Paper presented at the Plenary Conference of the Institute for New Economic Thinking, Hong Kong April 4 -7, 2013

New Metrics for Economic Complexity: Measuring the Intangible Growth Potential of Countries

L. Pietronero, M. Cristelli and A. Tacchella

Institute of Complex Systems, ISC-CNR, and University of Rome Sapienza, Rome, Italy

Abstract: In this paper we provide a summary and a guide to the literature for a new line of research which goes under the name of Economic Complexity and is partly performed in collaboration with INET. This line of research portrays economic growth as an evolutive process of ecosystems of technologies and industrial capabilities. Complex systems analysis, simulation, systems science methods, and big data capabilities offer new opportunities to empirically map technology and capability ecosystems of countries and industrial sectors, analyse their structure, understand their dynamics and measure economic complexity. This approach provides a new perspective for data-driven fundamental economics in a strongly connected, globalised world.

In particular here we discuss how it is possible to assess the competitiveness of country and complexity of products starting from the archival data on export flows that is the COMTRADE dataset which provides the matrix of countries and their exported products. According to the standard economic theory the specialization of countries towards certain specific products should be optimal. The observed data show that this is not the case and that diversification is actually more important. Specialization may be the leading effect in a static situation but the strongly dynamic and globalized world market suggests instead that flexibility and adaptability are essential elements of competitiveness as in bio-systems.

The crucial challenge is therefore how these qualitative observations can be turned into quantitative variables. We have introduced a new metrics for the Fitness of countries and the Complexity of products which corresponds to the fixed point of the iteration of two nonlinear coupled equations. The nonlinearity is a key feature because it translates in mathematical terms the fact that the upper bound on the Complexity of a product must be mainly given by the less developed country able to produce it. The information provided by the new metrics can be used in several ways. As an example, the direct comparison of the Fitness with the country GDP *per capita* (Fitness-Income Plane) gives an assessment of the non-expressed potential of growth of a country. This can be used as a predictor of GDP evolution or stock index and sectors perfomances.

The global dynamic in the Fitness-Income Plane reveals, however, a large degree of *heterogeneity* which implies that countries can evolve with different level of predictability according to the specific zone of the Fitness-Income plane they belong to. This heterogeneous dynamics is often disregarded in usual economic analysis. When dealing with heterogeneous systems, in fact, the usual tools of linear regressions become inappropriate. Making reliable predictions of growth in the context of economic complexity will then require a paradigm shift in order to catch the information contained in the complex dynamic patterns observed.

These methods and concepts can give concrete contributions, as other possible applications, to risk analysis, investment opportunities analysis, policy-modelling of country growth and industrial planning.

Keywords: Economic Complexity; Big Data; Ecosystems; Bipartite Network; New Metrics; Measuring intangibles; Non monetary variables; Industrial competitiveness; Technological evolution; Evolvability;

1. New Economic Thinking: Economic Complexity

A major challenge stimulated by the financial crisis is to reconsider economic theories and economic growth from a new perspective. The basic idea is to increase the level of scientific content of economic models by making them more realistic with respect to the complexity of the real economy and linking them to data in two ways. On one hand data are the source of inspiration for models, on the other hand they also represent the playground for testing them.

Economic growth is a highly complex and disaggregated phenomenon. Traditionally, economists have analysed growth in an aggregate perspective at the global, national, or industrial sector level [1–9]. However, recent developments in ICT tools, the availability of "Big Data", network analysis techniques, and ideas from systems science and complex systems theory enable a much more disaggregated, bottom-up, evolutionary view of economic growth [8,9]. This disaggregated point of view naturally implies considering also the strong interactions between the various components. This is the challenge of global system science which requires a fundamentally novel attitude in terms of defining the appropriate questions, introducing new methods and algorithms, dealing with immense amount of data and finally turning all these elements into practical recipes which should be relatively simple to understand and implement.

The standard approach to analyse systems in terms of their individual parts as independent entities and in a sort of equilibrium framework, has proven to be inappropriate in forecasting systemic crisis or in many of the complex situations embedded in a strongly interacting environment, of which globalized markets are an example. The recent financial crisis in 2007 has led to a large interest in the study of interconnected financial systems. Here we intend to implement this perspective beyond the limits of finance by addressing some basic questions for the very foundations of economic science. Growth and innovation will be considered as key features an ecosystem with complex interactions. This is the playground of Economic Complexity.

This approach brings novelty in various directions. First, the whole approach is data-driven. This requires a careful selection of meaningful data and the introduction of appropriate algorithms to extract the relevant information. This body of experimental information also represents the testing ground for the models. The continuous feedback between data, algorithms and models will provide a firm scientific basis to the whole approach.

The term <u>Economic Complexity</u> has been introduced in a recent series of papers [10-14] and refers to a set of <u>intangible, non-monetary and non-tradable assets</u>, or capabilities, that each national economy owns, and that allow material production. Complexity is in the interaction of these assets, and how the combination of them results in competitive products, as well as in the emerging *Globalization* and interconnectedness of the world market, where national economies, and their set of capabilities, compete. Measuring these intangible non-monetary values is a key element in economics because its comparison with the monetary performance can reveal new information on the hidden potential of a country which is the fundamental driving element for future growth.

Our goal is to develop a fundamental theory of national and local industrial development in terms of the relative competitiveness that each country and region can achieve. This is defined by the benefits of hosting a diversified set of industries that, through their interaction, are able to make more complex products while also being more flexible in dynamic global networked markets. While traditional analysis focuses on the amount of exports produced, our techniques emphasize the complexity and diversity of a country's export basket which is the expression of the technologies and capabilities it is able to harness. This complexity determines the level of national competitiveness as an emergent property.

2. Specialization *versus* Diversification: Economic Complexity of Countries and Products

Which are the key ingredients for the economic performance of a country and its future development? Traditionally economic performance is measured by means of monetary figures such as the gross domestic product (GDP) but this, at most, reflects the present status. Concerning evolution and growth, the situation is highly controversial and many intangible elements are invoked: good education, financial status, labour cost, high-tech industry, energy availability, quality of life, etc. These concepts are usually discussed in a qualitative fashion. Now we propose a new way to measure the industrial hidden potential of a country more directly, by linking it to the complexity and diversity of the products a nation produces. The basic idea is to indirectly measure these intangibles by considering the diversification and complexity of the products that a nation is able to produce. This is the hidden potential of countries: an intangible element underpinning the very concrete reality of how industrial growth will develop in the future.

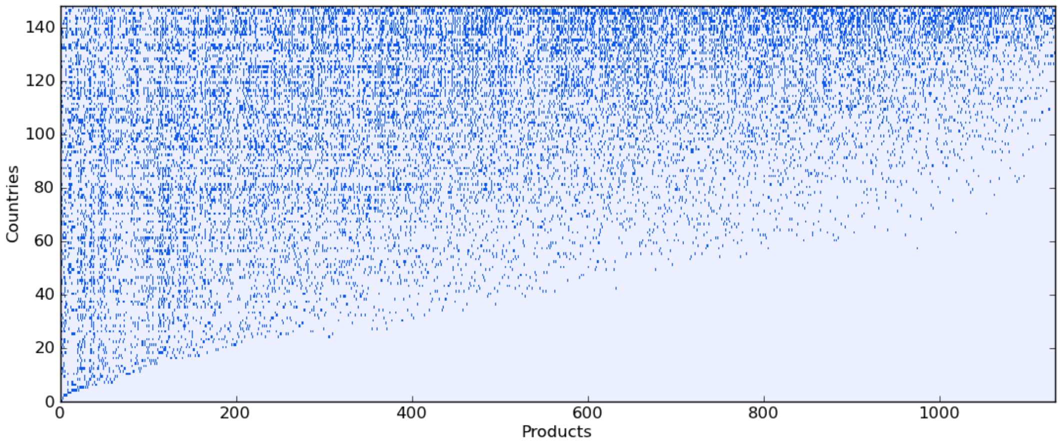


Figure 1 Diversification *versus* Specialization.
According to the standard analysis the specialization of countries on few specific products should be an optimal strategy but this is valid only in a static situation. The strongly dynamical situation of the world market suggests that diversification inducing flexibility and adaptability is even more important. On this account mainstream theories would predict an almost diagonal country-product matrix while, ordering rows and columns with respect to our metric for countries' fitness and product's complexity, we observe a triangular shaped matrix. Namely each country has a maximum level of complexity of the products it can produce but, below this level, it is able to produce almost all the simpler products, essentially down to the very simple ones.

The starting observation [11] is purely data-driven. Considering the database of the exported products (Fig. 1), one can see that each country has a maximum limit for the Quality or Complexity of its products. Below this limit the country produces many more products as well, but with a lower Complexity. Diversification is therefore a strategic element and recalls concepts which are natural in ecology like the adaptability of species to a fluctuating environment. From this perspective one can speculate that specialization is probably optimal only in a static context.

The strategy is to measure indirectly these intangibles by considering the diversification and complexity of the products that a nation is able to produce. This information is taken from the export database (i.e. COMTRADE) but this is not a traditional study of export. We use the export data to know what type of products a country is able to produce, independently on their monetary volume. From this qualitative information and introducing suitable algorithms, it is possible to derive new metrics for the competitiveness of countries and the complexity of products [10-14].

Poor countries export a small collection of simple products, which are not very palatable for the globalized market. By contrast, more successful countries export a greater number and broader range of products, some of them very exclusive and sophisticated, apart from almost all the rest. They might be spacecraft components, medical equipment, yachts, computers, super-cars, but also clothing, light bulbs, brick and nails. This means that they are in a pretty good shape, or they have a high Fitness according to the new definition. The key element is how to turn these qualitative considerations into quantitative tools.

3. New Algorithm for the Fitness of Countries and the Complexity of Products

In order to quantify the effect of diversification, we have recently introduced a suitable algorithm which defines a new, <u>non-monetary metrics</u>, based on the level of Complexity of products to measure the industrial capability of a country (<u>Fitness</u>) defined as the number of exported products weighted by their <u>Complexity</u>. A crucial new concept is that if various countries produce the same product it is the less competitive country which sets an upper bound to the complexity level of the product. This leads to a non-linear scheme which, together with other elements, leads to results which appear robust and meaningful. Of course the optimization of the algorithm with respect to suitable benchmarks represents a very important point to explore. This implies the availability of new, reliable and meaningful datasets.

Specifically, we argue that the fitness of nations and the complexity of products ought to be linked in two ways. First, the fitness of a nation should be reflected in the diversity and complexity of the products it exports. Fitter nations produce both more products and more complex products. Second -- and less obviously -- the complexity of a product should be reflected by the nations that produce it, but in an inverse way. That is, a product of low complexity, being relatively easy to make, should be produced by many nations, while high-complexity products should only be produced by a few high-fitness nations.

These relations can be captured in two simple equations (Eq. 1), which can be used, with real economic data, to produce an estimate of the fitness of various nations and the complexity of different products. The results show some aspects that would be expected -- the U.S., China and Germany all rank high in economic fitness -- and also some surprises: some nations with similar GDP appear to rank quite differently in terms of their true economic complexity.

The strength of this analysis, relative to earlier analyses, is that it naturally reproduces the realistic pattern for the ranking of nations by economic performance. Empirical data shows, for example, that the distribution of nations by performance follows a so-called Pareto law, with wide differences between a few top performers and many that perform significantly less well. This pattern emerges naturally from this new analysis.

$$\begin{cases} \tilde{F}_c^{(n)} & = & \sum_p M_{cp} Q_p^{(n-1)} \\ \tilde{Q}_p^{(n)} & = & \dfrac{1}{\sum_c M_{cp} \dfrac{1}{F_c^{(n-1)}}} \end{cases} \rightarrow \begin{cases} F_c^{(n)} = \dfrac{\tilde{F}_c^{(n)}}{\langle \tilde{F}_c^{(n)} \rangle_c} \\ Q_p^{(n)} = \dfrac{\tilde{Q}_p^{(n)}}{\langle \tilde{Q}_p^{(n)} \rangle_p} \end{cases}$$

Eq. (1)

For a detailed discussion of the algorithm see Ref. [12].

The main properties of this new algorithm are:

- The Fitness of countries (F) is given by diversification weighted by the Complexity of its products. Iterating the algorithm increases the accuracy of the analysis but it does not change the meaning of the variables to be computed. This is in the spirit of Google PageRank algorithm but, in Economics, additional important elements have to be considered which make the algorithm nonlinear.
- The Complexity of a product (Q) is related in an inverse way to the number of countries that can produce it. In addition if low Fitness countries can produce a certain product this fact bounds its complexity even if this product is also produced by other competitive countries. This leads to a nonlinear and in some sense extremal algorithm which is essential for a proper definition of the product complexity. A practical consequence of this is that in our framework Oil and in general raw materials are a relatively simple product in terms of industrial capabilities even if it is produced also by advanced countries like US and UK. The availability of Oil is basically due to chance and not to the industrial potential of US and UK.
- The iteration leads to a broadening of the distributions for Fitness and Complexity which resemble the real Pareto-like behaviour for monetary variables.
- The new variables F and Q represent a quantification of intangible values like the industrial competitiveness of countries and the intrinsic Complexity of products. The comparison of these new variables with the standard monetary ones like GDP or the added value for products can be informative for future growth, as discussed in the next sections.

4. The Properties of Fitness and Complexity

Consistency tests:

- The triangularity of the C-P matrix (Fig.1) is enhanced once the countries and the products are ordered with the final ranking rather than with the initial one which is given only by the number of products made by a country without introducing their complexity. This is a sort of bootstrap consistency test.
- The addition of more information, like product complexity, leads to broad, Pareto Like distributions for the Fitness which compare very well with indicators of intensity like the GDP *per capita* (Fig. 2). This means we are indeed describing the economic system in a broad sense but then the specific differences between the two variables will identify the trends of future growth.

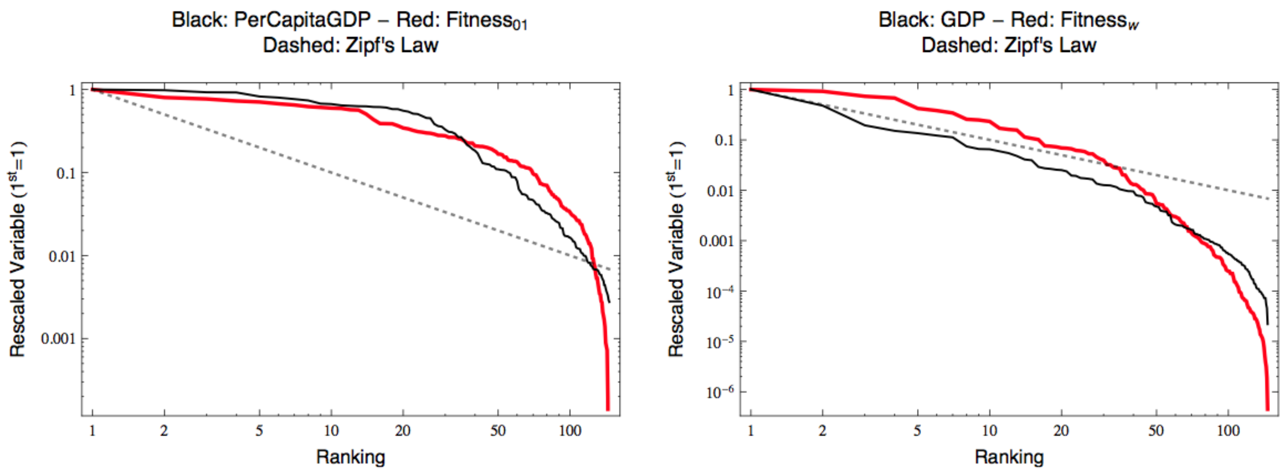


Figure 2 Data Analysis: intensive and extensive metrics.

On the left we show the rank-size law of the intensive fitness (red) as measured by the non-monetary metric compared with the GDP per capita (black). The fact that our fitness shows a broad Pareto like distribution similar to that of the GDP per capita is an important indication that this variable is related to real economy. On the other hand the differences between the two variables will provide important information on growth, opportunities and risk. On the right side we show the same variables corresponding to the extensive case in which they refer to countries. In this case they also follow a Zipf Law [15].

More importantly, the analysis may offer a mean to gain deeper insight into the real factors influencing a nation's past performance and prospects for future growth. For example, the present analysis casts a novel perspective on the recent performance of the so-called BRIC countries, Brazil, Russia, India and China. The conventional analysis based on GDP reveals that all these countries' GDP growth is higher than in western countries. But our analysis finds that economic fitness of both Brazil and Russia has actually been decreasing in recent years. This suggests that their GDP growth is really fuelled by the increasing prices of raw materials rather than any true development in the capabilities of their industry. Despite their increasing GDP, the complexity of their productive systems is not growing as it happens, in contrast, for China and India. The observed India and China's GDP growth does appear to reflect a genuine development of the capabilities.

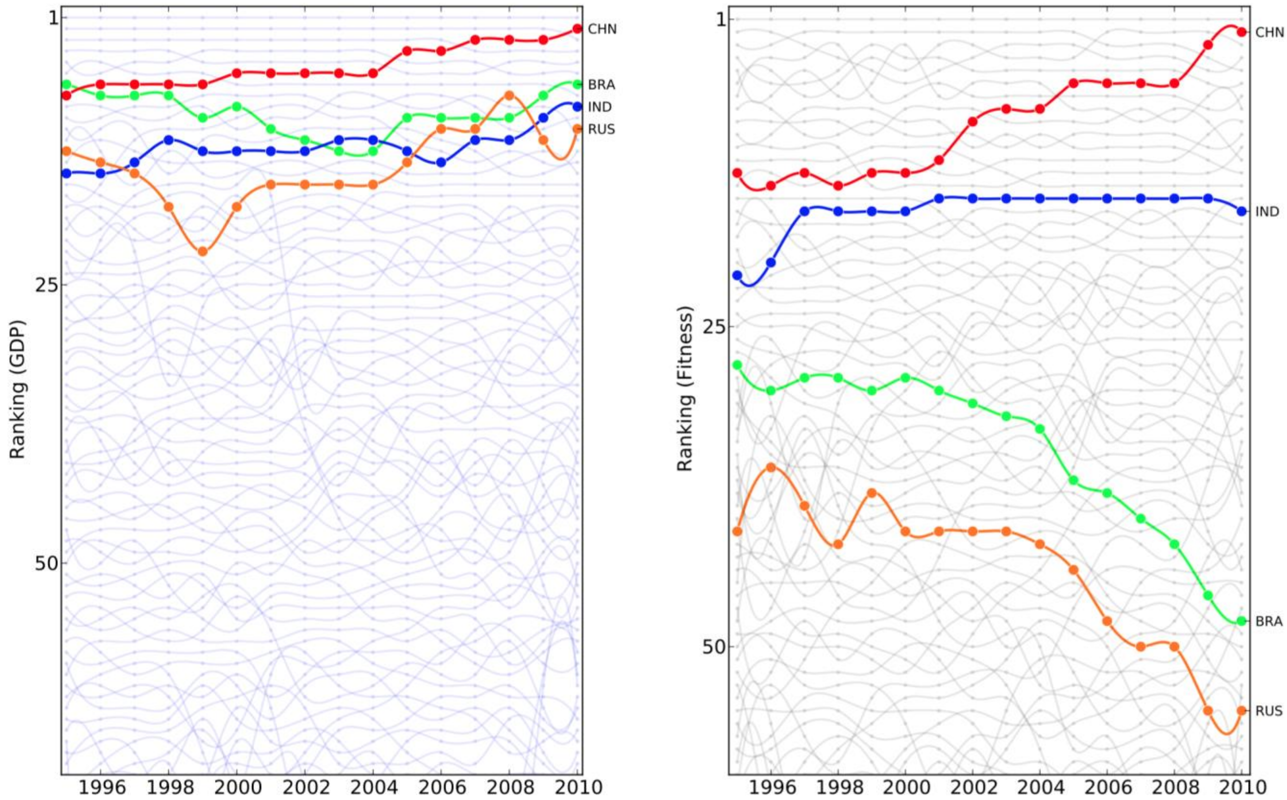


Fig. 3 The analysis of BRIC countries: Fitness *versus* GDP

On the left we show the GDP ranking in the past years for the BRIC countries, on the right we report our fitness for the same period. Russia is increasing its GDP in the last years but its Fitness shows an opposite behaviour. We can interpret this result as the fact that the increase of GDP is basically due to the export of raw materials but not to the industrial potential. A similar behaviour is observed for Brazil. Note that in the standard analysis this problem of Brazil has been pointed out only in the last couple of years while our fitness would have indicated this problem long before. For China the two variables are very coherent showing a healthy and steady increase of the industrial potential and corresponding GDP.

When retrofitting this model with data from 1995 to 2010, it is possible to see that results reflect well what has occurred in the real world over that period. In particular, in 2001 Goldman-Sachs analysts defined Brazil, Russia, India and China as the countries that would dominate the world economy in the next 50 years. However, in the light of the new algorithm, it would have been evident in 2002 that China and India showed a sound hidden potential due to their industrial improvement, while Russia and Brazil's GDP mostly relied on commodities. Only recently the standard analysis is converging to this point of view which, with the new metrics, would have been evident since 2002. Today strong growth is predicted for Thailand and The Philippines, in agreement with standard analysis, but also for Vietnam which is unexpected. For more discussions and examples see [12-14] and [16,17].

5. Heterogeneous Dynamics and Economic Predictability

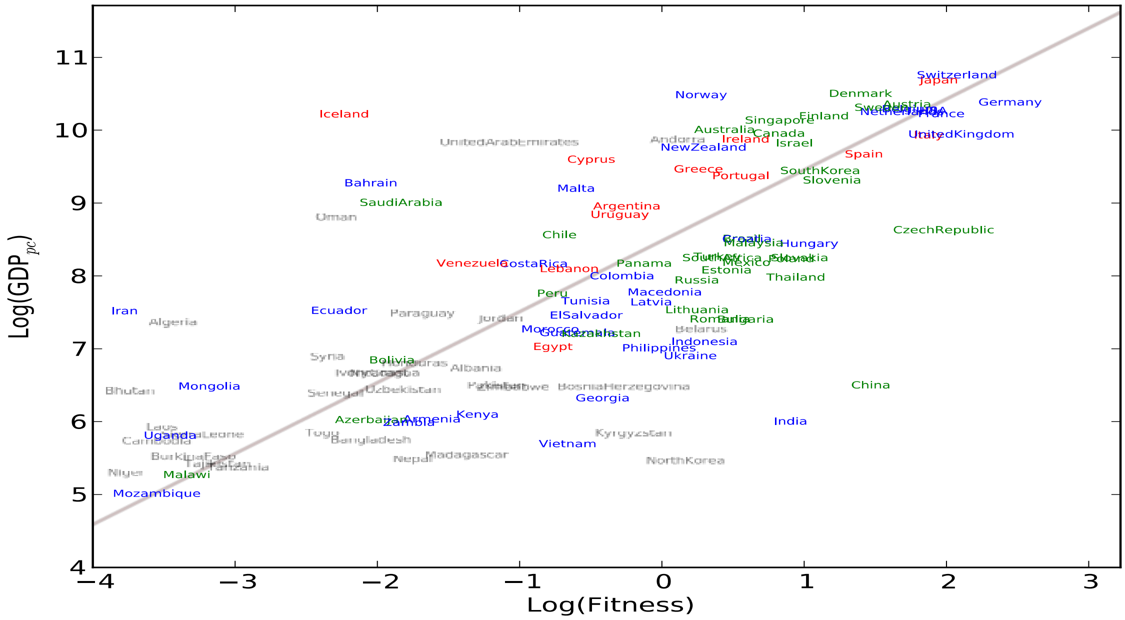
The fitness of a country we introduce measures the competitiveness of the productive systems and quantifies the intangible factors which determine the competitive advantage of a country. By comparing the fitness with the income of a country we can turn the metrics into a predictive tool for many macro-economic indicators of growth. In simple terms *it is like defining how good you are and compare it with how much money you make*. A country with high Fitness and low GDP is highly competitive and most likely it will grow in the future. This difference reveals a crucial information. Suppose a developing country is mature enough to jump into the making of higher sophisticated products than it used to make. This indicates that the country has made a quantum leap in productive terms, in so raising its fitness dramatically. The nation has shown the ability not only to evolve, but to improve its ability to evolve over and over, like in a virtuous circle. This might not be immediately noticeable in terms of revenues, but its future success is already there: in its still unexpressed potential that, eventually, will translate into a higher income. The opposite case represents a risky situation unless stabilized by external elements like the value of the exported raw materials.

Depending on whether a country has a lower or higher level of *per capita* income with respect to what expected given its level of fitness, we expect to detect strong and stable growth trends of countries in specific regimes. We observe the emergence of different regimes of economic complexity and in particular there exist several regimes for the dynamics with respect to the fitness. On this account, according to the position in the income-fitness plane, we are able to distinguish two main regimes: a laminar-like regime in which the fitness appears to be predictive or informative on the country growth and a chaotic-like regime in which the fitness seems poorly (or even completely) uncorrelated with the evolution of the country wealth. A more complete analysis which will be reported in subsequent studies (Ref. [19-20]) reveals an even richer ecology and at least four different types of dynamics can be uncovered (see Fig. 4):

- Low Fitness, low income: countries with a very low fitness tend to increase their fitness before entering in a fast growth rate, rather than reaching the equilibrium not modifying their fitness. In this zone the fitness is not big enough to be the driving factor of growth and development and it competes with other aspects, such as politics or climate.
- Low fitness, high income: in this area industrial competitiveness is not able to explain the income. Some of these countries have shown to be risky (e.g. Iceland, Ireland), others are oil-exporters. Here the dynamic is chaotic. All the countries which experienced a major downgrade of their rating in the past years are in this region (red trajectories in Fig. 4).
- Medium-high fitness, low income: here fitness becomes the driving factor and countries experience fast growth towards the equilibrium line. The flow is laminar and the level of predictability is maximum for this zone (green trajectories and big green arrow in Fig. 4).
- High fitness, high income: this region corresponds to developed countries (black trajectories) which produce almost all products, the flow is still laminar in the income-fitness plane but the dynamics is much slower and shows a reduction of industrial competitiveness, which is eroded by the emerging countries.

Concerning the second regime *(Low fitness, high income)*, the countries belonging to this area are characterized by a wealth which cannot be explained in terms of their industrial production. The origin of the missing competitiveness in some cases (for instance Ireland and Iceland) can be traced back to the fact that in our datasets services and finance are not included.

On other hand, the absence of services in principle may penalize countries strongly relying on these aspects as it happens for United Kingdom which has a fitness significantly lower than the other leading EU countries (i.e. Italy, France and Germany). However, we believe that countries as UK for which services and finance are crucial to estimate the competitiveness are very few. As an



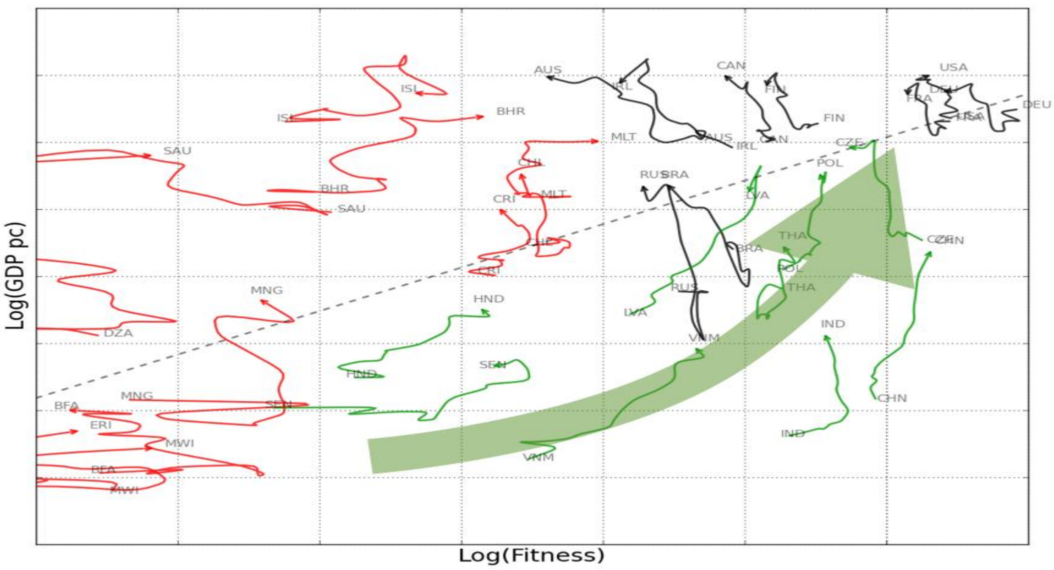


Fig 4 Fitness *versus* GDP: Heterogeneous dynamics and predictability

In the top figure we show the comparison of our fitness (industrial potential) with the GDP per capita for 1995. In the lower figure we show the dynamic evolution of a selection of countries in the subsequent 15 years, namely between 1995 and 2010. The idea is that the comparison between these variables can give new insight for growth prediction and risk analysis. For example countries like China and India in 1995 show an appreciable fitness but a rather limited value of the GDP. One could therefore predict a substantial growth as one can see in the lower figure. Also other countries in the lower-right part of the figure show a rather predictable behaviour leading to an average flow represented by the green arrow. In other parts of the diagram the dynamics is less predictable. This heterogeneous behaviour of the economic dynamics is a new concept which has important implications for predictability and risk analysis.

example, India, where many services of western countries are delocalized shows, as previously argued, a strong growth pattern even if services are not included.

In addition to this consideration, whether finance and services must be considered as a capabilities or as a product in the economic scenario of a country is still unclear. On this account Iceland case is an example of the fact that services and finance, if considered as products, have a different nature with respect to standard products considered in our dataset. Adding a product to the export basket is in general an advantage for countries, in the case of services and finance not necessarily. The economic system of Iceland, too much dependent on finance, has been the main cause of the default of this country.

We are developing a model based on the coarse grained dynamic features of the GDP-Competitiveness (i.e. the Fitness-Income plane) phase space (Ref. [20]). In particular we want our model to answer the following questions: given the level of income and the fitness at year x, what will be the level of income in year x+n? And how reliable is this forecast? The evolution of countries in this space is characterized, from preliminary analyses, by clearly heterogeneous behaviour. The fundamental consequence of this observation is that regression-like approaches are not a suitable tool to provide a correct quantitative description. New approaches must be developed to characterize this out-of-equilibrium scenario for economic growth. These situation calls for approaches closer to those used in meteorology.
We expect that reliable forecasts are possible only in the laminar-like flow regime of the growth phase space, and not possible only by means of studies of real industrial production in the chaotic regime.
We plan to extend our non-monetary methods for quantifying economic fitness to predict several monetary indicators such as sovereign debt behaviour, debt/GDP, inflation, etc. An alternative approach to deal with the observed heterogeneity in the GDP-competitiveness space phase is to consider the possibility that adding new variables to the analysis may reduce or eliminate the chaotic-like region. It is difficult to predict if this line of development can be successful but we will consider this possibility.

6. Spectroscopy of Countries Production

The information on a country productive competitiveness can be made much more structured and informative beyond the simple value of its Fitness. In fact we have all the information to define the complete production spectrum of each country. In Fig. 5 we show some examples. In the horizontal axis we list all the products ranked by their Complexity, the most complex are on the right. Then in the vertical axis we show the volume of the (export) production corresponding to the various products. In this way we can enter into the details of all sectors and products and go much beyond the simple value of the Fitness [19].

In Fig. 5 we show the production spectrum of the four BRIC countries for 2010. Clearly these data confirm the conclusions previously made in relation to Fig. 3 but permit a much more detailed analysis in terms of the complexity of the various industrial sectors.
One can see that China's production covers the whole spectrum up to the products of high complexity. In fact, according to our analysis, its industrial competitiveness is second in the world after Germany. For India the situation is good but there is a clear drop on the side of the high tech products. The situation of Brazil shows a decrease of high complexity products with respect to India and this trend is much more evident for Russia. Our conclusion is that, while for China and India the economic performance is based on a sound industrial competitiveness, for Brazil and much more for Russia the GDP performance is too much dependent on raw materials (and in general on primary sector) rather than on real industrial capabilities.

Fig. 5 Analysis of the production spectroscopy for the BRIC countries (2010)

In the horizontal axis products are ranked in terms of their complexity as arising from the new algorithm. The vertical axis represents the volumes exported for the various products. An analysis of the BRIC countries shows that their production spectrum is quite different confirming the preliminary analysis of Fig. 3.

7. Conclusions and Perspectives

We believe the analysis we have discussed represents a first step to a novel perspective for the study and industrial planning of a country, it also provides information on the GDP growth and an estimate of the global risk in relation of fundamental economics. We consider this step the beginning of a novel era for economics in which the large amount of high quality data and some original ideas permit us to move from qualitative to quantitative considerations.

The analysis we have shown can be clearly improved in many directions and it has natural additional lines of development we are considering. For example here we consider the triangular property of the matrix of Fig. 1 as the starting point of all our discussion and modelling. However, a very interesting question is to study under which conditions an economic system develops such a property. In this perspective the triangular matrix would be the final target instead of the starting point. We plan to develop an Agent-based model (ABM) for international trade and technological development which mainly focuses on two aspects:

- The interplay between specialization and diversification: how the loss in efficiency caused by a more diversified economy is balanced by an increased commercial competitiveness and stability.
- The role of the interconnectedness of the market (i.e. the Globalization) in the balancing between specialization and diversification

One of the primary goals of this model would be to give a microscopic and quantitative explanation of what are the mechanisms governing the real-world diversification of export baskets. But, more importantly, we expect the model to be able to outline a phase space defined by diversification and globalization and to give a better understanding of what the optimal strategies are for a given level of market interconnectedness.

The new metrics of F and Q, besides providing a quantitative measure for the complexity of national economies, also make available a self-consistent measure of the complexity of products. This can be the foundation of a novel perspective in the longstanding problem of the Theory of Value. Along this line it is possible to build a hierarchical categorization of products, unveiling links and interdependencies among them, and to integrate the resulting network structure with the novel information contained in the Product Complexity. With this novel characterization of the product-space we aim to study economic development of nations in the context of single industrial sectors, as emerging from the community detection in the product network. It is also possible to explore the possibility to extend this kind of analysis from the country-product network to the firm-patents network, with the objective of forecasting development at the single-company level.

This brings us to consider other elements in the economic production like individual companies and the process of development of new technologies [8,9] and [21-25]. The general considerations we have made about the economic complexity of countries and products find another fundamental playground for this other problems and INET has been giving seminal contributions in this direction [26-36]. The two driving forces behind the emergence of global system science are globalisation and connectivity across subject domains. A consequence of both is that, in an increasingly integrated market economy, business enterprises find themselves in rapidly changing environments. Traditional indicators of profitability, such as market share, are in many industries no longer predictive. Nor is being at the top of the industry rankings a promise of future success; the correlation time between company rankings have plummeted (many more companies now move in and out of the top, per unit time).

In this new approach economic growth is considered as a process of evolution of ecosystems of technologies and industrial capabilities. This implies to focus explicitly on the global network of technologies and study its dynamics, robustness and adaptability. From this study one can derive new concepts to control and predict which areas in the space of technologies are more likely to grow. The final goals will be to make better forecasts of technological progress and to provide quantitative methods that support better decision-making in the allocation of technology investments.

Bibliography

[1] Smith A (1776), The Wealth of Nations. W. Strahan and T. Cadell, London
[2] Ricardo D (1817) On the Principles of Political Economy and Taxation. John Murray.
[3] Romer PM (1990) Endogenous technological change. *Journal of Political Economy* 98: 71-102.
[4] Grossman GM, Helpman E (1991) Quality ladders in the theory of growth. *Review of Economic Studies* 58: 43-61.
[5] Flam H, Flanders MJ (1991) Heckscher-Ohlin Trade Theory. MIT Press, Cambridge MA.
[6] Gaulier G, Zignago S (2010). Baci: International trade database at the product-level. URL, http://www.cepii.fr/anglaisgraph/workpap/pdf/2010/wp2010-23.pdf
[7] Balassa B (1965) Trade liberalization and 'revealed' comparative advantage. Manchester School 33: 99-123
[8] Beinhocker, E. (2006). The Origin of Wealth: Evolution, Complexity, and the Radical Remaking of Economics. Boston: Harvard Business School Press.
[9] Beinhocker E. (2011). Evolution as Computation: Integrating Self-Organization With Generalized Darwinism. Journal of Institutional Economics, 7:3, 393-423
[10] Hidalgo, Cesar, Bailey Klinger, Albert-Lazlo Barabási, and Ricardo Hausmann, The product space conditions the development of nations, *Science* (2007) 317: 482-487.
[11] Hidalgo, C. and R. Hausmann. The building blocks of economic complexity. *Proceedings of the National Academy of Sciences,* (2009) 106: 10570-10575.
[12] Tacchella, M. Cristelli, G. Caldarelli, A. Gabrielli and L. Pietronero, A New Metrics for Countires Fitness and Products complexity, Sci. Reports 2, 723 (2012).
[13] Caldarelli G, Cristelli M, Gabrielli A, Pietronero L, Scala A, et al. (2012) A Network Analysis of Countries' Export Flows: Firm Grounds for the Building Blocks of the Economy. PLoS ONE 7(10): e47278. doi:10.1371/journal.pone.0047278
[14] M. Cristelli, A. Gabrielli, G. Caldarelli, A. Tacchella, L. Pietronero, New metrics for the economic complexity of countries and products, Submitted for Pubblication.
[15] M. Cristelli, M. Batty, L. Pietronero, There is more than a power law in Zipf, *Nature Scientific Reports* 2, 812 (2012)
[16] M. Cristelli, G. Caldarelli, A. Gabrielli, L. Pietronero, A. Scala, A. Tacchella, Competitors' communities and taxonomy of products according to export fluxes, *Eur. Phys. S.T.* 212, 115-120 (2012)
[17] A. Tacchella, M. Cristelli, G. Caldarelli, A. Gabrielli, L. Pietronero (submitted to *JEDC (2012)*)
[18] F. Battiston, M. Cristelli, A. Tacchella, L. Pietronero (submitted to *Complexity in Economics*)
[19] R. M. Crea, M. Cristelli, A. Tacchella, M. Viola, L. Pietronero (in preparation)
[20] M. Cristelli, A. Tacchella, L. Pietronero (in preparation)
[21] Lucas, Robert. E, Jr. On the mechanics of economic development. *Journal of Monetary Economics* (1988) 22: 3-42.
[22] Mankiw, N. Gregory, David Romer, David N. Weil. A Contribution to the Empirics of Economic Growth. *Quarterly Journal of Economics,* (1992) 107: 407-438.
[23] Boston Consulting Group, Perspectives on Experience. Boston Consulting Group Inc., 1968.
[24] K. Arrow, The Economic Implications of Learning-by-doing. Review of Economic Studies, 29

(1962) 155-173.
[25] L. Argote and D. Epple, Learning curves in manufacturing. Science, 247 (1990) 920-924.
[26] Farmer, J. Doyne and Jessika Trancik. “Dynamics of Technological Development in the Energy Sector. In *London Accord Final Publication*. Eds. J-P Onstwedder and M Mainelli. (2007).
[27] Bailey, A.G.; Bui, Q.M.; Farmer, J.D.; Margolis, R.; Ramamoorthy, R. (2012). Forecasting Technological Progress, in Proceedings of the International Workshop on Complex Sciences in the Engineering of Computing Systems, February 28, 2012, Munich, Germany. Lecture Notes in Informatics.
[28] Nagy, Béla, J. Doyne Farmer, Jessika E. Trancik, and John Paul Gonzales. Superexponential Long-Term Trends in Information Technology. *J. of Technological Forecasting and Social Change* 73 (2011): 1061-1083.
[29] Auerswald, Philip & Kauffman, Stuart & Lobo, Jose & Shell, Karl, 2000. "The production recipes approach to modeling technological innovation: An application to learning by doing," Journal of Economic Dynamics and Control, Elsevier, vol. 24(3), pages 389-450, March. McNerney,
[30] McNerney, James, J. Doyne Farmer, Sid Redner, and Jessika Trancik. “Role of Design Complexity in Technology Improvement. *PNAS* 108(22) (2011): 9008-9013.
[31] Rosenberg, Nathan. Inside the Black Box: Technology and Ec*onomics*. (1983) Cambridge: Cambridge University Press.
[32] Arthur, Brian. *The Nature of Technology: What It IS and How It Evolves.* (2009) New York: Free Press.
[33] Strumsky, Deborah, José Lobo and Sander van der Leeuw. “Using Patent Technology Codes to Study Technological Change.” Economics of Innovation and New Technology, (2012) Vol. 21, Issue 3, pages 267-286.
[34] Schwab, K. et al., *The Global Competitiveness Report 2011-2012,* World Economic Forum, Geneva, 2011.
[35] Nagy, Béla, J. Doyne Farmer, Quan M. Bui and Jessika E. Trancik, “Statistical basis for predicting technological progress”, http://lanl.arxiv.org/pdf/1207.1463v1.pdf (to appear in PloSOne).
[36] McNerney, James, J. Doyne Farmer, and Jessika Trancik. “Historical Costs of Coal-Fired Electricity and Implications for the Future. *Energy Policy* 39(6) (2011): 3042-3054.