Pedro Pinheiro
Centro ALGORITMI
School of Engineering
University of Minho
Portugal

Goran D. Putnik
Full Professor
Centro ALGORITMI
Department of Production and Systems Engineering
School of Engineering
University of Minho
Portugal

Alrenice Castro
Department of Rural Education and Mathematics and Natural Sciences
Center for Teacher Training (CFP)
Federal University of Recôncavo da Bahia (UFRB)
Brazil

Hélio Castro
Centro ALGORITMI
School of Engineering
University of Minho
School of Technology
Polytechnic Institute of Cávado and Ave
School of Engineering
Polytechnic of Porto
Portugal

Rodrigo Dal Bosco Fontana
Department of Agronomic and Engineering
Federal University of Fronteira Sul (UFFS)
Brazil

Fernando Romero
Assistant Professor
Centro ALGORITMI
Department of Production and Systems Engineering
School of Engineering
University of Minho
Portugal

Industry 4.0 and Industrial Revolutions: an Assessment based on Complexity

The evolution of society can be related to industrial revolutions. Revolutions are disruptive and transformative phenomena that change and interact with several systems. Industrial revolutions depend on changes in scientific, and mostly technological, paradigms and require people's participation. They are not only created with individual political intentions, because they are collective and complex systems. The expression Industry 4.0, created in Germany in 2011, denotes the so-called fourth industrial revolution. The question considered in this paper is whether Industry 4.0, as the fourth industrial revolution, is effectively underway or is it still only a vision of the future?
This article analyses, from the point of view of the science of complexity, the transformations and the relations of industrial systems with other selected systems. It was made through fractal analysis using indicators of four countries, namely, United Kingdom, United States of America, Germany and China. Considering the evolution of population growth, Gross Domestic Product per capita, communication technologies and intellectual property, the results of the analysis show that the factor that stands out is the protection of intellectual property.
The analysis of the previous indicators showed that it is not possible to claim that the fourth industrial revolution is underway, implying that Industrial 4.0 may stil be a vision of the future. The results obtained can not be considered conclusive and more research is needed.

Keywords: *Industrial Revolutions, Industry 4.0, Evolution, Paradigm, Cyber-Physical Systems, Complexity, Fractal.*

1. INTRODUCTION

Industrial systems are mutually influenced by social, economic, technological and scientific systems. Industrial revolutions are defined by new paradigms, the destruction and transformation of old paradigms, and by cycles of innovation that create disruptive conditions, increase uncertainty, and are influenced in complex and non-linear ways by scientific evolution.

Countries are interested in leading the new industrial revolution because considerable competitive advantages can be gained, not only in the manufacturing sector but also in other sectors, such as services.

The question considered in this paper is whether Industry 4.0, as the fourth industrial revolution, is effectively underway or is it still only a vision of the future?

This article investigates, from the point of view of the science of complexity, transformations and relations of industrial systems with other systems through the fractal analysis of the irregularities of several indicators of four countries, namely United Kingdom (UK), United States of America (USA), Germany and China.

This paper is organized in five chapters. The first is a short historical perspective of the phenomena of industrial revolutions, exploring the concept of industrial revolution and its implications.

The second chapter explores more deeply the concept of Industry 4.0, making some considerations regarding technological, social and policy aspects.

The third chapter displays some indicative technological indicators in the UK, USA, Germany and China, and relates those indicators to the rationale of analysis that will be performed later in the paper. These countries were chosen because they played, or are playing, important roles in the development of industrial revolutions. In this chapter it is introduced the concept of "fractal dimension" (FD) an important analytic tool that will be used later on.

The fourth chapter presents the data on which the analysis will be performed. The fifth chapter presents

Received: May 2019, Accepted: June 2019
Correspondence to: Dr. Hélio Castro
School of Engineering, Polytechnic of Porto,
Porto, Portugal
E-mail: hcc@isep.ipp.pt
doi:10.5937/fmet1904831P

and discusses the results obtained through FDs, with a focus on the stability/instability of the different systems. The level of stability of the system is associated with the level of dissemination or implementation of the industry 4.0 concepts and technologies.

2. INDUSTRIAL REVOLUTIONS

2.1 Outline of industrial revolutions

In the 17th century, there was a revolutionary change in the quality of western science, which was characterized by a strong intellectual confrontation between the so-called "ancients", which embodied a stream of thought deeply rooted in an Aristotelian tradition, and the "moderns", a stream of thought linked to new perspectives related to enlightenment and rationalism [1], institutionalized by the creation of scientific academies which encouraged discussion and research between men of science and technologists [2]. This occurs after the printing press was invented by Johannes Gutenberg in the fifteenth century. Physics, and in particular mechanics, in which the application of mathematical logic was instrumental to yield the best results, made spectacular progress, and fascination with this progress was such that gradually a mechanical conception of the universe came to prevail [3]. The successive emergence of many technical changes are not random and they are interconnected with other innovations in many other systems, which are related with a disruptive change that we call "revolution" or change of technological paradigm [4, 5].

Technology as we know it today, that is, systematic, organized work and knowledge on material tools of man, coincides (or at least becomes more institutionalized) with the first industrial revolution. It was produced by collecting and organizing existing knowledge, by applying it systematically, and by publishing it [6]. All three of the industrial revolutions have a complex mix of social, economic and technological transformations, typically acting in tandem [7], often in unpredictable ways, and self-reinforcing each other. Every step comes from accumulated technological experience coupled with the new meanings that science unravels through hypothesis and discovery [8]. Industrial revolutions are made possible because of ever more systematic knowledge production and inventions, which are the creative applications of knowledge in new productive forms that increase the set of techniques and products commercially available, and turning obsolete existing ones. Untermann [9] and Schumpeter [10] argue that the capitalist systems are in a permanent state of "creative destruction", characterized by the surge of radical innovations which alter industry structure [9, 10], collapse old behaviours and emerge new ones, increasing complexity and "creating" revolution.

Peter Drucker [5] assumes that Industrial Revolutions depend on technology, with focus on its use. The emergence of new technology not only enables rapid progress, but allows the establishment of subject fields as systematic disciplines to be taught and learned, feeding science with new disciplines [5]. This approach agrees with Kuhn's scientific revolutions model, in which the revolutions are inaugurated by a growing new consciousness, and when an older paradigm has ceased to explain adequately a plethora of phenomena and it is replaced in whole or in part by an incompatible new one. The incapability of old theories or approaches to explain phenomena or to provide technological solutions is a prerequisite to revolution [11].

The concept of scientific revolutions proposed by Kuhn is related to the concept of industrial revolutions, in the sense that a period of "normality" characterized by a stable knowledge base and practice is followed by a period of intellectual disruption or revolution, which imposes new theories and perspectives, or tools and technologies that replace the old ones.

The concept of industrial revolutions is also related to the concept of long waves of economic cycles of Kondratieff [12] and by the interpretation of those cycles suggested by some authors. The so-called Kondratieff waves are patterns of growth and declining rates of Gross Domestic Product (GDP) that last approximately half a century. They are characterized by a phase of increased growth rates in GDP followed by a second phase of relative stabilization and by a third phase of decreasing growth rates of GDP, which is then followed by another wave. Some authors believe that these patterns are not based only on changes in general trends of growth that affect all industries but are instead explained by technological disruptions and widespread social and economic structural change [4, 13]. The increasing rates of growth are due to a combination of factors that impose a new techno-economic paradigm. There are combinations or constellations of several incremental and radical innovations, technically and economically related, together with organizational innovations, with ramifications to several economic sectors that give rise to new technological systems. A new "techno-economic" paradigm takes place, due to large changes in the technological system, innumerable constellations of innovations, several new technological systems, with a vast scope of application of new technologies affecting all productions sectors and conditions. There is a new input with such a low cost that it has enormous impact on cost structures and a profound change in the "common-sense" and "mental set-up" in the search for solutions. These new conditions attract large amounts of financial resources that are invested in the new business models that the new techno-economic paradigm enables. The financial resources are diverted from traditional sectors and technologies, that gradually disappear, giving rise to a period of structural adjustment to the rapid rise of a new constellation of technological opportunities for investment. This period is characterised by slower rates of growth (the decreasing phase of the Kondratieff wave) which is followed by the increasing phase of the wave, when the new paradigm is substantially consolidated [14,15] and by relative stabilization before the decreasing cycle of another wave starts to build up. The industrial revolutions can be considered as part and consequence of the technological changes that occur in these waves.

Industry 4.0, and the changes that it implies, is often compared with three periods of industrial revolution that occurred before, and that were caused by fundamental changes in technology and science. The first industrial revolution was based on mechanical science and on the steam engine technology. Industrial production saw a large shift from manufacturing based on traditional artisanal techniques to manufacturing based on machines powered by steam engines. The second industrial revolution was based on the science of electricity and magnetism, on chemistry and on heavy mechanization of the factory, coupled with mass production and extensive division of labour. The third industrial revolution was based on electronic science and information and telecommunication technologies, which lead to extensive computerization and automation of the production process. The fourth industrial revolution (Industry 4.0) is based on cyber physical systems, cloud technologies and virtual reality, and will lead to a qualitative change of the production process, characterized by digitalization, extensive and intelligent process integration and self-organization.

2.2 Industry 4.0

First used in Germany in 2011, the concept "Industrie 4.0", a title of an Hanover Fair, raised numerous discussions, similar to the ones that had occur in the consumer world with the Internet in the early 1990s [16]. For instance, Schroeder [17] assumes that the term "Industrie 4.0" is an invention of German research politicians, who aim to circumvent expressions such as "Cyber-Physical Systems" (CPS), and explicitly refers to the digital dimension of the future industrial structures. The term CPS, by its part, was coined by Helen Gill, in 2006, at the National Science Foundation in the U.S. to refer to the integration of computation with physical processes [18]. In that workshop, the capability of the CPS was referred to as "Globally Virtual, Locally Physical".

Assuming that industry 4.0 is just a synonym that characterizes the CPS, then it can be defined as advanced connectivity that ensures real-time data acquisition from the physical world, information feedback from the cyber space and intelligent data management, analytics and computational capability inherent of cyber space [19]. Industry 4.0 is a phenomenon that represents the integration of several new or improved technologies, and whose integration enables new functions and enhances old capabilities. It is a process of change, which has radical elements. At the present moment, it is possibly a technological trajectory with no return.

However, in addition to CPS, Industry 4.0 can be related with other notions like smart factory, self-organization, open innovation, systems theory, and network integration (although these were referred in Industry 3.0 as well).

Countries are trying, with specific programs, to support and accelerate the so-called fourth industrial revolution. For our purposes, the main issue is not the designation, but the existence of the phenomenon and an evaluation of its dynamics.

For instance, besides Germany, which kick-started the concept of Industry 4.0, and which is actively implementing policies to support industrial transformation [20], China created the "Made-in-China 2025" program in 2015, trying to follow the trend created by the neologism "industry 4.0". Its goals are to "enhance industrial capability through innovation-driven manufacturing, emphasize quality over quantity, achieve green development, optimize the structure of Chinese industry, and nurture human talent" [21].

Chinese firms have shown a capacity to become more innovative, following reforms in the protection of intellectual property rights (IPR) and in the education system [22]. This evolution resembles and is in line with the thought of Russell [23], who argued that China's undoubtedly rapid change is necessary, and that the three main requirements were: "(1) The establishment of an orderly government; (2) industrial development under Chinese control; and (3) the dissemination of education" [23].

However, there is also an inherent uncertainty surrounding the development and adoption of emerging technologies, meaning that we do not know yet how the transformations are driven by this industrial revolution, its level of complexity, and how the interconnections will be between the different structures [24].

Marsh [25] argues that some of the emerging individual features will not be completely new, but the impact will come from the way they interact. Apparently, there will be a trend towards deepening the production concepts of "mass customization" and "mass personalization", so as to expand choice and provide more personalization opportunities. This will inevitably make the design and manufacture of the products more complex [25].

With Industry 4.0, new types of advanced manufacturing and industrial processes encompassing machine human collaboration [26] and symbiotic product realization, which requires that the customer is an intrinsic and active part of the production process, will emerge [27]. Changes dictated by a technology-push process can be identified: (1) "autonomous" manufacturing cells; (2) digitalization and networking; and (3) miniaturization [28]. These concepts are related with the smart factory (or CPS) that represents an engineering system that mainly consists of three aspects: interconnection, collaboration and execution [29].

To face the paradigm shift of an industrial revolution, people must be prepared for the disruptive changes that may arise. For instance, Banathy [30] predicts changes that will affect all society, and argues for the need of exploring the educational implications that will emerge following the changing knowledge base and the changes and transformations that have already happened in several spheres of the society.

With regard to technology, many assumptions are available. Possible decisions about the selection of manufacturing facilities will be evaluated by considering the economic costs of using robotic systems. However, the replacement of people by machines is a controversial issue, and its consequences are not well assessed [31].

The revolutions are only perceived as such by hindsight. When the process is taking place, disruptions of the social fabric seem slower, and the process is much more a gradual modification of structures and processes, and a concomitant gradual adaptation [32].

3. COMPLEX DYNAMIC SYSTEMS AND FRACTAL DIMENSION: METHODOLOGICAL CONSIDERATIONS

The manufacturing system is not monolithic. Instead, it is a multifaceted socio-technical system. As mentioned above, complexity has increased with industrial revolutions, and management needs to recognize and understand the connections and reactions between systems to observe the disturbance of different indicators and to decide accordingly.

3.1 Manufacturing complexity and change assessment

A decrease in the economic cycle accompanied by the growth of product diversity is probably an indication of the complexity and dynamics of new systems that are rising and replacing old ones [33]. New solutions are experienced in manufacturing, but evidence of significant industrial process change is often undervalued.

Changes brought about by emergent technologies and constellations of innovations are characterized by phases of irregularity but also by phases of relative stabilization, as it was described earlier. So, it is difficult to assess which phase of the process is actually running. This paper proposes an approach that addresses that difficulty, based on fractal theory and the associated concept of “fractal dimension”.

3.2 Fractal dimension

The FD analysis provides us with the possibility to understand other sides of different indicators besides the tendencies shown in the functions, by considering the irregularities that are inherent to those tendencies and indicators. This type of approach, in addition to computer graphics, has been used for several areas in economics, especially after the crisis of 2008 [34, 35].

First presented by Mandelbrot, based on the work of Richard Lewis Richardson, self-similarity and fractional dimension was used with the purpose of measuring Earth lines [36].

These concepts were studied later in 1977 in “The Fractal Geometry of Nature”. The term fractal is derived from the latin adjective “*fractus*”, which has the meaning of “fragmented” and “irregular”, and from the corresponding latin verb “*frangere*” that means "to break” [37].

The generalized dimension (D), which is closely related to the Renyi entropy, extends the simple Euclidean concept of dimension. The D values for any object must be between the topological dimension of the object and the dimension of the space where the object is: zero for a point, unit for a line segment, two for a square, and so on [38].

D was coined by Mandelbrot as FD. An improved method to estimate the FD of those time series, which is used here, is called "Box-counting" and the FD can be represented in terms of D of a set X as defined by Eq. (1) [39].

$$D = \frac{\text{Log } N}{\text{Log}\left(\frac{1}{r}\right)} \tag{1}$$

where N is the entire number of dissimilar copies related to X and X is scaled down by a fraction of $1/r$.

In the fractal analysis of a function f(t) the dimension of D is limited between 1 and 2. If D is closer to 1 means that the system is in a stable or equilibrium condition. If the value of D approaches 2 means that system is in a rough situation, close to chaos. However, the difficulty of comparing two indicators with a different nature continues to be manifested, since fractal analysis disregards their nature. This means that the same fractal dimension, in two different systems, may not be comparable. For instance, the heart beat of two different species may not be comparable because their normal or average beat rate is inherently different.

Notwithstanding that feature, which can be a limitation, in this paper the fractal analysis allows for the analytic unification of the indicators. We assume that the value $D = 1$ signals the stability of the system or the agreement or acceptance of all elements of the system, and that the greater the difference of D from the value 1, the greater the instability. However, instability or endogenous desire to change the system can mean either progression or regression, and this can be assessed only by the trend of the data.

3.3 Selection of indicators

To analyse the different indicators, we selected the UK and USA for having been the initiators of the first industrial revolution, Germany for being the largest European economy and China, which has grown considerably in the last two decades. For the indicators, in addition to economic and demographic data, we selected one related to IPR and two indicators resulting from the third industrial revolution related to telecommunications and technologies.

The indicators related to demography and GDP were chosen because they serve as proxies of the social and economic consequences induced by the technological and social changes of the industrial revolutions. Regarding the growth of economic output, all industrial revolutions have increased productivity and the volume of output. Indeed, the increase in productivity is at the centre of every industrial revolution [40].

The demographic changes are also a reflection of fundamental changes. In 1820, by the time of the first industrial revolution, people in the world had a life expectancy of 26 years although UK, USA, and Germany had values around 40 years, and China 24 years. Between, 1900 and 1950, despite two world wars, life expectancy increased approximately 20 years in the world. In 1950, at the end of the second industrial revolution, Germany, USA and UK had 67, 68 and 69 years for life expectancy, while China had a life expectancy of 41 years, the same value for the life expectancy in Germany in 1820 [2]. This shows that industrial revolutions changed demographic patterns and rates of growth of the population.

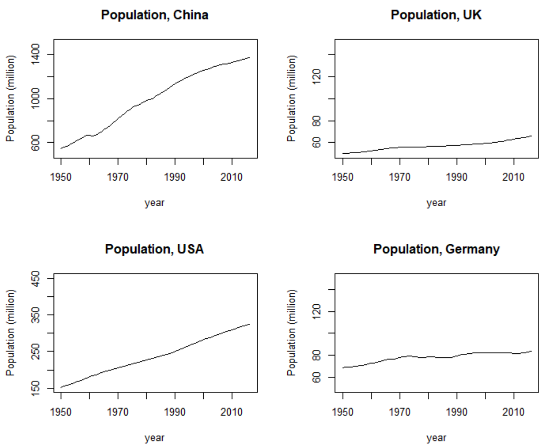
The other two indicators, internet access and IPR, can be considered proxies for the technological impact of the fourth industrial revolution. They will be important in analysing one of Kuhn's paradigm-changing conditions and in observing the evolution of the internet network, the main tool for information sharing, substitute for Gutenberg's printing, and a fundamental driver and structural element of Industry 4.0.

Knowledge is a fundamental production factor and today it is protected by IPR. The debate around this legal mechanism is divided between two main arguments. One is in favour of stricter control of IPR because it says it stimulates innovation, from which all regions of the world benefit. The other side advocates that stricter IPR control only strengthens the monopoly power of large companies based in industrialized countries, subjugating the others [41], and, as a matter of fact, it only reduces and depresses inventive and innovation activities all over the world, both in industrialised and in developing countries. The first argument relies on the notion of meritocracy and the second argues that the mechanism increases asymmetries and inequities between rich and poor. Indeed, IPR is a matter of power and it is an important indicator of the transformation that is occurring in the knowledge base of society, and as such, in the implementation of the Industry 4.0 concept. Some indicators are presented in absolute values (population, IPR) and other indicators are presented in relative values (GPD per capita, mobile phones). We do not believe that such difference will affect the analysis, the final results, and, principally, the conclusions, because the calculation principles and methods of the values of the FDs are independent of these data characteristics. This is not to say that if the data had other characteristics, those would eventually not affect the results.

4. DATA DESCRIPTION

4.1 Social and economic data

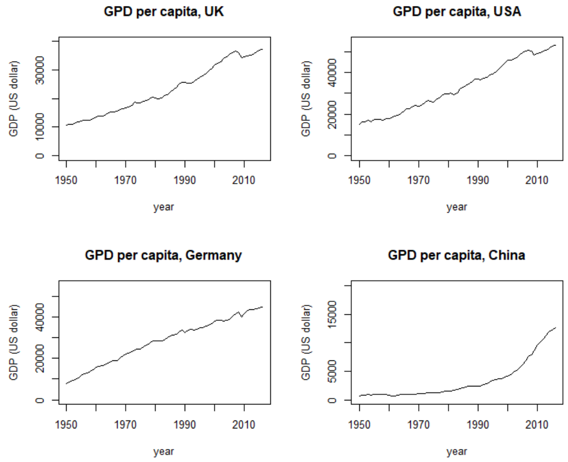
The data presented in figure 1 are comprised between 1950 and 2016 [42]. During this period there was a population increase of 151% in China, 113% in the USA, 31% in the UK, and 22% in Germany.



Source: World Bank (2019)

Figure 1. Population evolution in four countries between 1950 and 2016

With regard to economic growth per capita, the USA and the UK show, in figure 2, the greatest growth between 1982 and 2000, China has grown exponentially since 2000 and Germany has had an impressive recovery between 2009 and 2012, followed by a residual growth [42].



Source: World Bank (2019)

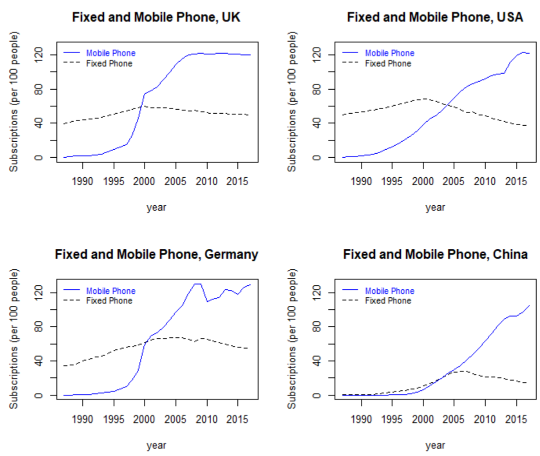
Figure 2. GDP per capita evolution in four countries between 1950 and 2016

In all countries populations has continued to grow, which, as argued above, maybe an indication of technological change and eventually changes of a deeper nature.

4.2 Technological data

The data in figure 3 refer to the number of subscriptions of fixed and mobile phones per 100 people, for the period between 1987 and 2017 [42].

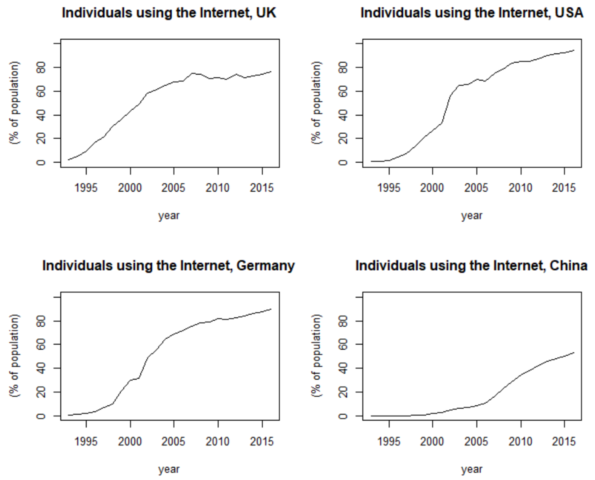
The emergence of mobile phones (a new technological system) and their acceptance by people have made fixed analogue phones obsolete. It is noteworthy that the evolution of fixed analogue telephone subscriptions in China had a residual adhesion relative to the other countries of this study, contrasting with the per capita values for mobile phones that are not so far away and still show a growing trend. This technology transition takes place between 1998 and 2003.



Source: World Bank (2019)

Figure 3. Evolution of fixed and mobile phones subscriptions in four countries between 1987 and 2017

Figure 4 shows the graphs of the percentage of Internet users and refers to the period between 1993 and 2016 [42]. In the number of Internet accesses, growth starts at the same time as the transition between previous technologies, except for China, which shows a higher growth 6 years later. It should be noted that these technologies are associated with inventions of the microprocessor and the Internet in 1969, precursors of the third industrial revolution.

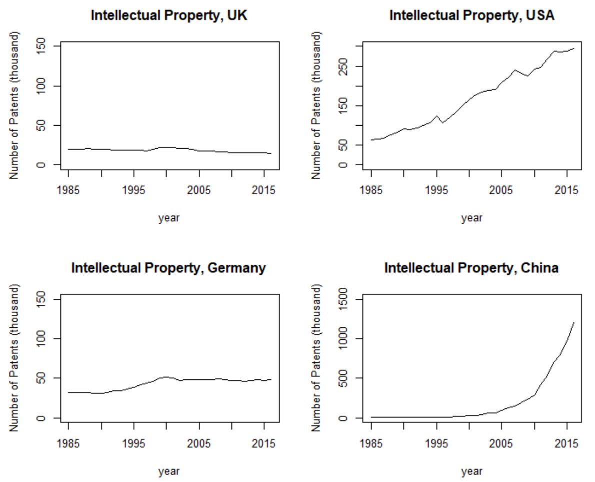


Source: World Bank (2019)

Figure 4. Percentage of individuals using Internet in four countries between 1993 and 2016

4.3 Intellectual property data

Regarding intellectual property, the data in figure 5 refer to the period between 1985 and 2016 [42]. This important indicator of knowledge protection reveals that the commitment of the four countries is disparate. In China it comes with an exponential growth, in Germany with a stabilization, in the UK with a regression and in the USA with an approximately linear growth.



Source: World Bank (2019)

Figure 5. Number of patents in four countries between 1985 and 2016

5. FRACTAL DATA ANALYSES

It should be noted that the analyses performed depend on the time periods of the indicators which determines the size of the samples. Although the fractal dimension is recommended for samples of a large dimension, the dimension of the present samples are enough for the FD to recognize states of instability, although with less accuracy. Fractals are complex mathematical structures that cannot be measured only through their topological dimension. The FD then appears as an alternative and complement of measurement, since it assumes fractional values, from which one can obtain the degree of complexity of a form or process that can be natural or artificial. Thus, fractals may provide information that otherwise or by other methods would not be possible to obtain.

All analysis were made in The R Project for Statistical Computing [43] and used the Box Count Method with package 'fractaldim' [44].

The FD will be used for the following purposes: (1) indicate the existence of a paradigm shift, and (2) indicate the most disruptive indicator that affected each country.

5.1 Fractal Dimension of Indicators

The graphs of the FDs of all the indicators treated in chapter 4 are present in the appendix of this paper.

Table 1. Fractal Dimension (*D*) values of four countries

Indicator	Country			
	UK	USA	Germany	China
Population	1.07	1.06	1.12	1.07
GDP per capita	1.11	1.12	1.11	1.09
Fixed Telephone	1.15	1.20	1.10	1.15
Mobile Cellular	1.14	1.15	1.17	1.18
Internet	1.13	1.15	1.13	1.16
Patents	1.31	1.21	1.18	1.15

The obtained values for each indicator will be analysed separately, in a first instance, because, as stated above, the absolute values of each indicator may not be directly comparable. Then, an overall assessment will lead to final conclusions.

The results obtained in Table 1 show that, in the four countries analysed, the FDs of the population growth is the closest to the value 1. This value indicates a behaviour which is mostly characterized by predictability, regular behaviour and routine activity because no significant irregularity or disruption was observed during the sample period. In the indicator of population growth, Germany is the country with the greatest instability with a D = 1.12. The USA has the lowest FD which may indicate that amongst the four countries it is the one that it is closest to the state of equilibrium.

The GDP per capita indicator shows that the USA and China are in different situations, although not in a significant way. China, of all countries is the most stable (with D = 1.09), while the USA shows the most irregular behaviour. In both cases the level of irregularity does not seem to be a signal that points to a state of disruption.

In the case of the indicators chosen to analyse the technological state, fixed analogue telephone and mobile cellular subscriptions and Internet users, we can verify that all values of the fractal dimensions are higher than the previous ones, except for fixed analogue telephone subscriptions made in Germany. These results seem to corroborate the notion of a paradigm shift, which was argued by Kuhn and by others [3, 11, 45], with mobile cellular phones showing a slightly higher FDs than the Internet. Both are related to information and communication, which are fundamental technologies behind the third and the so-called fourth industrial revolution. The values of FDs for both indicators are not much higher than 1, which may suggest, on the one hand, that the indicators are relevant in terms of an eventual transformation that is occurring, but, on the other hand, that the values are not high enough to point to large transformations. A large change in these indicators may be important in signalling significant transformations.

Regarding knowledge protection, China shows the FD closest to the value 1, but nevertheless with a significant value of 1.15. The values of the FDs of the IPR indicator are the highest of all, except for China, which presented its highest values in the subscriber index of mobile phones and Internet users. It seems to suggest that the knowledge dimension is the most important one, compared with the other indicators. It points to transformations that are occurring, but it is difficult to say, given the characteristics of the FD, if the they are the evidence of deep and structural transformations.

6. CONCLUSION

In this paper we considered whether Industry 4.0, as the fourth industrial revolution, is effectively underway or is it still only a vision of the future, and in order to answer that question, we used a different approach based on fractal analysis and complexity theory.

The restrictive analysis of only a few factors compromises the evaluation of a system, but the indicators used in this paper and the proposed research indicate the advantages for a holistic, and not only economic, technological or functional, approach.

Time is a key issue in manufacturing assessment. A cross-sectional perspective limits and distorts any evaluation of the system. A chronologically consistent sample is required to ensure the consistency of the decision-making process, and there was a preoccupation concerning that aspect, in the choice of the indicators and the time frame. Some data limitations that we have acknowledge do not, in our perspective, compromise the validity of the conclusions.

If revolution begins at the time of inventions then we do not know if we are in the fourth industrial revolution because its effects will only be manifested later on, after some time has elapsed. This situation was observed in the third industrial revolution with the invention of microprocessors and Internet.

Due to a significant increase in complexity that still hinders the recognition of patterns, fractal analysis was used to identify irregularities and disturbances in the different variables. The FDs indicators of population growth and economic growth per capita shows that the USA is the most "controlled" in the first indicator and "unsatisfied" in the second. However, the FDs values of these indicators are generally lower than all others. The FDs values for mobile phones and internet access reveal significant but not outstanding values, casting some doubts on the structural impact that can be derived from them. The not insignificant value for the internet is important because it is connected to knowledge diffusion. The appearance of mobile phone, as a new technological system, may confirm one of Kuhn's theses. The FDs values showed that the IPR is the most disturbing factor for all countries, that is, it is recognized and it stands out of the analysis as a critical development factor and it is an indication of change of the knowledge base.

We recognise that there are some limitations on the research approach and on assumptions made concerning the data, but the results show that this research approach provides complementary and useful results. The approach is potentially useful to be applied in other contexts. Future research may involve gathering longer time series data and enlarging the number of indicators.

ACKNOWLEDGMENT

This work has been supported by FCT – Fundação para a Ciência e Tecnologia within the Project Scope: UID/CEC/00319/2019.

REFERENCES

[1] Cipolla, C. M.: *Before the Industrial Revolution: European Society and Economy 1000-1700*: Routledge, 2004.

[2] Maddison, A.: *The World Economy: A Millennial Perspective*: OECD, 2001.

[3] Perez, C.: Technological revolutions and techno-economic paradigms, *Cambridge journal of economics*, vol. 34, No. 1, pp. 185–202, 2010.

[4] Schumpeter, J. A.: *Business cycles: A theoretical, historical and statistical analysis of the capitalist process*. New York: McGraw-Hill Book Company, 1939.

[5] Drucker, P. F.: The technological revolution: notes on the relationship of technology, science, and culture, *Technology and Culture*, vol. 2, No. 4, p. 342, 1961.

[6] Haldane, A. G.: Growing, Fast and Slow. Speech given at University of East Anglia, Feb. 17 2015.

[7] Monod, J.: *Chance and Necessity an Essay on the Natural Philosophy of Modern Biology*. New York: Vintage Books, 1972.

[8] Courvisanos, J.: *Cycles, Crises, Innovation: Path to Sustainable Development A Kaleckian-Schumpeterian Synthesis*: Edward Elgar Publishing, 2012.

[9] Untermann, E.: *Science and revolution*: CH Kerr, 1905.

[10] Schumpeter, J. A.: *Capitalism, socialism and democracy*. New York: Harper & Row, 1975 (first edition 1942).

[11] Kuhn, T. S.: *International Encyclopedia of Unified Science: The Structure of Scientific Revolutions*: The University of Chicago Press, 1962.

[12] Kondratieff, N. D. and Stolper, W. F.: The Long Waves in Economic Life, *The Review of*

Economics and Statistics, vol. 16, pp 105-115, 1935.
[13] Dosi, G., Freeman, C., Nelson, R., Siverberg, G. and Soete, L.: *Technical Change and Economic Theory*. London: Pinter Publishers, 1988.
[14] Freeman, C. Louçã, F.: *As Time Goes By: From the Industrial Revolutions to the Information Revolution*. Oxford: Oxford University Press, 2001.
[15] Korotayev, A., Zinkina, J. and Bogevolnov, J.: Kondratieff waves in global invention activity (1900–2008), *Technological Forecasting and Social Change*, vol. 78, No. 7, pp. 1280–1284, 2011.
[16] Drath, R. and Horch, A.: Industrie 4.0: Hit or hype?[industry forum], *IEEE industrial electronics magazine*, vol. 8, No. 2, pp. 56–58, 2014.
[17] Schroeder, W.: *Germany's Industry 4.0 strategy*. London: Friedrich Ebert Stiftung, 2016.
[18] Lee, E. A. and Seshia, S. A.: *Introduction to embedded systems: A cyber-physical systems approach*: MIT Press, 2016.
[19] Lee, J., Bagheri, B. and Kao, H.-A.: A cyber-physical systems architecture for industry 4.0-based manufacturing systems, *Manufacturing letters*, vol. 3, pp. 18–23, 2015.
[20] Kagermann, H., Wahlster, W. and Helbig, J.: *Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0*. München, 2013.
[21] Li, L.: China's manufacturing locus in 2025: With a comparison of "Made-in-China 2025" and "Industry 4.0", *Technological Forecasting and Social Change*, vol. 135, pp. 66–74, 2018.
[22] Wei, S.-J., Xie, Z. and Zhang, X.: From" Made in China" to" Innovated in China": Necessity, prospect, and challenges, *Journal of Economic Perspectives*, vol. 31, No. 1, pp. 49–70, 2017.
[23] Russell, B.: *The problem of China*: Century, 1922.
[24] Schwab, K.: *The fourth industrial revolution*: Currency, 2017.
[25] Marsh, P.: *The new industrial revolution: consumers, globalization and the end of mass production*: Yale University Press, 2012.
[26] Brkić, V. S., Putnik, G., Shah, V., Castro, H. and Veljković, Z.: Human-computer interactions and user interfaces for remote control of manufacturing systems, *FME Transactions*, vol. 41, No. 3, pp. 250–255, 2013.
[27] Lu, Y.: Industry 4.0: A survey on technologies, applications and open research issues, *Journal of Industrial Information Integration*, vol. 6, pp. 1–10, 2017.
[28] Lasi, H., et al.: Industry 4.0, *Business & Information Systems Engineering*, vol. 6, No. 4, pp. 239–242, 2014.
[29] Chen, B. *et al.:* Smart factory of industry 4.0: key technologies, application case, and challenges, *IEEE Access*, vol. 6, pp. 6505–6519, 2018.
[30] Banathy, B. H.: *Designing social systems in a changing world*: Springer Science & Business Media, 2013.
[31] Kamble, S. S., Gunasekaran, A. and Gawankar, S. A.: Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives, *Process Safety and Environmental Protection*, vol. 117, pp. 408–425, 2018.
[32] Gramsci, A.: *The Gramsci reader: selected writings, 1916-1935*: NYU press, 2000.
[33] Šmit, T. and Šulce, F.: Future approaches to meet complexity requirements in material handling systems, *FME Transactions*, vol. 37, No. 4, pp. 159–166, 2009.
[34] Kristoufek, L.: Fractal markets hypothesis and the global financial crisis: Scaling, investment horizons and liquidity, *Advances in Complex Systems*, vol. 15, No. 6, pp. 1–13, 2012.
[35] Lahmiri, S.: Long memory in international financial markets trends and short movements during 2008 financial crisis based on variational mode decomposition and detrended fluctuation analysis, *Physica A: Statistical Mechanics and its Applications*, vol. 437, pp. 130–138, 2015.
[36] Mandelbrot, B.: How long is the coast of Britain? Statistical self-similarity and fractional dimension, *science*, vol. 156, No. 3775, pp. 636–638, 1967.
[37] Mandelbrot, B. B.: *The fractal geometry of nature*. New York: WH Freeman, 1983.
[38] Lowen, S. B. and Teich, M. C.: *Fractal-based point processes*: John Wiley & Sons, 2005.
[39] Bohdalová, M. and Greguš, M.: Markets, Information and Their Fractal Analysis, *E-Leader, New York: CASA*, pp. 1–8, 2010.
[40] Pereira, A. C. and Romero, F.: A review of the meanings and the implications of the Industry 4.0 concept, *Procedia Manufacturing*, vol. 13, pp. 1206–1214, 2017.
[41] Helpman, E.: Innovation, Imitation, and Intellectual Property Rights, *Econometrica*, vol. 61, No. 6, pp. 1247–1280, 1993.
[42] World Bank: *World Development Indicators [Data file]*. [Online] Available: https://databank.worldbank.org/data/source/world-development-indicators#. Accessed on: Apr. 26 2019.
[43] R Core Team: *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Fundation for Statistical Computing, 2019.
[44] Gneiting, T., Sevcikova, H. and Percival, D. B.: Estimators of Fractal Dimension: Assessing the Roughness of Time Series and Spatial Data, *Statistical Science*, vol. 27, No. 2, pp. 247–277, 2012.
[45] Gersick, C. J. G.: Revolutionary change theories: A multilevel exploration of the punctuated equilibrium paradigm, *Academy of management review*, vol. 16, No. 1, pp. 10–36, 1991.

ИНДУСТРИЈА 4.0 И ИНДУСТРИЈСКЕ РЕВОЛУЦИЈЕ: ЈЕДНА ПРОЦЕНА НА ОСНОВУ НА ТЕОРИЈИ КОМПЛЕКСНОСТИ

П. Пињеиро, Г.Д. Путник, А. Каштро, Х. Каштро, Р.дал Боско Фонтана, Ф. Ромеро

Еволуција друштва може бити повезана са индустријским револуцијама. Револуције су фено-

мени који ремете и трансформишу и који се мењају и који су у интеракцији са неколико система. Индустријске револуције зависе од промена у научним и претежно технолошким парадигмама и захтевају учешће људи. Оне нису створене само са индивидуалним политичким намерама, јер су то колективни и комплексни системи. Израз Индустрија 4.0, створен у Немачкој 2011. године, означава такозвану четврту индустријску револуцију. Питање које се разматра у овом раду је да ли је Индустрија 4.0, као четврта индустријска револуција, стварно у току или је то још само визија будућности?

Овај рад анализира, са становишта науке о комплексности, трансформације и односе индустријских система са другим изабраним системима. Анализа је урађена кроз фракталну анализу користећи индикаторе четири земље, односно Уједињеног Краљевства, Сједињених Америчких Држава, Немачке и Кине. Имајући у виду еволуцију раста становништва, бруто домаћи производ по глави становника, комуникационе технологије и интелектуалну својину, резултати анализе показују да је фактор који се истиче заштита интелектуалне својине.

Анализа претходних показатеља показала је да није могуће тврдити да је у току четврта индустријска револуција, што значи да Индустрија 4.0 може бити визија будућности. Добијени резултати не могу се сматрати закључним што значи да је потребно више истраживања.

APPENDIX

The figures presented below refer to the graphs of the fractal dimensions of the indicators presented in Chapter 4, the results of which are summarized in Table 1.

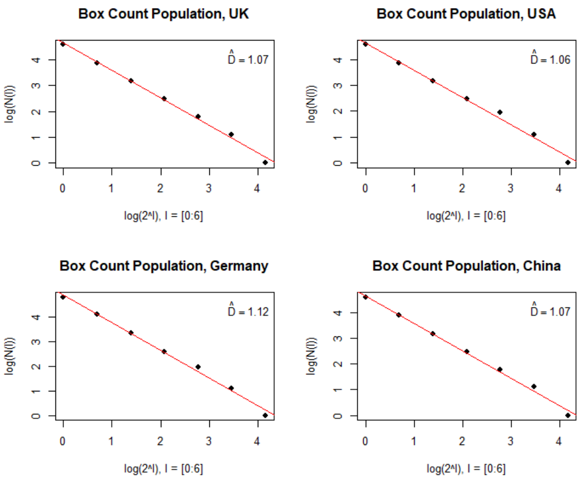


Figure 6. FD using Box Count of population

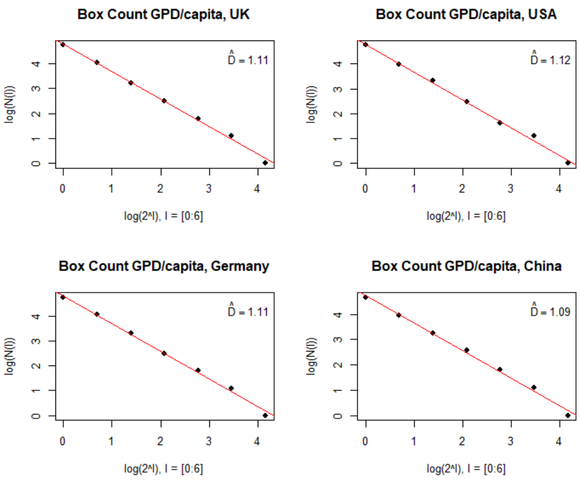


Figure 7. FD using Box Count of GDP per capita

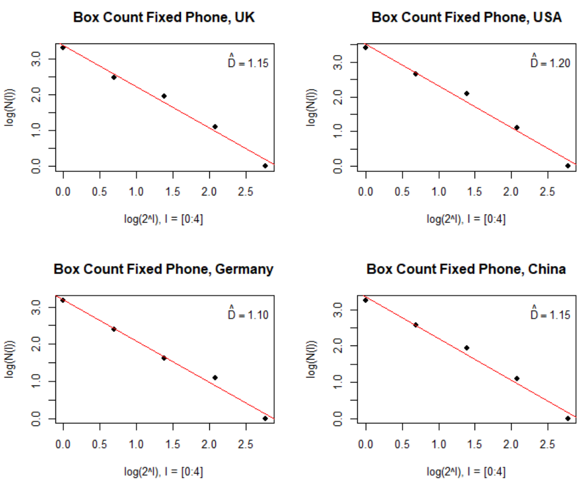


Figure 8. FD using Box Count of fixed telephone subscriptions

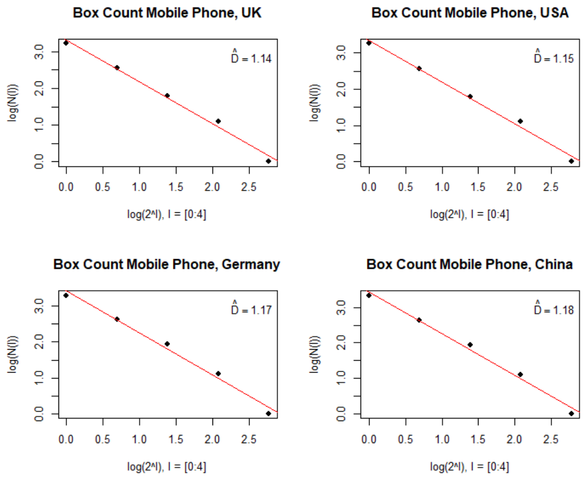


Figure 9. FD using Box Count of mobile cellular subscriptions

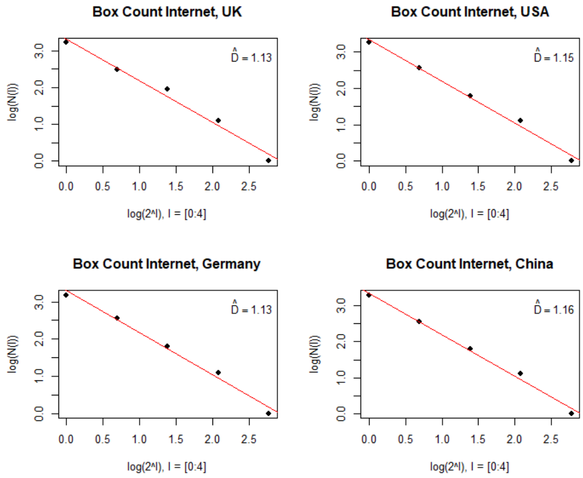


Figure 10. FD using Box Count of Internet users

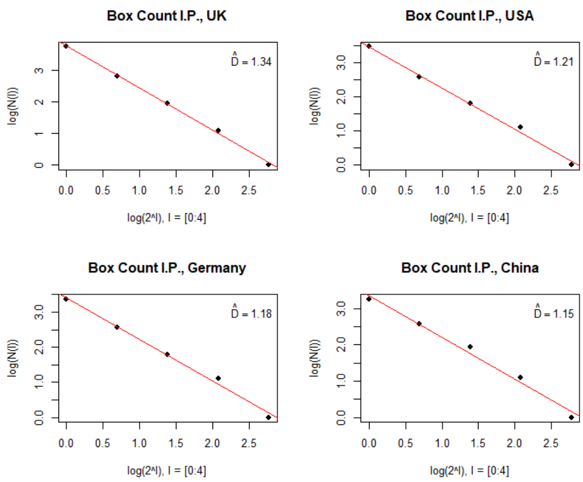


Figure 11. FD using Box Count of Patents