generations of durable goods that destroy, directly or indirectly, similar products present in markets in order to support their competitive advantage and/or market leadership (cf., Calvano, 2017). These disruptive firms support technological and industrial change and induce consumers to repeat their purchase in order to adapt to new socioeconomic environment. Firm strategy of these leading firms is directed to support innovation and market leadership with new technology. An example of disruptive firms is Apple Inc. that has the following organizational behaviour (cf., Backer, 2013; Barney, 1986; Fogliasso & Williams, 2014; Heracleous, 2013; O'Reilly *et al.*, 1991; Schein, 2010).

1- A main and central leader in the organization, represented in the past by the founder Steve Jobs and subsequently by the CEO Tim Cook (Apple Inc., 2017). The hierarchy in Apple's organizational structure supports strong control over the organization that empowers top leader to control everything in the organization. This organizational behavior generates limited flexibility of lower levels of the hierarchy to respond to custom needs and market demand but it provides a clear leadership for R&D and strategic management of innovative products.

2- A large market share in mobile technology and associated industrial leadership. Samsung is the largest vendor in smartphones but it only captured 14% of smartphone profits, while Apple Inc. gathered 91% of them in 2015. Apple holds nearly 45% of the U.S. OEM (Original Equipment Manufacturer) market, and in a distant second is Samsung Electronics with 28% of the market. Notably, Apple is one of the only companies to actually advance its market share (from October through January), from 42.3% to 44.6%, for a 2.3% gain. Samsung's market share declined 2% from 30% in late 2016. Apple's iPhone accounted for 34% of all smartphone activations in the U.S. last quarter, leading all other smartphone brands. Samsung was just behind the iPhone at 33%, followed by LG at 14% share of activations (Kilhefner, 2017).

3- Founded in 1976, more than 40 years ago. The firm has a long presence and experience in the sector of computer hardware, software and electronics.

4- Headquarters is localized in a high-tech region, California, of a powerful country with socioeconomic influence on wide geoeconomic areas.

5- Apple's organizational culture is also highly innovative to support firm's product development processes and firm's industry leadership. Creativity and excellence are especially important in Apple's rapid innovation processes. Moreover, secrecy is part of the company's strategy to minimize theft of proprietary information or intellectual property. Apple employees agree to this organizational culture of secrecy, which is reflected in the firm's policies, rules and employment contracts. This aspect of Apple's organizational culture helps protect the business from corporate espionage and the negative effects of employee poaching. These characteristics of the company's organizational culture are key factors that enable success and competitive advantage (cf. also, Csaszar, 2013; Damanpour & Aravind, 2012, Lehman & Haslam, 2013).

Some characteristics of the organizational behavior of AstraZeneca (AZ) are (Coccia, 2014a, 2015, 2016a):

1- A characteristic similar to previous firm is a long experience in the market and leadership position in specific segments of the biopharmaceutical sector. In fact, Astra AB formed in 1913 (Sweden) and British Zeneca Group formed in 1993. Moreover, AstraZeneca is a large corporation in industry.

2- Higher specialization of technological capability in new research fields of genetics, genomics and proteomics to support drug discovery process.

3- Another characteristic of AZ is a division of scientific labour (cf. 'division of innovative labour' by Arora & Gambardella 1995; Coccia, 2014a). R&D strategy of this incumbent firm is to create strategic alliances with emerging firms for a division of scientific labour directed to reinforce and accelerate discovery process. In fact, AZ has strategic partnerships with organizations to complement in-house technological and scientific capabilities. In this manner, AZ supports rational modes of drug discoveries by integrative capabilities developed in collaboration with biotechnology firms (cf., Coccia, 2016b; Henderson 1994, pp. 607ff; Paruchuri & Eisenman, 2012). In particular, AZ builds and reinforces the scientific capabilities by strategic alliances with external sources of innovation: i.e., partnership with academic institutions, biotechs and other pharmaceutical companies to share skills, knowledge and resources through all phases of R&D process. In addition, the acquisition of the biotechnology firm MedImmune has improved and enlarged the R&D function and technological capabilities (AstraZeneca, 2015). This R&D management of AZ organizes the R&D labs with a network structure based on strategic alliances for supporting the process of disruptive innovations (figure 2). Network R&D organization reinforces the integrative capabilities in scientific fields, collective and cumulative learning between in-house R&D and external sources of innovation. Moreover, network structure of R&D generates a multiplicity of scientific stimuli and the adoption of different and complementary R&D management approaches (cf., Coccia, 2014a, 2016b; Henderson, 1994; Jenkins, 2010).

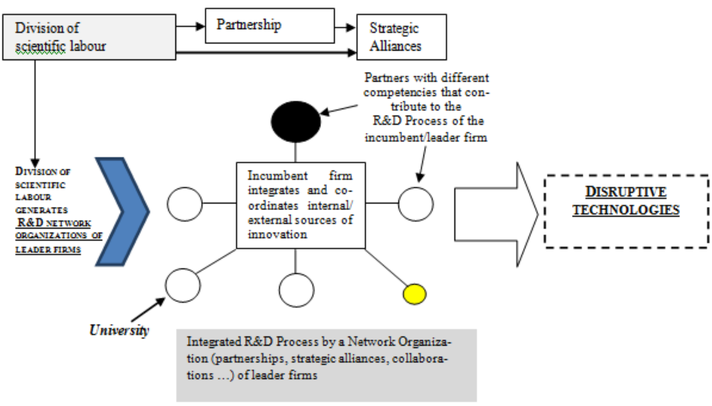

Figure 2. *Network of R&D function of disruptive firms to support new technologies in innovative industries.*

Generalization of characteristics of disruptive firms that generate technological and industrial change

The industrial dynamics shows that the theory of disruptive technology seems to be not consistent for explaining the R&D and diffusion of major innovations in main sectors such as ICTs and biopharmaceuticals. The inductive study here suggests that patterns of technological innovations in markets are dominated by incumbents rather than entrant firms, which have not the market power and structure to support path-breaking innovations across markets (Coccia, 2014a, 2015, 2016b, Daidj, 2016; Liao, 2011). In short, this study proposes the shift of the locus of one of basic causes of technological change, from disruptive technologies to disruptive firms that support path-breaking innovations and market shifts.

The case study research here reveals some general characteristics of disruptive firms that generate technological change. In particular, 1- Large size, associated to a strong market power that supports an industrial leadership.

2- Disruptive firms can or cannot generate radical and/or incremental innovations but they have the market power to spread and support new technology in markets generating industrial change.

3- Forward-looking executives seeking to pioneer radical innovations in competitive markets.

4- High R&D investments to lead the markets towards new technological trajectories, sustain competitive advantage, the goal of a (temporary) profit monopoly and industrial leadership.

5- A long historical presence and expertise in the industry for many years (e.g., more than 40 years). The historical development path in industries supports the accumulation of technological knowledge, technical expertise and experience in the sector, more and more important for R&D and strategic management.

6- Organizational and managerial behavior based on competence-destroying and competence-enhancing.

7- Strong dynamic capabilities based on combinations of competences and resources that can be developed, deployed, and protected in order to stress exploiting existing internal and external firm specific competences and to address changing environments.

8- R&D organization of disruptive firms is more and more based on a division of scientific labour. Network R&D organizations reinforce integrative capabilities, collective and cumulative learning between in-house R&D and external sources of innovation. Moreover, strategic alliances and partnership with innovative firms, university labs and suppliers support learning processes, accumulation of new knowledge and acceleration of innovation processes.

Concluding observations

The theoretical framework of disruptive technologies seems that does not explain the dynamics of technological and economic change (cf., Christensen, 1997). The study here endeavors to clarify, whenever possible, one of driving forces of technological change based on the role of leader firms, called disruptive firms. The central contribution of this work is an approach that integrates current frameworks in management and industrial organization to explain the sources of industrial and technological change (Cooper 1990; Dosi, 1988; O'Reilly III & Tushman, 2004; 2008).

In general, firms have goals, such as achieve and sustain competitive advantage (Teece *et al.,* 1997).

One of the main organizational drivers of disruptive firms is the incentive to find and/or to introduce innovative solutions in new products, using new technology, in order to reduce costs, achieve and support the goal of a (temporary) profit monopoly and market (industrial) leadership. Case study research here also shows that R&D management of leading firms has more and more a division of scientific labour directed to accelerate innovation process and develop new technology. Disruptive firms generate significant shifts in markets with an ambidexterity strategy based on competence-destroying and competence-enhancing (cf., Danneels, 2006; Henderson, 2006; Hill & Rothaermel, 2003; Tushman & Anderson, 1986). Moreover, a main role in disruptive firms is also played by "forward-looking executives seeking to pioneer radical or disruptive innovations while pursuing incremental gains" (O'Reilly III & Tushman, 2004, p. 76). In general, disruptive firms, generating path-breaking innovations, grow more rapidly than other ones (Tushman & Anderson, 1986, p. 439).

On the basis of the argument presented in this paper, based on a case study research, we can therefore conclude that one of principal sources of technological and economic change is due to leading subjects, disruptive firms, which can be the distal sources of disruptive innovations in competitive markets, ceteris paribus. Disruptive firms have specific dynamic capabilities that generate learning processes, a vital cumulative change and path dependence in innovative industries (cf., Garud *et al.,* 2010; Teece *et al.,* 1997).

The results of the analysis here are that:

The conceptual framework here assigns a central role to leading firms (subjects) –disruptive firms- rather than disruptive technologies (objects) to sustain technological and economic change.

Disruptive firms are firms with market leadership that deliberate introduce new and improved generations of durable goods that destroy, directly or indirectly, similar products present in markets in order to support their competitive advantage and/or market leadership. These disruptive firms support technological and industrial change and induce consumers to buy new products to adapt to new socioeconomic environment.

The establishment and diffusion of disruptive technologies in markets are mainly driven by incumbent (large) firms with a strong market power. However, small (entrant) firms can generate radical innovations but they have to cope with high economic resources needed for developing new technology (cf., Caner *et al.*, 2016). This financial issue explains the strategic alliances and partnerships between some incumbent and entrant firms to develop disruptive technologies. These collaborations mark a new phase in business development of innovations.

Finally, the conceptual framework here also shows that R&D management of disruptive firms is more and more based on a division of scientific labor directed to reinforcing the integrative capabilities and collective learning between internal and external sources of innovation in order to accelerate discovery process.

Overall, then, the conceptual framework here, has several components of generalization that could easily be extended to explain the source of technological and economic change. To conclude, this study suggests that one of principal sources of industrial change is due to disruptive firms in competitive markets. To put it differently, this study provides a preliminary analysis of driving forces of technological change based on disruptive firms rather than disruptive technologies per se. However, the conclusions of this study are of course tentative. Most of the focus here is based on a case study research, clearly important but not sufficient for broader understanding of the complex and manifold sources of technological change. Moreover, the evidentiary basis of this paper is also weak, but this study may form a ground work for development of more sophisticated theoretical and empirical analyses to explain, whenever possible general causes of the technological and economic change. Hence, there is need for much more detailed research to explain the reasons for technological change in industries because we know that, in competitive markets with market dynamism, other things are often not equal over time and space. In fact, Wright (1997, p. 1562) properly claims: "In the world of technological change, bounded rationality is the rule".

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6 Superpowers and evolution of technology for socioeconomic change

Introduction

Superpowers are nations with a high economic-war potential and the ability and expertise to exert influence on other geoeconomic regions at global level to achieve and/or support their global leadership also with conflict development and/or resolutions.

Superpowers or great powers or leader countries (these terms can be used interchangeability) have aa scientific and technological superiority that plays a vital role during conflicts (cf., Coccia, 2015, 2017, 2017a, 2017b; Mendershausen, 1943; Smith, 1985). Stein & Russett (1980) argue that the strength of superpowers is due to a superior "military sophistication" that can support the final victory in wars. A better investigation of the role of superpowers needs to clarify the war economy and consequences associated with conflict development and resolutions ("resolution means to employ behaviour used in similar situations, adapted if necessary, so as to obtain an outcome that is good enough", Ackoff & Rovin, (2003, p.9). In particular, international conflicts guided by superpowers influence negatively and/or positively some economic processes in a permanent way. In fact, superpowers can develop conflicts to have fruitful socioeconomic consequences in the long run (Mendershausen, 1943). Neurath (1919) showed the stimulating effect of conflicts developed by superpowers on long-run technical and organizational progress of countries (cf., Hirst, 1915, p. 3ff; Kramer *et al.,* 2009). Recently, some social scientists have paid more attention to effects of wars driven by superpowers on technology and economic growth (cf., Ruttan, 2006; Mowery, 2010; Coccia, 2018; Coccia, 2005, 2009, 2010, 2010a, 2010b, 2010c, 2011, 2014, 2014a, 2014b, 2014c, 2014d, 2015, 2015a, 2015b, 2017, 2017a, 2017b, 2018, 2018a, 2018b, Coccia & Benati, 2018; Coccia & Bellitto, 2018; Coccia & Cadario, 2014; Coccia & Rolfo, 2010; Coccia *et al.,* 2015). Conflict development by superpowers can support both technological innovations and other types of innovations (Coccia, 2015). For instance, income tax, an innovative fiscal model, is originated in England during Napoleonic wars for restructuring the finance of government for military requirements (cf., Gini, 1921, p.205). In general, global conflicts between superpowersgenerate major socioeconomic consequences and long-term structural change worldwide (Stein & Russett, 1980, p.401; cf., Rasler & Thompson, 1985). In particular, conflict development by superpowers generatesdemand- and supply-side effects for domestic economy and for economies of allied countries. The demand-side effects of conflictsare a huge demand shock based on a massive increase in deficit spending and expansionary policy (cf., Field, 2008). In fact, conflict establishes main technological, economic and infrastructural preconditions for an "age of high mass consumption" (Rostow, 1959, pp.11-13). The demand effects generated by conflicts are coupled to powerful supply-side effects: learning by doing in military production, spin-off and spillover from military R&D, etc. These factors suggest a positive effect of military conflicts on output, productivity and technological growth of superpowers and inter-related countries (cf., Baumol, 1986; Ruttan, 2006). For instance, Wright (1997, p.1565) examines the "American technological leadership" and shows that critical manufacturing sectors for U.S. economy have taken advantages from fruitful demand- and supply-side effects of conflicts.Superpowers influence profoundly economic systems worldwide and with conflict development and/or resolutions can generate economic shocks for participants and neutral nations (Goldstein, 2003, p.215). In fact, superpowers, developing conflicts, induce R&D investments to produce military technologies that are transferred to civilian applications in the long term. The mobilization of human and economic resources by superpowers for conflict development increases the rates of inventions and technological innovations that in the post-war period are diffused to support long-run economic growth (Stein & Russett, 1980, p.412; Coccia, 2015)[4].

The consequences of conflict development and/or resolution also play a vital role in the distribution of power within international system (Modelski, 1972; cf., Levy, 1983; 2011). As a matter of fact, the conflict development and/or resolution by superpowers can fundamentally change the hierarchy of power between nations in the international system (Modelski, 1972, p.418). Modelski (1972, p.48) asserts that the "war causes the Great Powers", such as Roman Empire over 200BC ~ 400AD, Britain Empire in the 1710-1850 period, the USA from 1940s onwards, etc. (Stein & Russett, 1980).

Kindleberger (1989, p.203) argues that: The Thirty Years war from 1618 to 1648, culminating in the economic dominance of the Netherlands, from French revolutionary and Napoleonic wars from 1792 to 1815, ending in the Great Britain at the apex of the world economy, and the combined World Wars I and II, from 1914 to 1945 that led to the United States taking over as the world's leading economic power

Several nations have lost their status of superpower or imperial leadership as result of conflicts (e.g. Austria-Hungary in 1918; Italy in 1944; Germany and Japan in 1945; cf., Stein & Russett, 1980). Major conflicts between superpowers produce changes in the global leadership of world economy and affect "hegemonic cycles", which are longer than 150 years (Kindleberger, 1989, p.203ff; cf., Kennedy, 1987; Cipolla, 1970; Coccia, 2018; Olson, 1982). Hence, superpowers, winning international conflicts, can achieve and/or sustain a global leadership on wide geoeconomic regions (Coccia, 2015, p.203).

[4] cf., Coccia, 2005a, 2015b, 2016, 2017b, 2018e, 2018f

Linstone (2007, p. 115) states that: "the winner in each case became the leading global power, a new global political economy emerged, and democracy advanced" (cf., Devezas, 2006; Linstone, 2007a, 2010). In this context, superpowers are: "large-scale political organizations that might usefully be studied as complex systems. But they are also products of their age, and must be examined in the context of their time and place" (Modelski, 2010, p.1418).

Modelski (2010, p.1419) also argues that:

Empires are not the only form of large-scale political organization…. two other forms, global leadership (other terms used for it include hegemony – Greek for leadership – and global primacy), and ... global organization… (Britain) is a case of global leadership that toward the close of its trajectory exhibited imperial features. The United States, too, in relation to the world system, is an instance of global leadership. And global leadership can be seen as a transitional form evolving in the direction of enhanced global organization.

Ferguson (2010) notes that after the World War II, the U.S. assumes the global leadership, replacing U.K. and "shifting from an informal to a formal empire much as late Victorian Britain once did" (as quoted by Modelski, 2010, p.1419). As a matter of fact, Ferguson (2010) claims that the United States is similar to an Empire with a military, political, economic and technological leadership worldwide recognized. Instead, Modelski (2010, pp.1419-1420, original emphasis) argues that the United States have a network-based structure, which is oriented to long-distance trade in world system: "inclining at times to the temptations of 'informal empire' but in its basically non-imperial organization capable of responding flexibly to international crises… its proper name is global leadership, an evolutionary, and therefore transitional form capable of adaptation and self-transformation in response to mounting global problems". Finally, imperial aspirations with conflict development of superpowers are impracticable in current world, which is increasingly global, complex, turbulent, rich, interconnected and multilevel; the only feasible strategy of superpowers with conflict development is to achieve/sustain a global leadership based on economic and technological performances higher than other competitive nations (cf. Modelski, 2010, p.1419ff).

A possible relation between superpowers, conflict development and human progress

In general, the conflict development by superpowers has several negative effects, but it also seems to have a crucial connection with the progress in societygenerated by strategic investments in science and technology to solve relevant problems and to achieve/support global leadership (Coccia, 2015). Stein & Russett (1980) argue that conflict is one of the engines that propels economic change and supports progress in society. The conflict development by superpowers appear to be necessary phases for human development, which is not a monotonous and linear but rather a disequilibrium process of the dynamics of world system (cf., Bobbio, 1965; Gini, 1921; 1959). The conflict development by superpowers can be also due to prove military and scientific superiority towards other belligerent nations. At the same time, conflict development by superpowers stimulatesnew technology and innovation that, after conflicts, can be spread in wide geoeconomic regions (Coccia, 2015). In fact, superpowers, under environmental tensions and consequential environmental threats, have the incentive to exploit, particularly, the newest and less known discoveries and inventions in science and technology (cf., Gini, 1921; Coccia, 2015). Hence, the technological progress of societies seems to be associated with socioeconomic shocks (e.g., international conflicts) governed by superpowers, which generate long-run structural changeon wide socioeconomic systems (Coccia, 2015).

Technological change would be vastly different and economic development would be substantially delayed without strategic (also military and defense-related) investments for conflict development and resolution by superpowers to achieve/sustain a global leadership. In fact, relevant needs and strategic problems for supporting the global leadership of superpowers are a strong incentive for generating new technology, which supports social, technological and economic change (Figure 1).

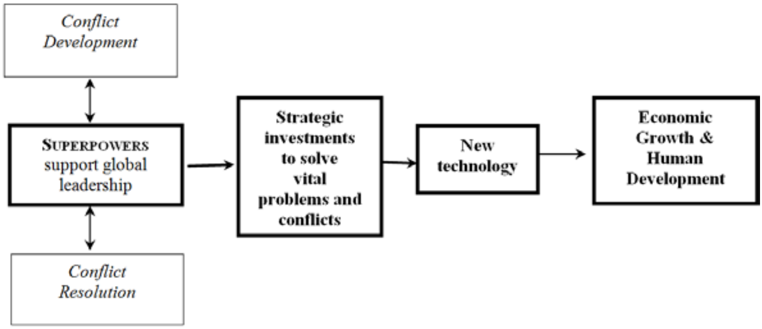

Figure 1. *Role of superpowers in conflict development and resolution for achieving and sustaining global leadership*

Hence, the role of superpowers in conflicts development and resolution is associated with the purpose of global leadership that in the presence of (effective or potential) environmental threats can generate new technology and historical paths of development (Coccia, 2015, 2017, 2017a).

Overall, then, superpowerstend to be a vital driving force of social, technical and economic change that supports human development in society (Coccia, 2015).

Conclusion

Development and resolution of international conflictsbetween superpowers are a major agent of social change with effects on individuals, groups, nations, societies and international systems (Stein & Russett, 1980). In fact, Coccia (2015) shows that long-term evolution of societies and human development is a process of disequilibrium governed by purposeful superpowers directed to achieve/sustain global leadership also with conflict development.

In the context of a World-Systems Theory, superpowers generate a power hierarchy between core and periphery, in which powerful and wealthy "core" societies dominate and exploit weak peripheral societies (Wallerstein, 1974; cf., Skocpol, 1977). The role of superpowersis based on dominant capitalist classes that want state protection for industry and their control of international trade. In fact, capitalists within superpowers want, need, and get the extra-economic assistance to satisfy their world market opportunities and maximize profit of international trade (Skocpol, 1977, pp.1076-77).

An economic boundary of superpowers is high expenditures to copy with conflict development. The high military expenses can increase public debt, create socioeconomic problems and possible economic shocks within superpowers (cf., Ferguson, 2003; 2010). Kennedy (1987, pp.539-540) argues:

To be a great power—by definition, as a state capable of holding its own against any other nation—demands a flourishing economic base… Yet by going to war, or by devoting a large share of the nation's ''manufacturing power'' to expenditures upon ''unproductive'' armaments, one runs the risk of eroding the national economic base… maintaining at growing cost the military obligations they had assumed in a previous period

Moreover, superpowersmay assume a worldwide role close to autocracy in order to sustain the global leadership with a behavior prone to a permanent "wartime" and strains in different geoeconomic regions (Linstone, 2007, p.237). Anyhow, superpowerscan also act as a worldwide referee for conflict resolution across nations to support geo-political equilibria and stability. Davis *et al.,* (2012, p.8) argue that: "The United States has an interest in dissuading military competition wherever it might arise… U.S. forward military presence displaying U.S. conventional superiority" (cf., Posen, 2003; The White House, 2010; U.S. Department of Defence, 2012).

Overall, then, superpowers have a vital role in world systems with conflict development and resolution that are directed to achieve/sustain global leadership to cope with consequential environmental threats and/or to take advantage of important economic opportunities worldwide. This role tends to generate economic, technological and social change and, as a consequence, human development in the long run.

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ISBN: 978-605-7602-88-6 (e-Book)
KSP Books 2019

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