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This version of 6 July 2022

Abstract

In this paper, we provide a brief overview of the field of complexity research in economics, and discuss directions of research that we consider to be promising in terms of solving open issues. We start the survey of the field with the research that emerged in the 1990s, when under the influence of earlier developments in the natural sciences (e.g., thermodynamics and chaos theory), the term complexity became in fashion to refer to theoretical ideas about how "ordered" patterns at an aggregate level can emerge from interaction between heterogenous agents at the microeconomic level. This gave rise to the notion of self-organization in dissipative systems, or "order at the edge of chaos" to describe economic dynamics. Because disequilibrium plays a large role in these theories, these ideas worked very well in combination with a Schumpeterian view of the economy, which also stresses disequilibrium.

In the current literature, economic complexity is mainly used to refer to the application of quantitative methods based on networks that can be created on the basis of very fine-grained data on production or trade. These data are used to produce aggregate measures of development, as well as to describe how production structures may evolve over time. This literature developed largely disconnected to the earlier complexity literature. The new economic complexity paradigm is largely void of economic theory, and instead aims to provide a set of data reduction techniques that are used to characterize development.

With regard to outlook for complexity research in (Schumpeterian) economics, on the one hand, we feel that the potential for analyzing the economy as a dissipative, out-of-equilibrium system has not been fully exploited yet. In particular, we propose that – in line with the field of "Big History" (which aims to describe and analyze a coarse history of the universe since the Big Bang) – there is work to be done on the larger issues in economics, in particular climate change and sustainability.

Keywords: Complexity; Complex systems; Economic dynamics; Schumpeterian economics; Disequilibrium dynamics; Economic complexity index;

JEL Codes: B52, O3, O31, O33

1. Introduction

Work presented at the bi-annual world conferences of the International Schumpeter Society has traditionally stressed the notion of the economy as a complex and evolving system. Such a view has strong roots in the work of Schumpeter himself, who developed this view over a 30-year period, from the *Theorie der wirtschaftlichen entwicklung* to *Capitalism, Socialism and Democracy*.

It is the aim of this keynote address to provide a brief outline of how the notion of complexity has been used and developed in the post-Schumpeter literature. Partly because it is such a broad concept, there are multiple ways in which complexity has been characterized and elaborated. We propose that this literature can roughly be divided into two parts: one that deals with the economy as a complex evolving system, and a later one that uses the term complexity to develop a set of methods that uses very disaggregated data to develop aggregate summary measures that aim to capture the key characteristics of the below-aggregate dynamics. These two strands of literature do not seem to have strong connections.

We will briefly discuss the two strands of complexity research below. Section 2 deals with the earlier literature that focuses on disequilibrium and economic evolution, while Section 3 looks at the "new" economic complexity literature. In Section 4, we briefly reach out to the field of so-called big history, which uses similar notions of disequilibrium and evolution. We use this section to make a plea for a return to addressing the big issues in economics, in particular sustainability and climate change, by focusing on systemic properties, and the way in which Schumpeterian economics provides an alternative to the mainstream equilibrium view. In Section 5, we summarize the main line of argument.

2. Complexity in Schumpeterian economics

The core of Schumpeter's economic thinking is that innovation is the driving factor in the dynamics and evolution of the economic system. While the mainstream economic theory sees economic dynamics as an equilibrium process that tends to a steady state, Schumpeter stressed the role of disequilibrium, even though he was inspired by the equilibrium system proposed by Walras. His *Theorie der wirtschaftlichen entwicklung* (Schumpeter, 1911), which was published in German and revised in the same language in 1926, then translated into English in 1934 (Schumpeter, 1934), contains the most comprehensive description of the role of equilibrium and disequilibrium in his theory.[1]

The central role in Schumpeter's disequilibrium process is played by the entrepreneur, who introduces innovation ("new combinations") into the economy. These innovations create disequilibrium, which is illustrated by the reference to Walrasian theory. In the

[1] Becker and Knudsen (2002) provide an overview of how this argument changed through the two German and one English editions, and also provide translations of German parts that do not appear in the original English translation.

Walrasian general equilibrium, the actions of the various economic agents lead to a state in which there are no incentives for change, as all behaviour is optimal. As the subsequent body of general equilibrium theory (Arrow and Debreu, 1954) argues, competition brings down profits to a uniform (and relatively low) rate of return to capital. Schumpeter's entrepreneur disrupts this equilibrium by creating higher profits by means of innovation.

Schumpeter (1939) saw (major) innovation as clustered in time, with "bandwagons of imitation" gradually eroding the large profits that innovation initially bring. The process of innovations disrupting equilibrium and imitation gradually bringing equilibrium back leads to long business cycles (see also the literature that closely followed Schumpeter's ideas from the 1970s onwards, e.g., Mensch 1979; Freeman et al., 1992). However, the economy is always out-of-equilibrium, because when the equilibrium steady state seems to come into reach, it is disrupted again by innovation.

In such a setting, the tools of economic equilibrium theory are of little use. This is why neo-Schumpeterians (e.g., Dosi et al., 1988) started looking for alternative (modelling) tools. They found inspiration in the natural sciences, especially in the field of thermodynamics systems theory (see, e.g., the popular account in Prigogine and Stengers, 1984). In this view, equilibrium-based mainstream economics is viewed as an emulation of physics and the steady state equilibrium that it embraces (Mirowski, 1991), while the theory of dissipative systems in thermodynamics is more in line with the notion of disequilibrium in Schumpeterian thought.

The key of dissipative systems is that they are open, i.e., they exchange energy and matter with their environment. A closed thermodynamic system will be subject to an irreversible process of increasing entropy, where we can see entropy as "degraded energy" that results as waste when heat is transformed into work. In a stylized example of a steam engine, we may imagine heat in the form of steam (water molecules) in a boiler separated from a cold area. Work is performed by letting the heat flow through a cylinder, thereby moving a piston that sets a wheel in motion. If the engine is a closed system, i.e., if we do not keep firing the boiler with more coal and oxygen brought in from outside, the engine will stop working when all heat is transformed into entropy, which corresponds to a mix of the cooled water molecules with their environment. Because this process is irreversible (entropy cannot be transferred back into heat in the closed system), the high-entropy state represents an equilibrium.

A dissipative system can avoid this thermodynamic equilibrium in which entropy is maximized, by bringing in energy from the outside. This means that a dissipative system operates (far) from equilibrium, but, as Prigogine and Stengers show, dissipative systems often exhibit structure, order and dynamic stability. It is this idea that attracted the neo-Schumpeterians in search of a dynamic disequilibrium theory reflecting Schumpeter's ideas. The key idea (Verspagen, 2005) is that with Schumpeterian disequilibrium dynamics, the world looks radically different from the mainstream equilibrium-based steady stage growth process in which everything grows at a constant rate (e.g., Solow, 1956; Romer, 1990).

The neo-Schumpeterian focus on dissipative systems can be situated in the broader field of complex systems and so-called self-organization. In the words of Silverberg (1988, p. 531):

> The theory of self-organisation deals with complex dynamic systems open to their environment in terms of the exchange of matter, energy and information and composed of a number of interacting subsystems … Many such systems have been shown … to lead to the spontaneous emergence of coherent macroscopic structures … from the seemingly uncoordinated behaviour of the component parts at the microscopic level. Moreover, self-organising systems can undergo a succession of … structural transformations.

This has roots in other earlier work in the natural sciences (Silverberg discusses, among others, Eigen, 1971; Haken, 1983), and gained momentum in the 1990s, partially under the influence of the Santa Fe Institute which brought together scholars from a range of (social) sciences, and united in the application of the complex systems idea to their fields (popular early accounts of research in this field are Lewin, 1992 and Waldrop, 1992). As the quotation from Silverberg emphasizes, the main idea in complex systems theory is that interaction at the micro level (in economics, e.g., interaction between individual firms, or between firms and consumers), while uncoordinated by higher-level structures, may lead to order at the aggregate level, either in the form of structurally stable outcomes (such as an economy operating near to full employment), or of dynamic equilibria that are characterized by change.

These aggregate ordered outcomes of systems with interacting agents (complex systems) are often called emergent properties of the system. Fuentes (2014) provides a formal definition of an emergent property as a discontinuity of an effective complexity measure along a particular property. Emergent properties have also become a key focus in so-called Agent-Based Models (ABMs), which attempt to formally model and simulate the micro-level interactions of complex systems, in order to observe emergent properties at the aggregate level (for an early overview, see, e.g., Tesfatsion, 2002; and see Dosi et al., 2010 for an application to Schumpeterian dynamics).

As the title of Waldrop's popularizing book (*Complexity. The emerging science at the edge of order and chaos*) suggests, the field of complexity science is closely related to the mathematical field of chaos theory (see Gleick, 1987 and Ruelle, 1991 for early popular accounts). In chaos theory, nonlinear dynamic models produce unpredictable outcomes that are hyper-sensitive to initial conditions. Thus, a model that is simulated with two sets of initial conditions that are very (up to a large number of decimals) similar may produce two very different outcomes after a few periods of simulation. The weather is seen as a standard case of this type of chaotic behaviour).

Chaos is an extreme example of disequilibrium, and Langton (1990) suggests that it is part of a continuum of types of systems behaviour, on which also the emergent properties of complex systems lie. He draws on the work of Wolfram (1984), who shows that cellular automata may produce different types of behaviour, such as reaching a homogenous state, periodic structures (cycles), chaos, and "very long transients" (Langton, 1990, p. 16). Langton shows how cellular automata may be parameterized, and how varying the key parameter

> we encounter a *phase transition* between periodic and chaotic dynamics, and while the behavior at either end of the … spectrum seems "simple" and easily predictable, the behaviour in the vicinity of this phase transition seems "complex" and unpredictable. (Langton, 1990, p. 24, original emphasis).

As suggested in the title of Langton's paper, this has led to the idea of complexity as a phenomenon that lives at "the edge of chaos".

Frenken (2006) provides a relatively early survey of how these ideas about complexity have been applied to the field of Schumpeterian analysis of innovation and economic change. He distinguishes three main categories: fitness landscapes, networks, and percolation models. In the category of fitness landscapes, the NK landscape model (Kauffman and Weinberger, 1989; Kauffman, 1993) represents evolution as a search for (local) peaks on a landscape. The NK landscape is N-dimensional and can be tuned in terms of the number of peaks that it displays by the parameter K. The larger K, the more "rugged" the landscape is, and the more difficult it becomes to find the global optimum by "walking the landscape". The NK model has been used by Levinthal (1997) to represent Schumpeterian innovation in a management science context. Another example is Frenken and Nuvolari (2004), who apply the model to the early history of the steam engine.

The second category of complexity approaches distinguished by Frenken (2006) is that of network models. He distinguishes approaches that model networks of agents (mostly innovating firms), as well as networks of technologies. In the networks of agents category, the small worlds model (Watts and Strogatz, 1998) is particularly influential. This approach is about how path length evolves as a function of the network structure, in particular "cliquishness", which is how cluttered the network is in terms of densely connected local neighbourhoods. Path length is seen as representative, for example, for how easily technological knowledge flows through a network. In the small worlds model, path length declines very rapidly when cliquishness decreases only marginally, which is reminiscent of the phase transition identified by Langton.

Another type of networks discussed by Frenken is that of endogenous networks, where theory explains the formation of network links between agents. An example is the principle of preferential attachment, which leads to networks in which centrality (how many links a node has) is distributed over nodes in a highly skewed way (so-called scale free networks, see Albert and Barabási, 2002).

Finally, Frenken (2006) distinguishes models based on percolation as a separate category of approaches. These models are used either for adoption of innovation, or for the dynamics of technology development. In the latter category, Silverberg and Verspagen (2005) perceive innovation as movement in a 2-dimensional lattice, where one dimension represents technological distance, and the other technological performance. Feasible technologies are those that represent an unbroken chain in this lattice, and R&D is performed by firms to find new "sites" to existing chains. This yields innovation size distributions that are very skewed, corresponding to the empirical reality in which many incremental innovations are observed, but only few radical ones.

Frenken's survey does not include agent-based models (ABMs), or models that are primarily aimed at economic phenomena such as economic growth or industrial dynamics. As we already stressed above, the ABMs especially relate strongly to the complexity idea by their focus on emergent properties. Full scale ABMs in Schumpeterian innovation analysis were preceded by smaller simulation models, for example Silverberg et al. (1988), who look at industrial dynamics in a dynamic economy with endogenous innovation, and Silverberg and Verspagen (1994), who look at long waves of innovation and economic growth. Pyka and Fagiolo (2007) provide an early survey of this literature. More recently, Schumpeterian ABMs have addressed more traditional macroeconomic issues, e.g., Dosi et al. (2010).

3. The "new" paradigm of economic complexity

While the work on complex systems is certainly still buoyant, also in the fields of innovation economics and economic geography, the term complexity and especially "economic complexity" is now predominantly used for a distinct subfield of the economic literature. This is the "economic complexity theory" (Hidalgo, 2021) or the "new paradigm of economic complexity" as Balland et al. (2022) call it. In his review article of the field, Hidalgo (2021, p. 92) refers to six "scholars [who] have long recognized economies as complex systems". Of these six, we would place at least the first four (Beinhocker, 2006; Holland & Miller, 1991; Miller, 1991; Kauffman, 1993) in the complex systems literature that we briefly summarized in the previous section. This suggests a continuity between the literature reviewed in the previous section and the new economic complexity literature.

On the other hand, Hidalgo (2021, p. 93) argues that "economic complexity can be … seen as a continuation of endogenous growth theory" and cites Romer (1990) and Aghion and Howitt (1992) as examples of this theory. Above, we already referred to Romer (1990) as an example of the type of equilibrium theory that is at odds with the Schumpeterian idea of disequilibrium. Aghion and Howitt, on the other hand, explicitly refer to Schumpeterian ideas such as creative destruction, and these authors have repeatedly referred to their own work as part of "Schumpeterian growth theory". However, while we do not wish to put an exclusive claim on Schumpeter's ideas, it is also fair to say that Schumpeter's idea about disequilibrium, as summarized above, are not part of these models (see Alcouffe and Kuhn, 2004 for a similar argument).

Similarly, Balland et al. (2022) argue that "economics has had difficulty in studying technology. It has tended to measure it through its consequences: as a shift parameter in aggregate production functions such as measures of total factor productivity ... But it does not provide a connection from its consequences to its causes". This is flat-out ignorance about the Schumpeter-inspired work on endogenous innovation, as well as the equilibrium oriented endogenous growth theory that Hidalgo refers to. And in particular it ignores the neo-Schumpeterian complexity literature that we summarized above, which criticizes the mainstream economics treatment of technology some 35 years prior to Balland et al. (2022), and subsequently built a wide catalogue of alternative approaches.

In terms of theoretical building blocks, the new economic complexity idea is based on the notion of capabilities, i.e., that in order to produce (or successfully export) particular products, specific productive and technological capabilities must be attained. These capabilities must be acquired by economic agents (firms), which requires resources and is a dynamic process. This idea of capabilities is also an important tenet of the Schumpeterian literature (see, e.g., Fagerberg et al., 2010 for an overview of this topic from the macro point of view; Dosi and Teece, 1998 take a micro perspective).

The new economic complexity literature adds the idea of relatedness (Frenken et al., 2007) to that of capabilities. While "relatedness measures the affinity between a location and an activity" (Hidalgo, 2022, p. 97), activities also share capabilities. This implies that relatedness can be seen as a predictor of which activities a location may newly develop, i.e., those that require capabilities that the location already possesses for the activities it currently undertakes. This idea of relatedness is closely related to that of "local search" by firms. For example, Nelson and Winter (1982) suggested that firms generally change their routines in small steps, while Levinthal (1997) models local search as walking down local paths on the NK landscapes imagined by Kauffman and Weinberger (1989). Sahal (1981) and Dosi (1982) argue that most innovation efforts by firms is aimed at incremental improvements on a basic design, which again suggests local search.

Although capabilities and relatedness are basic ideas underlying the new paradigm of economic complexity, they are not central elements in the development of this literature. While the early complexity literature as summarized in the previous section puts a lot of emphasis on elaborating the theoretical features of how the economy works, and what the likely outcomes of the market process in terms of growth and distribution are, the new economic complexity literature takes no specific interest in these issues. Instead, Hidalgo specifies the basic aim and achievement of the new literature as the development of relatedness and complexity *metrics*, which he describes as estimating "the availability, diversity and sophistication of the factors or inputs present in an economy … Unlike previous approaches to economic growth and development, … relatedness and complexity methods are agnostic about the nature of factors. Instead, they try to estimate their combined presence, without making strong assumptions about what these factors may be" (Hidalgo, 2021, p. 92).

Balland et al. (2022, p. 3) argue that these metrics "add to the toolbox of economics" by offering a dimensionality reduction technique that is tailored to the problem of how innovation is related to development (this is also stressed by Hidalgo, 2021). Dimension reduction refers to the process in which (micro) data are collapsed in other ways than mere aggregation, while preserving more information than aggregation would preserve, thus highlighting important properties of the system at the aggregate level that would remain hidden by mere aggregation. Thus, the information that is contained in the proposed (reduced) metrics is "useful for predicting economic growth, income inequality, and greenhouse gas emissions" (Hidalgo, 2021, p. 92; this point is also made in the overview by Balland et al., 2022).

As data reduction and the use of the reduced measures seem to be the main point of the new complexity literature, rather than arriving at a theoretical understanding of how the economy works, it would seem useful to compare the outcomes of the proposed complexity measures to those of other data reduction methods. Principal Components Analysis (PCA) is a well-known method of data reduction, which has been applied widely. Although it is clearly different from the Economic Complexity Index (ECI) proposed by Hidalgo and Hausmann (2009), which, in modified form, has become the standard of the literature, there are also some striking similarities in the technical workings of the two methods (Kemp-Benedict, 2014). Both methods draw on spectral decomposition (i.e., eigenvectors) of some matrix, which is computed as the product of 'some' normalization/ standardization of a common matrix M with 'some' normalization/standardization of the transpose of M.[2] The only difference is the ways in which the matrix M and its transpose are normalized/standardized.[3]

We present a brief comparison of the two methods for a dataset on international trade (value of exports) for the year 2012, covering 155 countries and 1,224 product classes in the 4-digit Harmonized System classification system in the appendix. We use both methods to map countries into *product space*, where the latter is defined as the two main dimensions that can be derived from each method. For PCA, these are the two first principal components. For ECI, we use the second and the third eigenvector of the complexity matrix (the first eigenvector is trivial; for details, see the appendix and the references there). Because the ECI method is more or less without theory, we see no

[2] M is the matrix of Revealed Comparative Advantages (RCA), elements of which indicate the extent to which a given country is 'specialized' in a given product.
[3] PCA standardizes columns of M (and rows of M transpose) by *z*-scoring, while ECI normalizes individual columns of both M and M transpose by their respective column sums.

reason why the interpretation should be restricted to the second eigenvector, and hence we also include the third.

Overall, the comparison shows that PCA and ECI both provide useful data reductions, that provide insights into what characterizes developed countries relative to less developed countries in terms of their trade patterns. If one would use the metric of correlation to GDP per capita, the ECI (second eigenvector) provides the best result. However, without a theoretical question that goes beyond asking for the highest possible correlation, there seems to be little reason to prefer either PCA or ECI over the other method.

4. Complexity and the "cosmological question"

The idea of complexity as related to dissipative systems (and hence the parallel to thermodynamics) also plays a large role in the field of big history (e.g., Spier, 2005, 2011; Chaisson, 2014). Big history aims to write a coarse history of the universe since the big bang, (necessarily) zooming out to a very general level. This is operationalized as the study of the emergence and evolution of complexity, where complexity is defined in the thermodynamic sense. Spier (2005, 2011) proposes to measure complexity by energy density (the amount of energy flow per unit of mass). Building on the theory of dissipative systems, complexity then arises in small regions of the universe (like planet Earth) where a state of low entropy (= high complexity) persists. This is "compensated" by other parts of the universe where entropy increases, leading to a net increase in entropy in the universe as a whole. Spier proposes the emergence of life as a first stage of complexity, followed by emerging civilization including an economy and culture. In Spier's view, increasing human complexity is closely related to increasing energy density in those systems.

Aunger (2007) links this interpretation of big history to Schumpeterian ideas about cycles, as, for example, in Schumpeter (1939) and Freeman and Loucã (2001). He views big history as a series of punctuated equilibria, which are separated by so-called non-equilibrium steady state transitions. These transitions are initiated by an energy-related innovation (e.g., the use of machinery during the 1st Industrial Revolution), which are coupled with organizational innovations (e.g., the factory system), and "control" in the larger societal system (e.g., in the form of institutions). This punctuated equilibrium sequence is reminiscent of the Schumpeterian theory of socio-economic paradigms (Freeman and Perez, 1988), and the regulation perspective of Boyer (1988). The emphasis on energy and entropy also reminds us of Georgescu-Roegen (1971) and the ecological economics that followed it.

The highly abstract big history reasoning is hard to apply to economics, because there is no obvious counterpart to the use of entropy in economic theory. In big history (or thermodynamics more generally), order and complexity correspond to a low entropy state. Although entropy as a concept has been used in economics (as an indicator of structural diversification), it does not have the same meaning as in the big history literature, and hence cannot be used as a generic measure of complexity. But the systemic evolutionary approach of Schumpeterian complexity economics seems very appropriate to address the big societal challenges in a comprehensive way. This is what Heilbronner (1984, p. 682) has called

> the cosmological problem of economics, namely, the social configurations of production and distribution-if you will, the macro and micro patterns-that ultimately emerge from the self-directed activities of individuals. That problem was first resolved by Adam Smith in his extraordinary depiction of a society that generated from its spontaneous activity both a tendency toward internal order and "external" expansion. What is remarkable about Marx, Keynes, and Schumpeter is that they are among the very few who have proposed resolutions to this problem of an imagination and scope comparable to that of Smith-but that their resolutions differ from one another almost totally. In Marx's great schema the system is destined to pass through successive crises that both alter its socioeconomic texture and gradually set the stage for a likely final collapse of some sort. In Schumpeter's view, the dynamics of the system give rise to a prospect of long-term, continually self-generated growth-not quite the "hitchless" growth of Smith's model-but growth dependable and powerful enough to form the basis for Schumpeter's "plausible capitalism." In Keynes the trajectory is much less certain because it depends on the outcome of a tug of war between the animal spirits of entrepreneurs and the constraints of saturable markets and propensities of thrift-a tug of war whose outcome, however, can be remedied by appropriate government intervention.

It seems unescapable that in the current day and age, Heilbronner's cosmological problem must include sustainability, i.e., it must concern the social configuration of production, distribution, as well as the living environment. It seems to us that the Schumpeterian view of the economy as a complex, evolutionary system is particularly well equipped to include sustainability into the analysis (see, e.g., Gowdy, 2013). But at the same time, it is probably also true that there is a contradiction between, on the one hand, Schumpeter's early, optimistic view about innovation stimulating growth, and the compatibility between growth and sustainability on the other hand. The unbridled capitalism of the early Schumpeter may well have come to the point of overstepping planetary limits.

Thus, we may be up for another transition of Schumpeter's (1942) "plausible capitalism". Whereas Schumpeter (1942) saw capitalism moving in the direction of socialism, this time we need a transition aimed at "sustainability" instead of "socialism". Academic work in the Schumpeterian tradition of complexity should be able to enlighten us about how a sustainable economic system, and society at large, may function, what role is to be played in such a system by entrepreneurs, workers, consumers, and governments. More likely than not, and in line with older debates in economics, such a Schumpeterian theory built on complexity will be very different from and much more useful than the equilibrium theories that are dominant in the mainstream.

5. Conclusions and outlook

Complexity is a guiding principle that enables natural scientists and social scientists alike to build a disequilibrium theory about development of evolutionary systems. This has been a major inspiration for economists working in the Schumpeterian tradition, in particular in the International Schumpeter Society. Complexity is also the chosen summary concept in a more recent economic literature that deals with relatedness and diversification. However, as we have argued in this paper, in this “new” literature, the meaning of the term complexity is very different from the earlier Schumpeterian literature, and there is no real effort in the new literature to connect to Schumpeterian ideas. Rather, it refers to the use of a set of new and original data reduction techniques.

We see the further development of complexity as a topic in the Schumpeterian community as an opportunity to extend our understanding of how disequilibrium leads to ordered patterns in evolutionary economic systems, i.e., we propose to keep building on the “old” complexity ideas. We also see these ideas about disequilibrium and evolution as a potentially fruitful theoretical basis for the “new” economic complexity literature. In this way, the data reduction techniques that are developed in the “new” literature may both find new and fruitful applications, and become better founded in theory. Without a foundation that can yield precise research hypotheses built on theory, the value of the proposed data reduction techniques may remain limited and *ad hoc*.

However, and above all, we argue that the complexity idea needs to be applied to the big societal challenges, first and foremost climate change and sustainability. Schumpeter is celebrated as a visionary because of his “grand views” on the functioning of capitalism. These views are well summarized and applied in the complexity literature on economic evolution. But Schumpeter was also aware that such systems produce history, i.e., they are path dependent and show irreversible structural transformations. Schumpeter witnessed such changes in the organization of innovation, which led to his *Capitalism, Socialism and Democracy*. It is for the current generation of scholars to witness the transition to a more sustainable economy, and to integrate this into a theory of *Capitalism, Sustainability and Democracy*.

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Appendix. Comparison of the economic complexity index and principal components analysis

Both methods (PCA and the economic complexity index) are implemented for a dataset on international trade (value of exports) for the year 2012, covering 155 countries and 1,224 product classes in the 4-digit Harmonised System classification system. We calculate the Revealed Comparative Advantage (RCA) indicator (scaled continuously in the [0,1] interval) of each country in each product class.

For the PCA analysis, the 1,224 products are considered as variables, and the 155 countries as observations. We then look at the first two principal components in the data (factor scores). These are constructed as weighted averages of the country's RCA, using the factor loadings as the weights. These loadings are the two eigenvectors corresponding to the two leading eigenvalues of the correlation matrix of the variables. These two principal components capture 35.2% of the total variance in the RCA data. The top panel of Figure 1 plots the 155 countries in the space corresponding to these two principal components. In other words, while without data reduction, the 155 countries are represented in a 1,224-dimensional space, they are now plotted in 2-dimensional space.

For the economic complexity measure, we first create a row-normalized and a column-normalized version of the comparative advantage matrix (RCA values arranged products by countries). The row-normalized version is created by dividing each element of the matrix by the sum of the column (sum of all RCA values of the country), and the column-normalized version is created by dividing each element by the sum of the row (sum of all country's RCA values for the product). We then create a new matrix by pre-multiplying the column-normalized version of the matrix by the transpose of the row-normalized version. This matrix plays a similar role in the complexity calculation as the correlation matrix of product RCAs in the PCA.

The first eigenvalue of this matrix is equal to 1, and the eigenvector belonging to this has identical values for each product. Hence we may consider it as a trivial case, and divert our attention to the second-dominant eigenvalue.[4] Product complexity is defined as the eigenvector that belongs to the second-dominant eigenvalue of the matrix. A country's Fitness can be calculated as the weighted average of the country's RCA values, using the eigenvector as the weights.[5] Hence we see the similarity to PCA in the use of eigenvectors as weights for RCA.

[4] The iterative procedure proposed in Hidalgo and Hausmann (2009) converges to the first eigenvector, but Hidalgo (2021) proposes to use the second-dominant eigenvalue and associated eigenvector.

[5] Or, one may transpose the original RCA matrix, normalize and multiply in the same way as before, and derive Fitness as the eigenvector belonging to the second-dominant eigenvalue of this matrix. The two ways are equivalent.

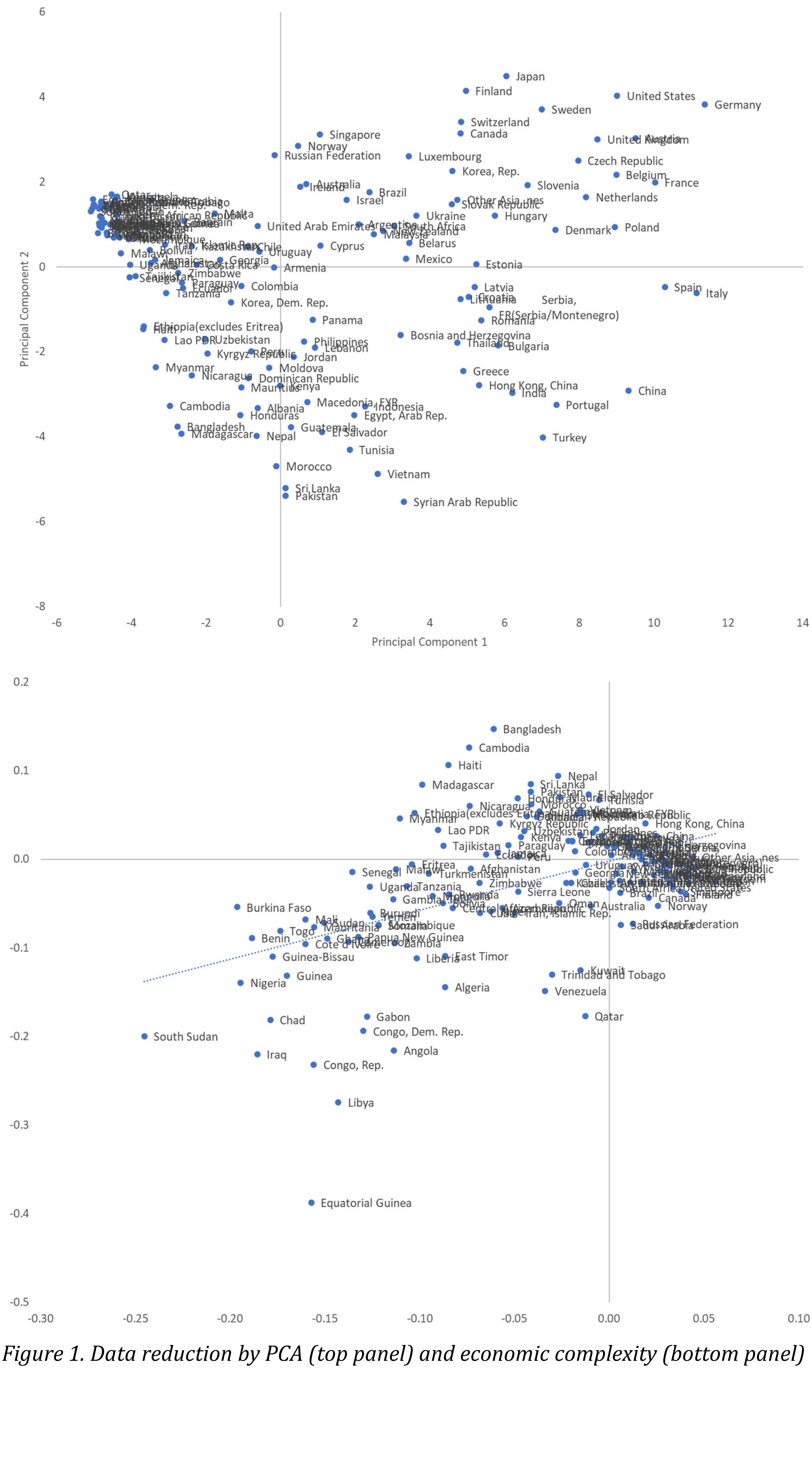

Figure 1. Data reduction by PCA (top panel) and economic complexity (bottom panel)

The complexity literature limits itself to the second-dominant eigenvector, considering this as the "Economic Complexity Index" (what we called Fitness above). However, there are N – 1 other non-trivial eigenvectors, so there is no reason to exclusively focus on the second-dominant one. Therefore, and similar to how we use the first two principal components in Figure 1, we plot the countries in the 2-dimensional space that corresponds to $Fitness_1$ and $Fitness_2$, which use the second- and third-dominant eigenvector, respectively. The two eigenvalues that are used for this correspond to 9.1% of the sum of all eigenvalues, while the first eigenvalue (equal to 1) corresponds to another 28.7%. While we reduce the original RCA data to two dimensions, we could obtain the 1-dimensional measure preferred in the new complexity literature by using only the horizontal axis of Figure 1.

The principal components and the fitness measures are correlated to each other: PC_1 and $Fitness_1$ have R = 0.807, PC_2 and $Fitness_2$ have R = –0.611. Nevertheless, there are some clear differences between the two data reduction methods. One of them is that while the principal components are orthogonal (zero-correlated) by construction, the Fitness measures are not. They show mild positive correlation, as indicated by the dotted trendline. Because this correlation is (very) far from complete, it is clear that the second eigenvector adds information, relative to the first. It appears that the economic complexity method, just like PCA, faces a trade-off between the degree of data reduction (i.e., lowering the number of eigenvectors) and the information present in the reduced data.

The other thing that immediately catches the eye is that both data reduction measures yield a part of 2-D space that is very cluttered, i.e., where a group of countries has very similar values in both dimensions. But this happens in very different parts of 2-D space: for the PCA method, it is mostly developing (low income) countries, while for the economic complexity method, it is mostly developed (rich) countries that are present in the clutter. Thus, which method provides most useful insights depends on which group of countries one is interested in.

From the comparison of the two data reduction methods, it is impossible to judge which one is "better". If one wants to take the correlation to (log) GDP per capita as a yardstick, then the economic complexity index ($Fitness_1$) performs better than the first principal component. However, also $Fitness_2$ and the subsequent $Fitness_3$ (which we have not documented in Figure 1) are also significant in a multiple regression for GDP per capita. In a technical interpretation, Fitness correlates stronger to GDP per capita than the principal component(s) because Fitness tends to stress differences between poorer countries (the cluttering in Figure 1), which have more variable growth rates (and per capita GDP levels). However, the literature does not offer a strong theoretical logic as to why this would happen, therefore the empirical superiority of either measure remains largely undecided.

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