Journal of
Social and Administrative Sciences
www.kspjournals.org
Volume 4 December 2017 Issue 4

The Fishbone diagram to identify, systematize and analyze the sources of general purpose technologies

By Mario COCCIA †

Abstract. This study suggests the fishbone diagram for technological analysis. Fishbone diagram (also called Ishikawa diagrams or cause-and-effect diagrams) is a graphical technique to show the several causes of a specific event or phenomenon. In particular, a fishbone diagram (the shape is similar to a fish skeleton) is a common tool used for a cause and effect analysis to identify a complex interplay of causes for a specific problem or event. The fishbone diagram can be a comprehensive theoretical framework to represent and analyze the sources of innovation. Fishbone diagram is applied here as a novel graphical representation to identify, explore and analyse whenever possible, the potential root causes of the source and evolution of General Purpose Technologies (GPTs). Overall, then, fishbone diagram seems to be an appropriate and general technique of graphical representation to explore and categorize, clearly and simply, the potential root causes of the evolution of technological innovations for an appropriate management of technology.
Keywords. Fishbone diagram, General purpose technology; Source of technical change, Management of technology, Technology evolution, Evolution of technology.
JEL. B40, O31, O33.

1. Introduction

Technological progress has a great weight in supporting patterns of economic growth over the long run (Helpman, 1998; Coccia, 2005b; 2007; 2009a; 2010a; 2010b; Ruttan, 2001; Rosenberg, 1982). A main element of the technical progress is the path-breaking innovations, which make prior technical knowledge obsolete and sustain industrial change (Sahal, 1981; Colombo *et al.,* 2015). A path-breaking innovation is the General Purpose Technology (GPT), which is one of the contributing factors of the long-run technological and economic change in society (Bresnahan, 2010). The GPTs are enabling technologies for a pervasive use in many sectors to foster new products and processes (Helpman, 1998). The GPTs generate changes of techno-economic paradigm ("Technological Revolutions"), which affect almost every branch of the economy (Freeman & Soete, 1987: 56-57) and support the "secular process of growth" (Bresnahan & Trajtenberg, 1995: 83; *cf.* Helpman, 1998; Lipsey *et al.,* 1998). Ruttan (2006) argues that GPT is basic to sustain productivity and economic growth of nations over time.

The driving forces of GPTs are different from those that support other innovations of less intensity (Helpman, 1998; Ruttan, 1997; Lipsey *et al.,* 1998, Coccia, 2005, 2005a; 2010, 2014, 2014a; 2015; Schultz & Joutz, 2010). Scholars have described several approaches to explain the source of technical change and technological evolution (*cf.* Wright, 1997; Hall & Rosenberg, 2010; Helpman, 1998:. 2; Coccia, 2015; Wang *et al.,* 2016; Li, 2015; Robinson *et al.,* 2007; von

[a†] Arizona State University, Interdisciplinary Science and Technology Building 1 (ISBT1) 550 E. Orange Street, Tempe- AZ 85287-4804 USA.
☎. + 85287-4804
✉. mario.coccia@cnr.it

Hippel, 1988), however, an appropriate visualization technique for identifying and analyzing the potential root causes of general purpose technologies (GPTs) is hardly known. In particular, a problem is to represent in a comprehensive theoretical framework the several drivers of General Purpose Technologies (GPTs) that support the technological evolution for technological and economic change in society over the long run (*cf.* Ruttan, 1997; 2006).

The study here confronts this scientific problem by using a graphical representation with the fishbone diagram, which seems to be an appropriate visualization technique for categorizing and analyzing the complex determinants of the technological evolution of GPTs over time. The main aim of this study is therefore to provide a novel graphical representation to explore whenever possible, the potential root causes of the source and evolution of general purpose technologies (GPTs) that explain the economic change in society.

2. Conceptual grounding

General Purpose Technologies (GPTs) are revolutionary changes from current technological trajectories (Bresnahan, 2010:763-791). These path-breaking innovations are mainly of transformative nature and generate a "destructive creation" (Calvano, 2007), which makes prior products and knowledge obsolete (*cf.* Colombo *et al.,* 2015). Lipsey and colleagues (1998:43) define the General Purpose Technology: "a technology that initially has much scope for improvement and eventually comes to be widely used, to have many users, and to have many Hicksian and technological complementarities". GPTs are enabling technologies that exert a pervasive impact across firms, industries and that permeate the overall structure of the economy (Coccia, 2005, 2010a). The diffusion of GPTs is by several ripples of effects that remove barriers and generate significant techno-economic change in society with new communications and transportation technology. Coccia (2005) classifies the GPTs, in the scale of innovation intensity with the highest degree of socio-economic impact. In particular, Coccia (2005, pp. 123-124) claims, referring to revolutionary innovations, such as GPTs, that:

> The means of human communication are radically changed and a new means of communication, which heavily affects all the economic subjects and objects, is born, forcing all those who use it to change their habits. A new technoeconomic paradigm is born… The propulsive capacity for development offered by seventh-degree innovation is so high that it hauls the entire economy. Thanks to the new methods of communication, there is also greater territorial, social, and human integration. Another characteristic of seventh-degree innovations is the ease of their spread. The mobility of people, goods, capital, and information increases and the time taken to travel and communicate is reduced.

Bresnahan & Trajtenberg (1995: 86-87) show that GPTs have a treelike structure with basic new technology located at the top of the tree and all derived technologies, for several industries, radiating out towards every branch of the economy. In fact, the General Purpose Technologies generate clusters of new technology in several industries because they are general mechanisms and/or components and/or infrastructure for the architecture of various families of products/processes that are made quite differently. The different applications of new GPTs are driven by firms to maximize the profit and/or to exploit the position of a (temporary) monopoly in different sectors and industries over time (Coccia, 2015).

In general, GPTs are characterized by pervasiveness, inherent potential for technical improvements, and 'innovational complementarities', giving rise to increasing returns-to-scale, such as the steam engine, the electric motor, and semiconductors (Bresnahan & Trajtenberg, 1995: 83, original emphasis)[1].

[1] *cf.* also Lipsey *et al.,* 2005; Bresnahan, 2010; Ristuccia & Solomou, 2014; Goldfarb, 2005.

Jovanovic & Rousseau (2005: 1185) show that the distinguishing characteristics of a general purpose technology are: (1) *Pervasiveness*: "The GPT should spread to most sectors". It has an impact on technical change and productivity growth across a large number of industries; (2) *Improvement*: "The GPT should get better over time and, hence, should keep lowering the costs of its users". It should lead to sustained productivity growth and cost reductions in several industries; (3) *Innovation spawning*: "The GPT should make it easier to invent and produce new products and processes" (*cf.,* Bresnahan & Trajtenberg, 1995). Lipsey *et al.,* (1998: 38) describe other main characteristics of GPTs, such as: the scope for improvement, wide variety and range of uses during its evolution and strong complementarities with existing or potential new technologies. Another main feature of GPTs is a long-run period between their initial emergence as invention and final commercial introduction in new products (Lipsey *et al.,* 1998; 2005). Rosegger (1980: 198) showed that the estimated time interval between invention and major innovation is about 50 years: *e.g.* electric motor is about 58 years, electric arc lights 50 years, telegraph about 44 years, synthetic resins 52 years, etc. Overall, then, GPTs are a complex technology that induce and affect other technological innovations/products and/or construct a long-run platform in communications and energy systems for corporate, industrial, economic and social change over time (Coccia, 2015). Electricity power, information and communications technology are regarded as the prototypic General Purpose Technologies (Jovanovic & Rousseau, 2005).

3. Study design and methodology

Firstly, to develop a theoretical framework for the technological analysis and representation of the evolution of GPTs over the long run,this study describes complex drivers of GPTs with a general overview of the socio-economic literature. *Secondly*, this study systematizes the *plexus* (interwoven combination) of drivers of GPTs by using a fishbone diagram, which can provide an appropriate visual representation of determinants underlying source and evolution of GPTs. Fishbone diagrams (also called Ishikawa diagrams or cause-and-effect diagrams) is a graphical technique to show the several causes of a specific event or phenomenon (fig. 1). In particular, a fishbone diagram (the shape is similar to a fish skeleton) is a common tool used for a cause and effect analysis to identify a complex interplay of causes for a specific problem or event. This causal diagram was created by Ishikawa (1990) in the research field of management.

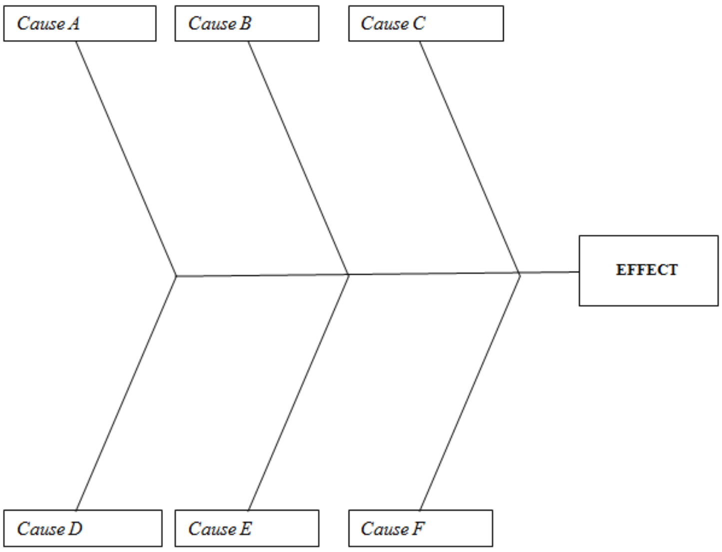


Figure 1. *A Fishbone Diagram*

As a matter of fact, this Cause and Effect Analysis was originally developed as a quality control tool, such as product design and quality defect prevention, to identify potential factors causing an overall effect. Each cause is a source of variation of the phenomena understudy. Causes are usually grouped into major categories to identify the overall sources of variation that lead to a main effect (Fig. 1). In general, the Fishbone diagram can be used as an appropriate visual representation of phenomena that involve the investigation of multiple cause-and-effect factors and how they inter-relate (*cf.* Ayverdia *et al.,* 2014; Buyukdamgaci, 2003; Ishii & Lee, 1996). Ramakrishna & Brightman (1986) compared their own Fact-Net-Model with Fishbone Diagram, and Kepner and Tregoe Method to show perceived differences. Overall, then, it seems that fishbone diagram can be an appropriate tool to represent the inter-related drivers of complex technologies, such as GPTs.

4. A general description of the plexus of determinants generating major innovations

The source and evolution of major innovations (*e.g.* GPTs) depend on complex drivers. Economic literature shows several determinants of GPTs (*cf.* Ruttan, 2006; Bresnahan & Trajtenberg, 1995; Coccia, 2010; 2014; 2014a; 2015; De Marchi, 2016; Scientometrics, 1984). Some of them are discussed as follows.

4.1. Relevant problem

GPTs are naturally directed to solve critical problems to achieve competitive advantages of leading nations (Coccia, 2015) or organizations in certain environments (Atuahene-Gima & Wei, 2011). Usher (1954) explained the evolution of new technology by using the theoretical framework of the Gestalt psychology. Usher's theory of cumulative synthesis is based on four concepts (*see* Basalla, 1988: 23): 1) Perception of the problem: an incomplete pattern in need of resolution is recognized; 2) Setting stage: assimilation of data related to the problem; 3) Act of insight: a mental act finds a solution to the problem; 4) Critical revision: overall exploration and revision of the problem and improvements by means of new acts of insight. This theory focuses on acts of insight that are basic to solve problems and generate vital innovations. The main implications of Usher's theory are the psychological aspects of invention and the evolution of new technology with a vital cumulative change (Basalla, 1988: 24). Coccia (2016) also shows, through an inductive study in medicine, that consequential problems support the evolution of several radical innovations, such as new and path-breaking technological trajectories of target therapy in oncology (*cf.,* Coccia & Wang, 2015).

4.2. Geographical factors and temperate climate

Technological innovation is a vital human activity that interacts with geographic factors and natural environment. Geographical characteristics of certain areas support concentration and location of innovative activities and are also determinants of vital technological innovations (Krugman, 1991). The new geography of innovation analyses several spatial factors relating to the origin and diffusion of technological innovation, *e.g.,* spatial proximity and agglomeration (Rosenberg, 1992; Smithers & Blay-Palmer, 2001; Howells & Bessant, 2012). In particular, new economic geography argues that "*all* production depends on and is grounded in the natural environment" (Hudson, 2001: 300). Feldman & Kogler (2010) claim that the natural advantages of resource endowments and climate in certain places can induce innovationand economic growth (*cf.,* Moseley *et al.,* 2014). Lichtenberg (1960) shows that geographical factors, rather than proximity to raw materials or markets, influence the production of knowledge and the cumulative nature of several innovations. Audretsch & Feldman (1996) confirm that the agglomeration of innovative activities and firms is related to advantages in the natural environment, such as available resources and other factors of the physical geography. In general, the concentration of human and natural resources is in specific geographical places, such as major cities, long known to be society's predominant engines of innovation and growth (Bettencourt *et al.*, 2007). The climate is also a main geographical factor that affects natural resources, natural environment and human activities, such as the technical change. Long ago, Montesquieu (1947[1748]) argued that the climate shapes human attitude, culture and knowledge in society. Recent economic literature shows that warm temperate climates have an appropriate natural environment for humans that, by an evolutionary process of adaptation and learning, create complex societies, efficient institutions and communications systems. This socio-economic platform supports, in temperate latitude, the efficient use of human capital and assets that induce inventions, innovations and their diffusion over time and space (Coccia, 2015a).

4.3. Cultural and religious factors

Barro & McCleary (2003: 760) argue that: "successful explanations of economic performance must go beyond narrow measures of economic variables to encompass political and social forces".In fact, modern literature is also analyzing social forces of economic development such as the culture (*e.g.* Guiso *et al.,* 2006: 23; Maridal, 2013). Weber (1956) discussed how the Protestant religious culture has affected the economic attitude of people and the entrepreneurship of capitalistic systems. Current socio-economic research also analyses the religion and culture as basic drivers of economic growth and innovation (*cf.* Barro & McCleary, 2003; 2005; Guiso *et al*., 2006; Spolaore & Wacziarg, 2013; Coccia, 2014). Guiso *et al.* (2003) show the interplay between intensity of religious beliefs and people's attitudes that are conducive to economic growth (*e.g.,* cooperation, trust, thriftiness, government, institutions, women's propensity to work, legal rules, and fairness of the market). In particular, Guiso *et al.* (2003: 225): "find that on average, religious beliefs are… conducive to higher per capita income and growth… Christian religions are more positively associated with attitudes conducive to economic growth" (*cf.* Bettendorf & Dijkgraaf, 2010). Religion shapes people's attitude of mind, education, culture and institutions of countries and likely is also a main socio-cultural determinant of the patterns of technological innovation (Coccia, 2014). A study displays that, on average, societies with a predominance of the Protestant, Jewish and Eastern religions have technological performance higher than societies with other predominant religious cultures. These results may be due to fruitful relation between religion and higher education institutions of countries that support high human capital. In addition, a higher religious fractionalization in advanced society, *ceteris paribus*, has a positive effect on technological outputs. This appears to be particularly true among richer and more democratic countries, which are mainly located in the European and North-American geo-economic areas (Coccia, 2014). However, these findings are tentative and there is need for much more detailed research into the relations between religion, culture and innovation patterns.

4.4. Population and demography

Population growth plays a main role for patterns of technological innovation. Kuznets (1960) claims that: "high population spurs technological change because it increases the number of potential inventors" (as quoted by Kremer, 1993). In particular, Kuznets (1960: 328) states: "Population growth… produces an absolutely larger number of geniuses, talented men, and generally gifted contributors to new knowledge whose native ability would be permitted to mature to effective levels when they join the labor force".Moreover, Kuznets (1960) and Simon (1977) argue that high populations have a higher probability to create potential inventors because larger populations have proportionally more individuals with new ideas. In fact, Jones states that: "'More people means more Isaac Newtons and therefore more ideas'" (as quoted by Strulik, 2005: 130). Moreover, many inventions and innovations are demand-driven by larger population, and an active demographic change and high population can play a vital role for supporting patterns of technological innovation in advanced national systems of innovation (Boserup, 1981: 5; Coccia, 2014a). Some studies also show that an optimal level of technological performance in advanced nations is due to positive growth rates of population but lower than 1% (percentage of annual population growth rates, Coccia, 2014a). This result confirms the study by Strulik (2005: 129) that: "long-run growth is compatible with a stable population".

4.5. Major wars and environmental threats

Ruttan (2006) argues that the war may be one of contributing factors that generates GPTs. In general, the high mobilization of scientific, technical, and financial resources during major conflicts might support GPTs. In particular, a major war, or threat of a major war, may be a vital condition to induce political and economic institutions of great powers to commit the huge resources necessary to generate and/or sustain the development of new path-breaking technologies directed to provide a competitive advantage in aversive environments (Ruttan, 2006). Hence, Ruttan (2006: 184) argues that a *war* and/or *a threat of a majorwar* can support the development of strategic GPTs that subsequently generate clusters of commercial innovations for the economic progress in society.

4.6. Purpose of global leadership

Coccia (2015) shows that the source of strategic GPTs is, *de facto*, due to purposeful systems (*e.g.* leading countries), with high economic potential and purposeful institutions having the purpose of achieving/sustaining a global leadership that can engender GPTs to cope with consequential environmental threats and/or to take advantage of important environmental opportunities. Coccia's (2015) theory generalizes the Ruttan's approach, developing the theoretical framework of global leadership-driven innovation: GPTs are originated by the purpose of the global leadership of great powers, rather than wars *per se*.

In short, this theory by Coccia (2015) stresses the thesis that the source of GPTs is due to the purpose of global leadership of great powers which generates a main impetus for solving relevant and strategic problems during military and political tensions, such as during the struggle to prove scientific and technological superiority, and military strength in space between U.S. and Soviet Union in the 1960s. This struggle for global leadership has generated major advances in ICTs and satellite technology, which are main GPTs in society. Another main example is given by U.S. Navy's Mobile User Objective System, a current GPT to support U.S. global leadership and, as a consequence, human progress (Coccia, 2016a).

4.7. Democratization

Democracy can be seen as a set of practices and principles that institutionalize and protect freedom (Modelski & Perry, 2002; Norris, 2008). Barro (1999: 160) points out that "increases in various measures of the standard of living forecast a gradual rise in democracy". Acemouglu *et al.,* (2008) analyze the relationship between income per capita and democracy and argue that political and economic development paths are interwoven. Coccia (2010) shows that democratization is an antecedent process (cause) to technological and economic change by historical and statistical analyses. In particular, democratization seems to be a main driving force for technological change: most free countries, measured with liberal, participatory, and constitutional democracy indices, have a level of technological outputs higher than less free and more autocratic countries. As a matter of fact, it seems that "democracy richness" generates a higher circulation of information and appropriate higher education systems that, in advanced countries, support high human capital for fruitful patterns of technological innovation with fruitful effects for the wellbeing and wealth over the long run (Coccia, 2010).

4.8. Research policy and national system of innovation

Governments in advanced economies devote much policy attention to enhancing investment in R&D to support the technical progress. In fact, R&D plays a key role for supporting both technical innovation and economic growth of modern economies, and includes expenditures by the industry, government, higher education and private non-profit sectors (*cf.* Jones & Williams, 1998: 1133*ff*; Coccia, 2012).

Griffith *et al.,* (2004) display that R&D has a direct effect on the growth of the Total Factor Productivity (TFP) across several OECD countries. Instead, Mamuneas & Nadiri (1996, p.57) claim that: 'The optimal mix of… [incremental R&D tax credit and immediate deductibility provision of R&D expenditures] is an important element for sustaining a balanced growth in output and productivity in the manufacturing sector''. Zachariadis (2004) investigates the relationship between TFP and R&D investment and finds a positive relation between these variables (*cf.* Goel *et al.*, 2008). Instead, Coccia (2012) shows that when R&D spending of business enterprise sector exceeds R&D spending of government sector, the labor productivity and GDP tend to growth, *ceteris paribus*. Moreover, a range of R&D investment as percentage of GDP between 2.3 per cent and 2.6 per cent seems to maximize the long-run impact on productivity growth of advanced countries (Coccia, 2009). This finding is the key to explain the political economy of R&D for sustained productivity, accumulation of scientific and technical knowledge, as well as of technology improvements that are becoming more and more necessary to modern economic growth of nations over time.

5. A comprehensive theoretical framework to represent the drivers of GPTs: the Fishbone diagram

This study suggests a comprehensive theoretical framework to represent and analyze the drivers of GPTs that explain the social and economic change over time. In particular, an appropriate visual representation of the complex drivers of major innovations can be the fishbone diagram. Figure 2 shows this comprehensive theoretical framework (Fishbone diagram) to explain the source and evolution of GPTs over time.

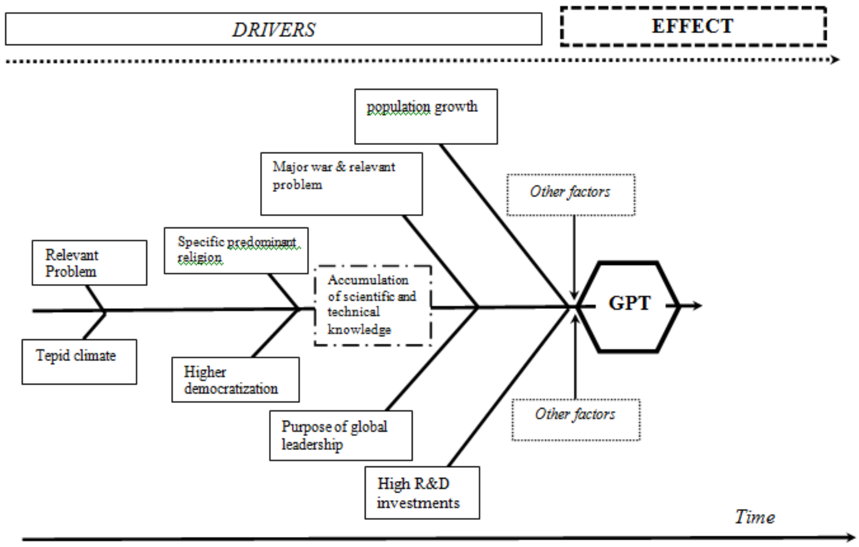


Figure 2. *Determinants of the source and evolution of GPTs in advanced nations represented with the fishbone diagram.*
Note: GPT = General Purpose Technology

In particular, the fishbone diagram in Figure 2 shows that the source of GPTs is due to a complex interplay of causes represented at left, which support the evolution of GPTs (hexagon at right). Firstly, the presence of relevant problems in temperate climate for advanced countries with socioeconomic potential is the first stage for laying the foundations for a GPT. This condition is a necessary, but not a sufficient factor because the GPTs need specific socioeconomic and cultural background represented by high level of democratization and specific predominant religions, such as Protestant religion that can fruitful affect the higher education system and culture of human resources in society. However, an appropriate socioeconomic background is an important base for the source of major innovations but GPTs thrive mainly when great powers have to achieve and/or support the purpose of global leadership to cope with consequential environmental threats and/or take advantage of important opportunities (*e.g.,* during major conflicts/threats and/or struggle to prove scientific superiority and military strength). These factors are supported by an efficient and strong national system of innovation that invests high economic and human resources to solve relevant problems by creating new technology and, as a consequence, strategic competitive advantages for sustaining patterns of economic growth. In this context, high growth rates of population also play a vital role to support the evolution of leading societies and long-term development of GPT and major technologies.

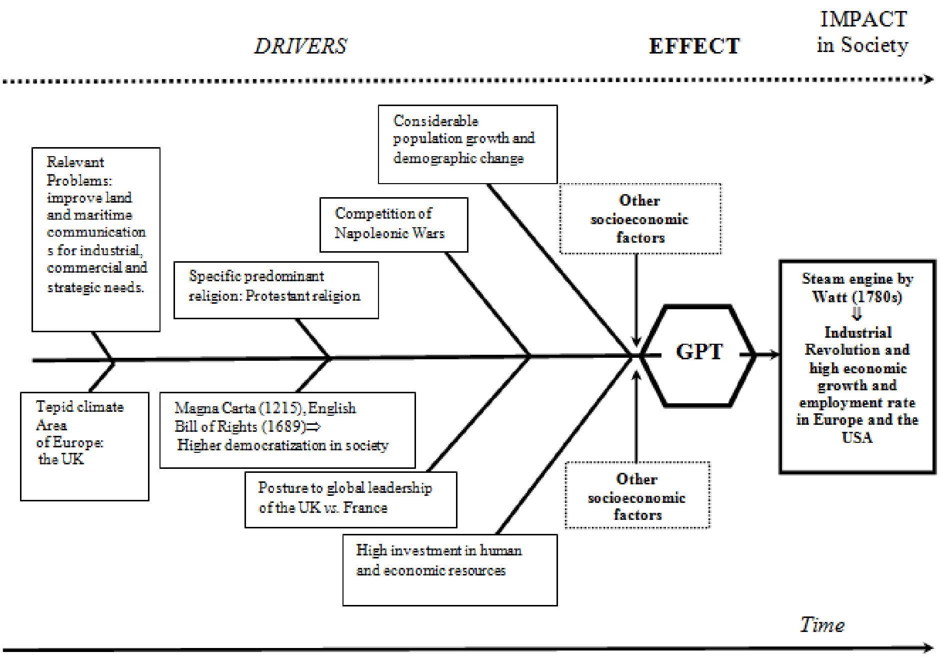
The sequential and complex factors, represented in Figure 2, are basic for the source of GPTs that support long-run human development in society.

A final and important implication of this theoretical framework is that some of the features and determinants that cause GPTs seem to be enduring and invariant properties of human societies, rather than accidental shocks/events (*cf. also* Wright, 2005). Hence, GPTs seem to have regularity in their historical developmental paths driven by specific environment in which great powers, with socioeconomic potential, endeavour to achieve and/or sustain the purpose of global leadership.

6. Examples of fishbone diagrams in history of technology

The source of some GPTs visualized with the Fishbone diagram is represented as follows.

Drivers of Steam Engine in England



IMPACT

Figure 3. *Determinants of the source of Steam engine from 1700s with the fishbone diagram*

The sources of the GPT of Information and Communications Technologies (ICTs) in the U.S. A.

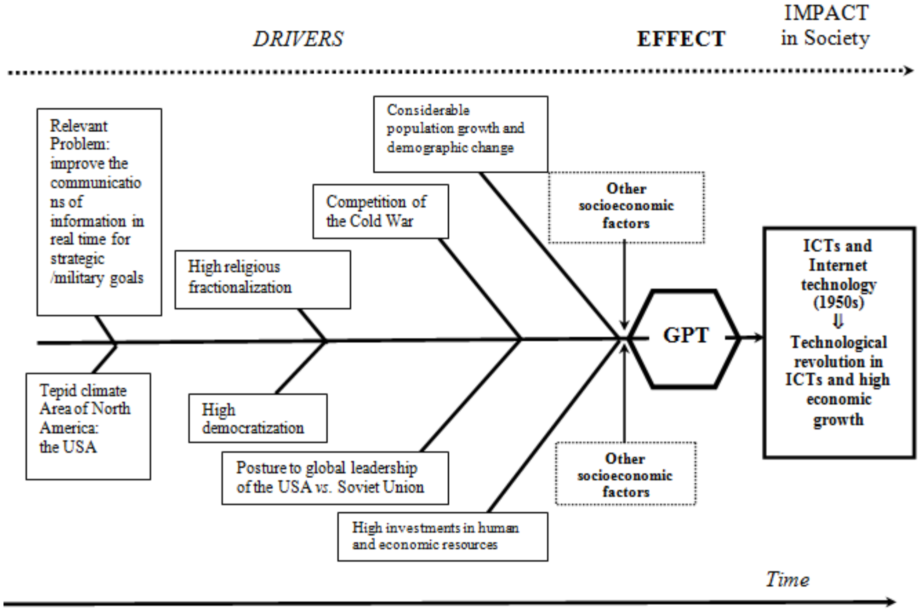


Figure 4. *Determinants of the source of ICTs from 1950s represented with fishbone diagram*

7. Conclusions

History of technology shows that GPTs create strategic platforms for several products/processes such as in communications and transportation technology for lung-run human development (Singer *et al.,* 1956). In general, GPTs are driven by a large number of factors and it is important a simple visual representation for explaining their source and evolution over time. What can be learned from fishbone diagram designed here to represent the determinants of GPTs?

A main finding of this study is that the fishbone diagram offers an appropriate theoretical framework for a visual representation and technological analysis of complex factors of major innovations over time. This tool shows clearly and simply the sequential and inter-related determinants of the source and evolution of GPTs over time and space.

In particular,

(1) The conceptual framework here shows a visual representation of complex and inter-related factors driving GPTs with a cause-effect approach over the long run;

(2) The visual representation here is able to show similar drivers of several GPTs and to detect regularity of sources over time and space;

(3) The visual representation here is able to explain *how* and *why* GPTs thrive in specific geo-economic areas and time period.

The theoretical framework of this study satisfies main concepts of the philosophy of science, such as *consilience, simplicity and analogy* (Thagard, 1988, Chp. 5). In particular,

This conceptual framework seems to be consilient, since it explains a greater number of similar drivers for different GPTs in the history of technology.

The simple elements of the study here are well known in economic and managerial literature. The idea that GPTs is associated to different factors is not new, however, the idea that a fishbone diagram can provide an appropriate visual representation of sequential and inter-related drivers of GPTs has not been used in current literature to display and explain the complex source of major innovations.

The characteristic of *analogy* of results is well-established by using the Fishbone diagram for representing and explaining the source of different major technologies at micro- and macro-level of analysis. In short, the fishbone diagram seems to be a general tool for technological analyses of sources of GPTs and other new technologies.

The findings of this study also show that some determinants of new technology can be contest-dependent, whereas other ones can be invariant factors for the origin of GPTs over time and space. Future research on these topics, to reinforce this study, should (1) focus on additional and intervening factors affecting the source of GPTs; (2) measure the evolution of GPTs and derived technological trajectories by using phylogenetic approaches.

Overall, then, the study here seems to establish a general comprehensive theoretical framework for an appropriate visual representation and technological analysis (the fishbone diagram) of the complex drivers of major innovations over time (*e.g.*, GPTs). However, we know that other things are often not equal over time and place in the history of technology and therefore results here are tentative. In fact, Wright (1997: 1562) properly claims that: “In the world of technological change, bounded rationality is the rule”. More fine-grained studies will be useful in future, ones that can more easily examine other complex predictors of emerging GPTs.

References

Acemoglu, D., Johnson, S., Robinson, J.A., & Yared, P. (2008). Income and democracy, *American Economic Review*, 98(3), 808-842. doi. 10.1257/aer.98.3.808

Atuahene-Gima, K., & Wei, Y. (2011). The vital role of problem-solving competence in new product success, *Journal of Product Innovation Management*, 28(1), 81-98. doi. 10.1111/j.1540-5885.2010.00782.x

Audretsch, D.B., & Feldman, M.P. (1996). R&D spillovers and the geography of innovation and production, *The American Economic Review*, 86(3), 630-640.

Ayverdia, L., Nakiboğlu, C., & Aydın, S.Ö.Z. (2014). Usage of Graphic Organizers in Science and Technology Lessons", *Procedia - Social and Behavioral Sciences*, 116, 4264-4269. doi. 10.1016/j.sbspro.2014.01.929

Barro, R.J. (1999). Determinants of democracy, *Journal of Political Economy*, 107(6), 158-183. doi. 10.1086/250107

Barro, R.J., & McCleary, R. (2003). Religion and economic growth across countries, *American Sociological Review*, 68(5), 760-781. doi. 10.2307/1519761

Barro, R.J., & McCleary, R. (2005). Which countries have state religions, *Quarterly Journal of Economics*, 120(4), 1331-1370. doi. 10.1162/003355305775097515

Basalla G. (1988) *The History of Technology*, Cambridge University Press, Cambridge.

Bettencourt, L.M.A, Lobo, J., Helbing, D., Kühnert, C., & West, G.B. (2007). Growth, innovation, scaling, and the pace of life in cities, *PNAS*, 104(17), 7301-7306. doi. 10.1073/pnas.0610172104

Bettendorf, L., & Dijkgraaf, E. (2010). Religion and income: Heterogeneity between countries, *Journal of Economic Behavior & Organization*, 74(1-2), 12-29. doi. 10.1016/j.jebo.2010.02.003

Boserup, E. (1981) *Population and Technological Change: A Study of Long-term Trends,* University of Chicago Press, Chicago.

Bresnahan, T. (2010). General purpose technologies, *in* B.H. Hall & N. Rosenberg (eds.) *Handbook of the Economics of Innovation,* Ch. 18, Vol. 2, Elsevier.

Bresnahan, T.F., & Trajtenberg M. (1995). General purpose technologies: 'engines of growth'?, *Journal of Econometrics, Annals of Econometrics*, 65(1), 83-108. doi. 10.1016/0304-4076(94)01598-T

Buyukdamgaci, G. (2003) Process of organizational problem definition: how to evaluate and how to improve, *Omega,* 31(4), 327-338.

Calvano, E. (2007). Destructive creation, Stockholm School of Economics. *Working Paper Series in Economics and Finance,* No.653. [Retrieved from].

Coccia, M. (2005). Measuring intensity of technological change: The seismic approach, *Technological Forecasting and Social Change*, 72(2), 117–144. doi. 10.1016/j.techfore.2004.01.004

Coccia, M. (2005a). Technometrics: Origins, historical evolution and new direction, *Technological Forecasting & Social Change*, 72(8), 944-979. doi. 10.1016/j.techfore.2005.05.011

Coccia, M. (2005b). Countrymetrics: valutazione della performance economica e tecnologica dei paesi e posizionamento dell'Italia, *Rivista Internazionale di Scienze Sociali*, CXIII(3), 377-412.

Coccia, M. (2007). A new taxonomy of country performance and risk based on economic and technological indicators, *Journal of Applied Economics,* 10(1), 29-42.

Coccia, M. (2009). What is the optimal rate of R&D investment to maximize productivity growth?, *Technological Forecasting & Social Change,* 76(3), 433-446. doi. 10.1016/j.techfore.2008.02.008

Coccia, M. (2009a). Measuring the impact of sustainable technological innovation, *International Journal of Technology Intelligence and Planning,* 5(3), 276-288. doi. 10.1504/IJTIP.2009.026749

Coccia, M. (2010). Democratization is the driving force for technological and economic change, *Technological Forecasting & Social Change*, 77(2), 248-264. doi. 10.1016/j.techfore.2009.06.007

Coccia, M. (2010a). The asymmetric path of economic long waves, *Technological Forecasting & Social Change,* 77(5), 730-738. doi. 10.1016/j.techfore.2010.02.003

Coccia, M. (2010b). Foresight of technological determinants and primary energy resources of future economic long waves, *International Journal of Foresight and Innovation Policy,* 6(4), 225–232. doi. 10.1504/IJFIP.2010.037468

Coccia, M. (2012). Political economy of R&D to support the modern competitiveness of nations and determinants of economic optimization and inertia, *Technovation,* 32(6), 370–379. doi. 10.1016/j.technovation.2012.03.005

Coccia, M. (2014). Socio-cultural origins of the patterns of technological innovation: What is the likely interaction among religious culture, religious plurality and innovation? Towards a theory of socio-cultural drivers of the patterns of technological innovation, *Technology in Society*, 36(1), 13-25. doi. 10.23760/2421-7158.2017.004

Coccia, M. (2014a). Driving forces of technological change: The relation between population growth and technological innovation-Analysis of the optimal interaction across countries, *Technological Forecasting & Social Change,* 82(2), 52-65. doi. 10.1016/j.techfore.2013.06.001

Coccia, M. (2015). General sources of general purpose technologies in complex societies: Theory of global leadership-driven innovation, warfare and human development, *Technology in Society*, 42, 199-226. doi. 10.1016/j.techsoc.2015.05.008

Coccia, M. (2015a). Patterns of innovative outputs across climate zones: the geography of innovation, *Prometheus. Critical Studies in Innovation*, 33, 165-186. doi. 10.1080/08109028.2015.1095979

Coccia, M. (2016). Problem-driven innovations in drug discovery: co-evolution of radical innovation with the evolution of problems, *Health Policy and Technology*, 5(2), 143-155. doi. 10.1016/j.hlpt.2016.02.003
Coccia, M., & Wang, L. (2015). Path-breaking directions of nanotechnology-based chemotherapy and molecular cancer therapy, *Technological Forecasting and Social Change,* 94, 155–169. doi. 10.1016/j.techfore.2014.09.007
Colombo, M.G., Franzoni, C., & Veugelers, R. (2015). Going radical: producing and transfering disruptive innovation, *The Journal of Technology Transfer*, 4(4), 663-669. doi. 10.1007/s10961-014-9361-z
De Marchi, M. (2016). A taxonomy of S&T indicators, *Scientometrics*, 106(3), 1265–1268. doi. 10.1007/s11192-015-1823-z
Feldman, M.P., & Kogler, D. F. (2010). Stylized Facts in the Geography of Innovation, *in* B. Hall & N. Rosenberg (Eds), *Handbook of Economics of Technical Change*, 1, (pp. 381-410), Elsevier.
Freeman, C., & Soete, L. (1987). *Technical change and full employment,* Basil Blackwell, Oxford, UK.
Goel, R.J., Payne, J.E., Ram, R. (2008). R&D expenditures and U.S. economic growth: A disaggregated approach, *Journal of Policy Modeling*, 30(2), 237–250. doi. 10.1016/j.jpolmod.2007.04.008
Goldfarb, B. (2005). Diffusion of general purpose technologies: understanding patterns in the electrification of US Manufacturing 1880–1930, *Industrial and Corporate Change* 14, 745–773. doi. 10.1093/icc/dth068
Griffith, R., Redding, S., & Van Reenen, J. (2004). Mapping the two Faces of R&D: Productivity growth in a Panel of OECD Industries, *Review of Economics and Statistics,* 86(4), 883–895. doi. 10.1162/0034653043125194
Guiso, L., Sapienza, P., & Zingales, L. (2003). People's opium? Religion and economic attitudes, *Journal of Monetary Economics*, 50(1), 225-282. doi. 10.1016/S0304-3932(02)00202-7
Guiso, L., Sapienza, P., & Zingales, L. (2006). Does culture affect economic outcomes?, *The Journal of Economic Perspectives*, 20(2), 23-48. doi. 10.1257/jep.20.2.23
Hall, B.H., & Rosenberg, N. (2010). *Handbook of the Economics of Innovation,* Vol.1; 2, Elsevier.
Helpman, E. (1998). *General Purpose Technologies and Economic Growth*. MIT Press, Cambridge, MA.
Howells, J., & Bessant,J. (2012). Innovation and economic geography: A review and analysis, *Journal of Economic Geography*, 12(5), 929-942. doi. 10.1093/jeg/lbs029
Hudson, R. (2001) *Producing Places*, Guildford, NY.
Ishii, K., & Lee, B. (1996). Reverse fishbone diagram: a tool in aid of design for product retirement, *Proceedings ASME design engineering technical conferences and computers in engineering conference*, 96-DETC/DFM-1272.
Ishikawa, K. (1990) *Introduction to Quality Control*, Taylor & Francis.
Jones, C.I., & Williams, J.C. (1998). Measuring the social return to R&D, *The Quarterly Journal of Economics*, 113(4), 1119–1135. doi. 10.1162/003355398555856
Jovanovic, B., & Rousseau, P.L. (2005). General purpose technologies, *in* P. Aghion & S.N. Durlauf (Eds), *Handbook of Economic Growth*, Volume 1B. Elsevier.
Kremer, M. (1993). Population growth and technological change: one million B.C. to 1990, *Quarterly Journal of Economics,* 108(3), 681-716. doi. 10.2307/2118405
Krugman, P. (1991). *Geography and Trade*, MIT Press, Cambridge.
Kuznets, S. (1960). Population change and aggregate output, *in Demographic and Economic Change in Developed Countries,* Special Conference Series No.11 Universities-National Bureau for Economic Research (Princeton University Press: Princeton), pp. 324-340. Reprinted in *Economic Growth and Structure: Selected Essays.* New York: W.W. Norton & Co., 1965.
Li, M. (2015). A novel three-dimension perspective to explore technology evolution, *Scientometrics*, 105(3), 1679-1697. doi. 10.1007/s11192-015-1591-9
Lichtenberg, R.M. (I960) *One-tenth of a Nation: National Fortes in the Economic Growth of the New York Region,* Harvard University Press, Cambridge, MA.
Lipsey, R.G., Bekar, C.T., & Carlaw, K.I. (1998). What requires explanation?, *in* Helpman E. (ed.) *General Purpose Technologies and Long-Term Economic Growth,* (pp.15-54), MIT Press, Cambridge, MA.
Lipsey, R.G., Carlaw, K.I., & Bekar, C.T. (2005). *Economic Transformations: General Purpose Technologies and Long Term Economic Growth*, Oxford University Press, Oxford.
Mamuneas, T.P., & Nadiri, M.I. (1996). Public R&D policies and cost behavior of the US manufacturing industries, *Journal of Public Policy,* 63(1), 57–81. doi. 10.1016/S0047-2727(96)01588-5
Maridal, J.H. (2013). Cultural impact on national economic growth, *The Journal of Socio-Economics,* 47, 136-146. doi. 10.1016/j.socec.2012.08.002
Modelski, G., & Perry, G. III, (2002). Democratization in long perspective revisited, *Technological Forecasting and Social Change*, 69(4), 359-376. doi. 10.1016/S0040-1625(01)00152-4
Montesquieu, C. (1947). *The Spirit of Laws,* Harper and Row, New York.
Moseley, W.G., Perramond, E., Hapke, H.M., & Loris, P. (2014). *An Introduction to Human-Environment Geography*, Wiley.
Norris, P. (2008). *Driving Democracy: Do Power-Sharing Regimes Work?*, Cambridge University Press, Cambridge (UK).

Ramahrishna, H.V., & Brightman, H.J. (1986). The fact-net model: a problem diagnosis procedure, *Interfaces,* 16(6), 86–94. doi. 10.1287/inte.16.6.86
Ristuccia, C.A., & Solomou, S. (2014). Can general purpose technology theory explain economic growth? Electrical power as a case study, *European Review of Economic History*, 18(3), 227-247. doi. 10.1093/ereh/heu008
Robinson, D.K.R., Ruivenkamp, M., & Rip, A. (2007). Tracking the evolution of new and emerging S&T via statement-linkages: Vision assessment in molecular machines, *Scientometrics*, 70(3), 831–858. doi. 10.1007/s11192-007-0314-2
Rosegger, G. (1980). *The Economics of Production and Innovation,* Pergamon Press, NY.
Rosenberg, N. (1982) *Inside the Black Box: Technology and Economics,* Cambridge University Press.
Rosenberg, N.J. (1992). Adaptation of agriculture to climate change, *Climatic Change*, 21(4), 385-405. doi. 10.1007/BF00141378
Ruttan, V.W. (1997). Induced innovation, evolutionary theory and path dependence: sources of technical change, *Economic Journal,* 107(444), 1520–1529. doi. 10.1111/j.1468-0297.1997.tb00063.x
Ruttan, V.W. (2001). *Technology, Growth and Development, An Induced Innovation Perspective,* Oxford University Press, New York.
Ruttan, V.W. (2006). *Is War Necessary For Economic Growth? Military Procurement and Technology Development,* Oxford University Press, New York.
Sahal, D. (1981). *Patterns of Technological Innovation*, Addison-Wesley Publishing Company, Inc., Reading, Massachusetts.
Schultz, L.I., & Joutz, F.L. (2010). Methods for identifying emerging General Purpose Technologies: a case study of nanotechnologies, *Scientometrics*, 85(1), 155–170. doi. 10.1007/s11192-010-0244-2
Scientometrics, (1984). Indicators of measurement of impact of science and technology on socio-economic development objectives, *Scientometrics*, 6(6), 449-463.
Simon, J.L. (1977) *The Economics of Population Growth*, Princeton University Press: Princeton.
Singer C., Holmyard E.J., Hall A.R., & Williams T.I. (1956). *A History of Technology*, Vol. I and II, Clarendon Press, Oxford University Press.
Smithers, J., & Blay-Palmer, A. (2001). Technology innovation as a strategy for climate adaptation in agriculture, *Applied Geography*, 21(2), 175–197. doi. 10.1016/S0143-6228(01)00004-2
Spolaore, E., & Wacziarg, R. (2013). How deep are the roots of economic development?, *Journal of Economic Literature,* 51(2), 1-45. doi. 10.1257/jel.51.2.325
Strulik, H. (2005). The role of human capital and population growth in R&D-based models of economic growth, *Review of International Economics,* 13(1), 129-145. doi. 10.1111/j.1467-9396.2005.00495.x
Thagard, P. (1988). *Computational Philosophy of Science,* The MIT Press, Cambridge, MA (USA).
Usher, A.P. (1954) *A history of mechanical inventions,* Harvard University Press, Cambridge.
von Hippel E. (1988). *The Sources of Innovation*, Oxford University Press.
Wang, C.-C., Sung H.-Y., & Huang M.-H. (2016). Technological evolution seen from the USPC reclassifications, *Scientometrics*, 107(2), 537-553. doi. 10.1007/s11192-016-1851-3
Weber, M. (1956). *The Protestant Ethnic and the Spirit of Capitalism,* Unwin, London.
Wright, G. (1997). Towards a more historical approach to technological change, *The Economic Journal*, 107(444), 1560-1566. doi. 10.1111/j.1468-0297.1997.tb00066.x
Zachariadis, M., (2004). R&D-induced growth in the OECD?, *Review of Development Economics*, 8(3), 423-439. doi. 10.1111/j.1467-9361.2004.00243.x