Structural Change and Economic Dynamics 39 (2016) 17–30

Contents lists available at ScienceDirect

Structural Change and Economic Dynamics

journal homepage: www.elsevier.com/locate/sced

The mature stage of capitalist development: Models, signs and policy implications

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ARTICLE INFO

Article history:
Received 1 August 2015
Received in revised form 27 May 2016
Accepted 7 June 2016
Available online 15 June 2016

Keywords:
Complex adaptive systems
Autocatalysis
Capitalism
Development stages
Economic growth

ABSTRACT

We investigate the possibility that capitalist economies – those that industrialized first and the whole OECD group – may be reaching the growth plateau naturally, in a similar way to other complex systems in nature. In the system model of autocatalytic growth we introduce endogenous and exogenous variables that provide negative feedbacks to material growth and push the economic system into the mature stage of development. Based on general developmental stages for dissipative systems, we identify variables that would uniquely mark the transition to maturity: p.c. energy consumption, GDP and energy consumption distribution, and sector composition of labor and GDP. Empirical findings suggest that the observed groups of economies may have terminated their historic phase of intensive economic growth and are entering the mature stage. This provides a tentative explanation of the observed slow-down of long-run rates of GDP growth in the G7 economies and in Western Europe.

1. Introduction

Global economic growth is a phenomenon that started about 1000 years ago, accelerated in the West since 1820 (Maddison, 2007, 73) and, again, in the post WWII period (International Bank for Reconstruction and Development (IBRD, 2008). The scale and speed of growth of the global socio-economic system since the mid- 20 century has been phenomenal—humanity has become a planetary-scale geological force in a single lifetime (Steffen et al., 2015a). Recently, some economists pointed out that long-run rates of growth have been declining in some of the largest and most advanced world economies—the so called G7 Group: US, Canada, Germany, UK, France, Italy and Japan (Diaz et al., 2014a,b; Schmelzer, 2015) and, more generally, in Western Europe (Chancel et al., 2013).

While it is widely recognized that modern economic growth, based on capitalist institutions, reduced poverty and raised the standard of living to unprecedented levels in the Western world, it has also caused depletion of natural resources and energy at the planetary scale. The pressure of economic activity on natural sources and sinks brought to critical condition many ecosystems globally (Millennium Ecosystem Assessment, 2005; Foley et al., 2005), and transgressed or approached the boundaries of several critical earth-system processes (Rockström et al., 2009a,b; Running, 2012; Steffen et al., 2015b). According to Burger et al. (2012) we have already surpassed the capacity of the earth to supply enough of essential resources to sustain even the current world population at the current levels of socioeconomic development in the West. These worrying developments are pointing not only at the physical limits of growth (Meadows et al., 2004) but rekindle an old debate whether capitalism[1] can be sustainable or not (O'Connor, 1994) and could it operate in a steady state (Smith, 2010; Lawn, 2011)—a condition that is generally accepted as a paradigm for sustainability.

This phenomenon of simultaneous approaching of planetary biophysical limits and declining long-run growth rates prompts the question if some systemic, endogenous, causes in concert with pressing global bio-physical constraints may put a long historic

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[1] We understand capitalism as a market driven economy with varying dose of state intervention and where private ownership over tangible and intangible capital prevails.

http://dx.doi.org/10.1016/j.strueco.2016.06.001

phase of capitalist growth to a definitive halt. More precisely, we are posing two research questions: (1) can a capitalist economy reach maturity naturally, in a similar way to other complex systems in nature, and (2), how observed decline in long-run growth rates may fit into this process. We propose a theoretic framework that relates the ending of economic growth to a mature stage of capitalist development and identify a set of variables that likely mark the transition to maturity, as well as negative feedbacks – environmental and economic – that are instrumental in that stabilizing process. Then we apply this theoretic framework at the group of economies that industrialized first and the OECD group and look for signs of transition to maturity. This ought to be the major contribution of the present work.

By looking at the market economy from a naturalist perspective, as an energy and matter transforming system that serves the purpose of providing for human material needs (Annila and Salthe, 2010; Herrmann-Pillath, 2015) we open the door of the socioeconomic domain to a general developmental theory of dissipative structures. By exporting theories from natural sciences we stress the view that all phenomena that concern the transformation of energy and matter on small or large scales, including humans and their organizations, should be viewed as reflecting certain general principles. From the practical perspective, we believe that if we reach a more natural understanding of a system's developmental tendency, then we can hope to achieve a better informed platform for policy making.

The paper is organized as follows: in the second section we present our theoretical framework and discuss systemic aspects of economic growth and development; the third section presents empirical data on the signs of maturity in a selected group of economies; the fourth and the fifth and sections close with discussion and conclusions respectively.

2. Theoretical framework

We are grounded in the understanding that economies are members of two large classes of natural systems: (1) dissipative systems (Prigogine, 1980) wherein order is temporarily created by using a free energy source while exporting entropy to the environment, and (2) its particular subclass—complex adaptive systems (Holland, 1995) wherein the process of order creation is additionally mediated by a large number of diverse, interacting agents which are capable of storing and transmitting information in time, and thus possess the ability to adapt and evolve.

We shall place economic growth[2] within a developmental framework, inasmuch as evolution is really not predictable (Salthe 1993; Longo et al., 2012), and use autocatalytic dynamics (Ulanowicz and Hannon, 1987; Ulanowicz, 1997) as the basic mechanism for growth and a source of negative feedbacks arising within the system itself.

Our discourse, therefore, is not about the evolution of societies, which is an unpredictable and open-ended process. We start from a general definition of development as 'predictable irreversible change', which has the properties of being directional, systematic and progressive (Salthe, 1993). Economic science does not provide a clear-cut definition of economic development which it is often equated with growth or confused with economic evolution. However, developmental economics points at some common features of development like changes in output distribution and economic structure (as, for example, a decline in agriculture's share of GDP and a corresponding increase in the GDP share of industry and services), self-sustaining growth, technological advances, social, political, and institutional modernization, and widespread improvement in human conditions (Herrick and Kindleberger, 1983, 49; Adelman, 2000; Cornwall and Cornwall, 2001, 7; Nafziger, 2006, 15).

Finally, determinism, as in historic materialism, is ruled out from this discourse: a developmental trajectory can branch because a current situation could be the basis for more than one subsequent situation. Therefore, we are talking about developmental *propensities* sensu Popper (1990).

Table 1
General developmental stages for dissipative systems.

Immature stage
Relatively high energy throughput per unit mass
Relatively small size and/or total matter/energy throughput
Growth rate high
Changing internally rapidly with high persistence
Stability to same-scale perturbations high
Mature stage
Declining energy density throughput still sufficient for recovery from perturbations
Size and total matter-energy throughput typical for the kind of system
Definitive form for the type of system acquired
Internal stability adequate for system persistence
Homeostatic stability to same-scale perturbations adequate
Senescent stage
Energy throughput per unit mass gradually dropping below functional requirements
Overall matter/energy throughput high, but its increase is declining
Increasing accumulation of deforming marks
Internal stability of system approaching inflexibility
Stability to same-scale perturbations declining

Note: modified from Salthe (2010).

2.1. General developmental stages for dissipative systems

We will apply a naturalistic perspective, sometimes referred to as "cycling models" (Abel, 2007, 65–67), to the development of capitalist economies. Natural developing systems follow three predictable stages: *immature*, *mature*, and *senescent*,[3] each characterized by its specific energy/matter flow rates and differential homeostatic stability to perturbations, as summarized in Table 1 and Fig. 1 (Salthe 1993, 2003, 2010).

Table 1 shows an overview of characteristic features of developmental stages that relate to energy flows, material growth, structural changes, and a system's stability. By identifying corresponding variables in the economic system it is possible to estimate its developmental stage and to propose some tentative predictions about its near future. What may be the likely unfolding in the per capita energy consumption in a socioeconomic system is presented in Fig. 1, which shows how entropy production changes across the three developmental stages of dissipative systems.

The hypothesis that a capitalist economic system (from a national to the global level) may follow three general developmental stages is grounded in the following premises. All living systems grow by degrading available energy gradients and in the early stages, like in the early successional stage of an ecosystem development, this growth is intense (Schneider and Sagan, 2005, 199). We

[2] Under economic growth we refer to its physical dimension only. See the distinction between matter and energy, versus monetary aspects of economic growth in Ekins (2009).

[3] Note that within the developmental perspective the growth stages are neither vitalistic nor value-laden—they are technical as they relate to theoretical specifics of energy flows, material growth, structural changes, and system stability. The terms themselves have been used in similar context before: see, for example, Rostow's (1960) fourth stage of growth - "Drive to Maturity" - and Baskin's (2013) "senescence", referring to a state's condition when it fails to adapt to changes driven by population growth.

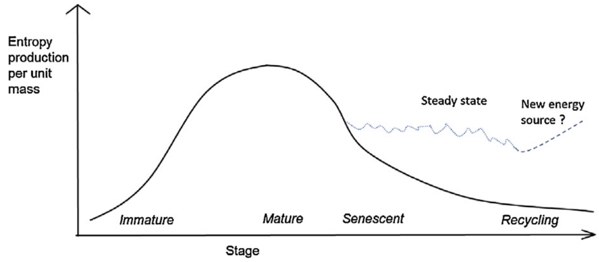

Fig. 1. Development stages and entropy production.
Note: modified from Salthe (1993, 2003). Mature state starts with declining p.c. energy consumption. Steady state refers to dynamic adjustments of economic throughput at levels compatible with biophysical planetary constraints. A new trajectory of growth in p.c. entropy production may be possible if some new source of high quality energy is tapped, like nuclear fusion or highly efficient solar energy transformation.

label this stage as *immature*. Since the industrial revolution, capitalist economies have experienced this kind of intensive, exponential growth as measured by energy and GDP (Maddison, 2007; Wrigley, 2010; Broadberry and Klein, 2012). However, as the unlimited growth of a subsystem (a national economy or the global economic system) in a materially closed meta-system (the planet) is impossible, any single economy and the world economic system as a whole must reach a stage when growth no longer happens (Georgescu-Roegen, 1971; Daly, 1973, 1996). We label this stage as *mature* but we cannot say anything about its duration because this depends upon many variables, societal and biophysical, and this is beyond the scope of the present work. Its characteristics are discussed in more detail in Section 3. A *senescent* stage is expected to follow the mature stage because of at least three coincident processes: (1) diminishing inflows of free energy needed to maintain a complex capitalist economy, (2) increasing accumulation of deforming marks in the material domain of the economic system and in the natural environment,[4] and (3), diminishing returns on societal investment in complexity (Tainter, 1988, 2006, 2011) as an established way to solve the problems that arise from processes (1) and (2). Dissipative systems in the senescent stage become informationally overburdened, committed to old habits, rigid, brittle, and, therefore, increasingly sensitive to environmental perturbations (Salthe, 1993, 154–226). The senescent stage is in some systems usually followed by reorganization (Holling and Gunderson, 2002), or by recycling after which a new qualitative state of immaturity and growth emerges.

There are, however, two possibilities for complex systems to escape recycling, at least temporarily. One is accessing a new, higher hierarchical level structure which will preserve the old systems or some of their derivatives as units in a higher-level development (Salthe, 1993, 226, 264). In our context a case in point would be a global governance system that would constrain market dynamics and resource exploitation under its particular goals. The other refers to emergence of new evolutionary structures that act as a negation of senescence as the end of development (Salthe, 1993, 226)—think about novel institutions, technologies and worldviews that may change human relationship to natural environment and establish new societal dynamics. Bearing on that, we cannot exclude the possibility that capitalist economy reaches a fluctuating domain within the regenerative and waste assimilative capacities of the supporting ecosphere (Lawn, 2011) at some lower level of entropy production but still large enough to support an advanced civilization (steady-state trajectory in Fig. 1). In our perspective, however, socioeconomic systems would have a "natural" propensity towards senescence and reorganization and considerable societal investments would be necessary to achieve the steady-state option (like institutional changes in the economic domain, population control, large-scale conservation, climate stabilization at about 2 °C, and technological breakthroughs in energy systems).

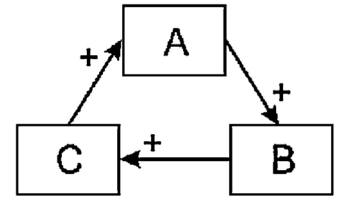

Fig. 2. A three-component autocatalytic cycle.

2.2. *Autocatalytic aspects of growth and development*

In order to represent economic development and growth from a naturalistic perspective, we introduce the notion of autocatalysis. Autocatalysis is the primary dynamical manifestation of growth in all living and ecological systems. It is a particular case of a positive feedback cycle wherein each node within the cycle benefits the next member. Thus, in Fig. 2 any increase in the activity of A can engender an increase in element B, which can augment the activity of C, which in its turn can benefit the origin of the change, A. The feedback is often exponential in nature and fuels a system into logistic growth.

Autocatalysis serves as a drive behind the aggregation of resources unto the configuration. If, for example, some change occurs in element B that enables it to bring in more of a limiting resource, that change will be rewarded. Autocatalytic selection favors increased acquisition by each and every member of the cycle, resulting in what has been termed *centripetality* by Ulanowicz (1997, 2009). That is, the autocatalytic cycle appears as the focus of movement of resources from the surroundings into the configuration. Centripetal pressure upon available external resources will tend to stretch those resources to the brink. In our context, we recognize this centripetal pressure in the joint processes of industrialization, mass consumption, and global economic integration that marked the twentieth century (McNeill, 2000, 314–324) and by which humans appropriated 38% of global net primary production (Running, 2012).

The autocatalytic economic process leads over time to asymmetric distribution of capital, income, and wealth among economic agents: from individuals, firms, and up to the nation states where the most advanced economies appropriate disproportionate portions of global resources and energy (Matutinović, 2002). Hodgson (2003) argued that as a consequence of the "march of complexity in modern capitalism", high levels of specialist skills were increasingly more rewarded compared to unskilled work, which brought about an increasing inequality of income. In our autocatalytic framework this means that more skilled workers contributed more to the system performance and growth, and thus were preferentially rewarded. Hence, we would expect that as an economic system matures, income and wealth inequality will increase.

2.3. *Negative feedbacks and the autocatalytic process*

Ulanowicz and Hannon (1987) emphasize that autocatalytic behavior drives the participating elements to the highest levels of activity possible under the prevailing circumstances, which implies greater dissipation and, therefore, more entropy produced.

[4] Deforming marks refer, for example, to wearing out of transport, energy, and urban infrastructure; long term degradation of agricultural land; proliferation of landfills and large accumulations of untreated waste like Great Pacific Gyre; irreversible degradation of ecosystems and consequent loss of their services to the economy, etc.

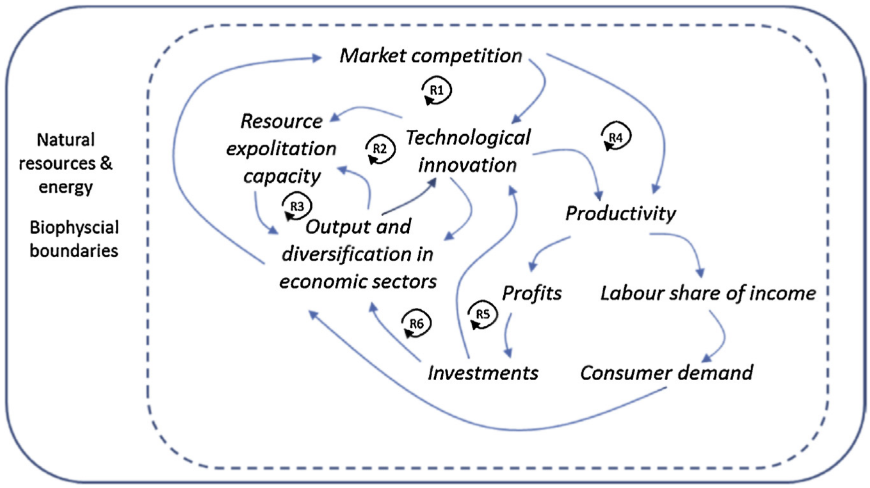

Fig. 3. Key drivers in the autocatalytic process of growth and development.
Note: The symbol "R" identifies positive or reinforcing feedback loop. Positive feedback loops are: (R1) market competition → technological innovation → output and diversification in economic sectors → competition; (R2) technological innovation → resource exploitation capacity → output & diversification → technological innovation; (R3) resource exploitation capacity → output & diversification → resource exploitation capacity; (R4) market competition → productivity → labor share of income → consumer demand → output & diversification → competition; (R5) technological innovation → productivity → profits → investments → innovation; (R6) technological innovation → productivity → profits → investments → output & diversification → competition → innovation. The process of diversification and increase in output in economic sectors under the (R1) imply also the process of qualitative structural transition from agriculture to industry to services in terms of respective shares in GDP and active workforce.

In nature, however, self-amplifying autocatalytic processes tend eventually to provoke their opposite – decelerating loops – that rein in tendencies for unfettered growth and move a system back toward balance (Schneider and Sagan, 2005, 101; Goerner et al., 2009). According to Ulanowicz and Hannon (1987), the constraint usually appears either as finite rate of supply to one or more of the interacting group, or there is attenuation of feedback due to increased dispersal of effect along the causal loop. There are no theoretical reasons to overlook the possibility that eventually, multiple negative feedback loops should arise in a complex adaptive system like capitalist economy. We propose three types of negative feedbacks on economic autocatalytic growth acting on two different hierarchical levels: (1) attenuation of positive feedbacks that arises spontaneously within the economic system itself; (2) the finite rate of supply of critical resources to economic system, and, (3) approaching of planetary biophysical boundaries (Rockström et al., 2009a,b; Burger et al., 2012; Running 2012; Steffen et al., 2015b) that happen at the higher hierarchical level, in which the global economic system is embedded. We shall discuss these in more detail in the Section 3.4.

Here we wish to emphasize that societal responses to feedbacks of the type 2 and 3 may be cybernetic (reactive) and anticipatory, where the latter means "the use of the information from its predictive model to change the present, so that a possibly different future from one that is originally predicted may result" (Louie, 2010). An example of reactive response would be investments in energy efficiency, designing a "circular economy", various methods used to remove already formed contaminants from a stream of air and water, and the restoration of degraded ecosystems. Based on global agreements, such as the Montreal Protocol of 1987 and the 2015 Paris Climate Conference COP21, where scientific models have been used to predict future states of ozone layer, global climate, and their respective impact on the human system, policies have been implemented to prevent those very states, and are examples of the anticipatory reaction mode. In our context that means that the very awareness at the societal level of approaching planetary biophysical boundaries may induce institutional responses that will constrain resource exploitation before physical limits has been actually reached.

2.4. System model of economic growth and development

We use causal loop diagrams to represent systemic relationships and feedbacks between variables in a model (Sterman, 2000, 137–156). Fig. 3 shows a systems model of the autocatalytic processes that represent the engine of economic growth and development in a capitalist economy. The model shows an open economic system that receives renewable and non-renewable material and energy inputs from a closed biophysical system. Major energetic support to economic growth and development is supplied by fossil fuels.

Competitive markets represent the key entrainment of the autocatalytic loop because they sustain technological innovation which, on the one side extends societal capacity for resource use, and on the other, via productivity growth, creates sustained income growth needed for boosting consumer demand for goods and services. Technological innovations boost both the capacity of economic sectors to increase and diversify their outputs and to extract new raw materials from natural environment and new sources of energy. New energy sources and raw materials in a positive loop increase the output capacity of economic sectors. During the immature stage of economic development of capitalist economies – from the beginning of industrial revolution up to mid-20th century – natural resources and energy would be abundant and endogenous negative feedbacks, if any, would not be interfering significantly with growth dynamics. Biophysical boundaries would appear still distant and non-interfering with economic process.

According to non-orthodox theoretic perspective, as economic systems grow and develop, "we should expect to observe the following: (1) an increase in total energy throughput; (2) the development of more complex structures; (3) an increase in autocatalytic cycling activity and the institutional embedding of these processes; (4) the emergence of greater diversity; (5) the generation of more hierarchic levels; and (6) an increase in knowledge structures and their relative importance" (Raine et al., 2006). We see these phenomena as being characteristic of the immature stage of capitalist development, although some of them, like the increase in total energy throughput, further complexification, and increase in knowledge structures may persist throughout the mature stage.

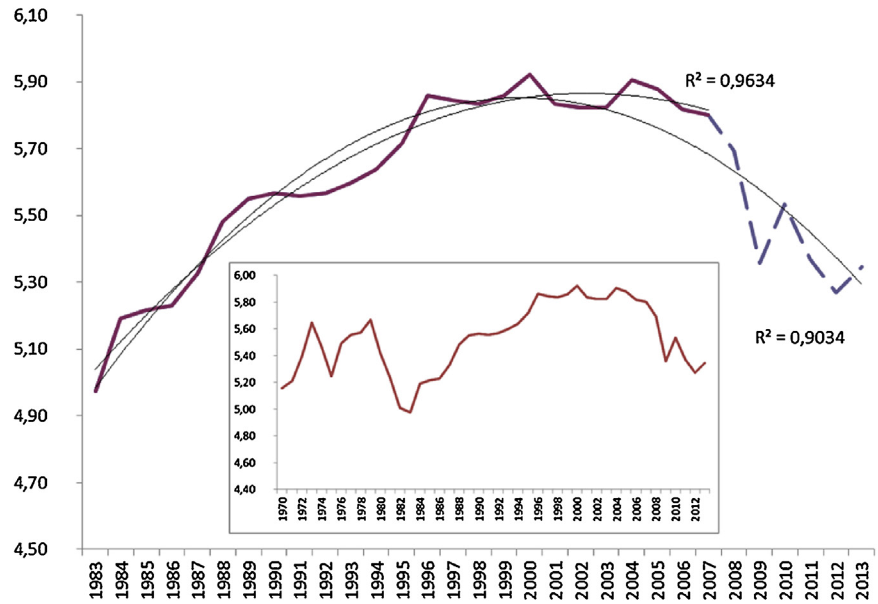

Fig. 4. Trends in energy p.c. consumption in countries that industrialized first: 1983–2007 and 1983–2013.
Note: energy units are in Toe. Countries selection in Europe is based on Broadberry and Klein (2012) classification: Early industrialisers: Belgium, France, Switzerland, UK; Later industrialisers: Austria-Hungary, Germany, Netherlands and Sweden. To these we added US and Japan as non-European countries that industrialized first. Energy consumption is summed across the countries and then divided by total population. The solid line refers to the period 1983–2007 and the dashed line to the period 1983–2013. The inset figure shows a larger time context from which the curve is extracted. Data sources: population: OECD.Stat http://stats.oecd.org/, extracted on 07 April 2015; missing population figures for the year 2013 were extracted from national statistical offices; energy consumption: BP Statistical Review of World Energy June 2014.

3. Entering the mature stage: empirical findings

We consider the global economy as an integrated system in which the capitalist development process occurs. However, we shall look for early signs of maturity at chosen lower levels of integration: the ten countries that industrialized first (see note in Fig. 4) and the OECD group. We present firstly some empirical findings that likely provide early signs of maturity in these economies according to the specification in Table 1 and then we turn to examine the impact of negative feedbacks.

3.1. Energy density

Considering "*declining energy density throughput*" we first looked at average trends in p.c. energy consumption in a sample of ten countries that industrialized first. We conjecture that it is the countries that industrialized first that may be those most likely to be undergoing the transition to maturity now. In order to capture trends that are not disturbed by exceptional geopolitical events, like the first and the second oil crisis,[5] we selected 1983 as a starting year. We also wished to eliminate the effect of the last major recession on energy consumption so we looked separately at the period 1983–2007.

For the period 1983–2007 (solid line in Fig. 4) the trendline for average p.c. energy consumption forms a plateau after its maximum in the year 2000 and declines after the year 2005. When we consider the period 1983–2013 (dotted line) we observe that the impact of the major post-war global recession on p.c. energy consumption has been such that it changed the trendline: instead of the plateau it shows decline right after the year 2000. Both trends suggest that the first decade of the 21st century may have marked a transition to the mature developmental stage for the group of ten capitalist countries that industrialized first. There is, however, considerable variability among the countries, some of which reached their maximum p.c. energy consumption several decades ago like the US, and UK but had significant rebounds afterwards. Most of them, however, peaked in the first decade of the 21st century (see Table 2).

To contextualize the findings in ten core capitalist countries, we look at the wider group of economies—those belonging to the Organization for Economic Cooperation and Development (OECD) (Fig. 5). The trendline in energy p.c. consumption for the period 1983–2007 year shows an asymptotic growth that suggests an approach to the mature stage. When we look at the whole period 1983–2013, the trendline shows a decline after a peak in 2005, similar to that in the first group. We tentatively conclude that average p.c. energy consumption trends in the group of economies that industrialized first precede in time that in the OECD group and that the same process of approaching maturity is present in both cases. We note that similar phenomena has been observed at the global level as well: a historical overview of world population and energy consumption since the year 1600 shows that energy consumption per capita grew exponentially from the fifties of the 20th century, peaked in the eighties, and then started to decline at the beginning of this millennium (Ehrlich et al., 2012).

Table 2
Peaks in energy p.c. consumption in Toe.

Country	Max	Year
Austria	4.28	2005
Belgium	6.28	2003
France	4.35	2004
Germany	4.75	1979
Netherlands	3.17	2005
Sweden	5.93	1987
Switzerland	6.35	2001
United Kingdom	4.34	1973
US	4.03	1973
Japan	8.55	2005

Sources: see Fig. 3.

[5] First oil shock refers to the oil embargo imposed by OPEC 1973–1974 and the second refers to the Iran and Iraq war in 1979–1981. As a consequence extreme oil prices slashed demand which bottomed in the year 1983.

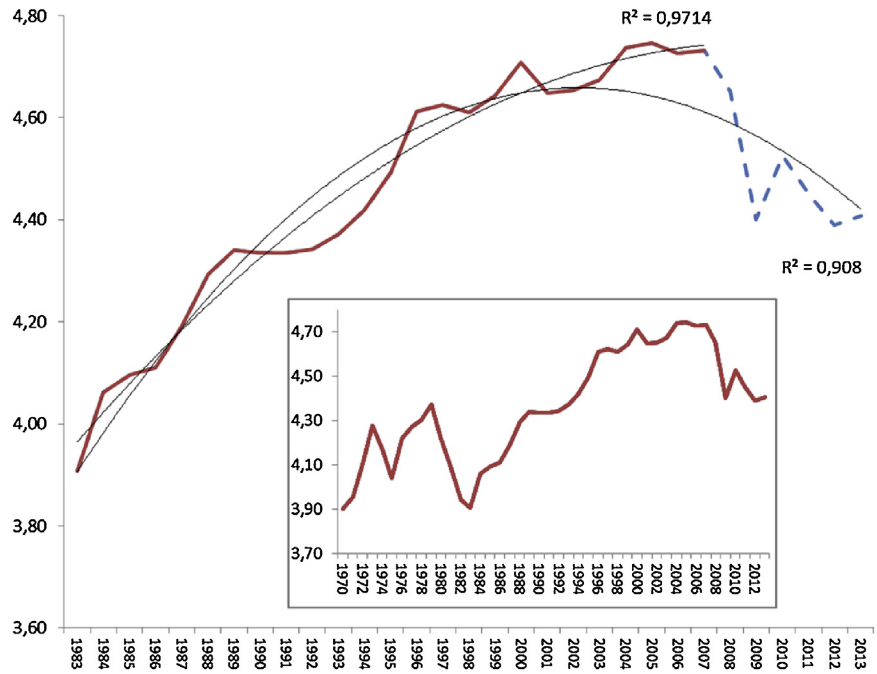

Fig. 5. Trends in energy p.c. consumption in OECD: 1983–2007 and 1983–2013.
Note: Energy units are in Toe. Solid line refers to the period 1983–2007 and the dashed line to the period 1983–2013. Data sources: population: OECD.Stat http://stats.oecd.org/, extracted on 07 April 2015; missing population figures for the year 2013 were extracted from national statistical offices; energy consumption: BP Statistical Review of World Energy June 2014. The solid line refers to the period 1983–2007 and the dashed line to the period 1983–2012.

3.2. Size, form and throughput

For theoretic statements “Size and total matter-energy throughput typical for the kind of system” and “Definitive form for the type of system acquired” we wish to explore if there exists a stable structural pattern that we could identify with an economic system’s maturity. Time invariance of a pattern and its specific form are the types of empirical signs we would consider as indicative of maturity.

Concerning “*size and total matter-energy throughput typical for the kind of system*”, we firstly note that size of socioeconomic systems is determined politically and historically and it is, therefore, unrelated to the kind of development process considered here. Because capitalist development is essentially a global process of competitive and cooperative interactions, we looked for patterns at the higher level unit of analysis—that of OECD. We looked at the shape of distributions of GDP and energy consumption in OECD in two distinct periods that span two and three decades respectively. We normalized the original data on GDP and energy consumption to show more clearly the structural time invariance of the variables. In both variables we found heavy-tailed distributions with almost invariant shapes (Figs. 6 and 7) that resemble a power-law distribution[6] when shown on log–log plot (see insets in the respective figures).

We conjecture that the mechanism that stands behind fat-tailed distributions in energy consumption and economic throughput is autocatalysis which “induces growth and selection and it exhibits an asymmetry that can give rise to the centripetal amassing of material and available energy” (Ulanowicz, 1997, 53). In the system of mutually interacting economies of the OECD group, the cumulative distribution of shares in GDP and in total energy consumption shows that the first nine countries, out of the total 34, account for from 82% to 80% of the total respectively. This centripetal amassing of materials and energy in the subgroup of the most efficient countries reflects the system’s organization, and the right-skewed distribution in the key variables is its characteristic signature. The same patterns have been found in the share of global energy appropriation, global GDP, and global trade flows (Matutinović, 2002). Symmetry breaking induced by autocatalytic dynamics (Ulanowicz, 2009, 77) takes time to materialize in characteristic patterns like fat-tail distributions. Therefore, we see these patterns and their time invariance as likely signs of system’s maturity.

Concerning the “*definitive form for the type of system acquired*” we look at two variables that describe the level of economic development in a synthetic and comprehensive way: the composition of labor and the composition of GDP by three main sectors of economic activity and output: agriculture, industry and mining, and services. The average readings in the OECD group (Table 3) are characteristic for high income capitalist economies, which include also those that industrialized first: the service sector is predominant at values of 70% and plus, and the agricultural sector is invariably at 5% and below. The latter cannot vanish altogether and, in the civilization that has built itself on a machine-based

Table 3
Labor and GDP share by sector in OECD: 2013 year.

	Labor input by activity	GDP Composition by Sector
Agriculture	5%	2%
Industry and mining	22%	28%
Services	73%	70%

Sources: GDP Composition by Sector: World Bank, Structure of output: 4.2. *World Development Indicators* 2014, The World Bank. http://wdi.worldbank.org/table/4.2 (accessed 5.05.15.).
Labor input by activity: OECD, data extracted on 04 Feb 2014 09:59 UTC (GMT) from OECD.Stat. http://stats.oecd.org/Accessed on May 5, 2015. Author’s calculation.

[6] We stress that our usage of “power-law” is loose in the sense that it denotes a rank-size (Zipf) distribution that gives a linear relationship in a log–log plot, and is not necessarily confirmed as a power-law in a strict statistical sense (Stumpf and Porter, 2012). It is also well known that linear relationship frequently gives way to exponential decay due to the finite size effects either of natural phenomena or measurements (Laherrère and Sornette, 1998; Jensen, 2001).

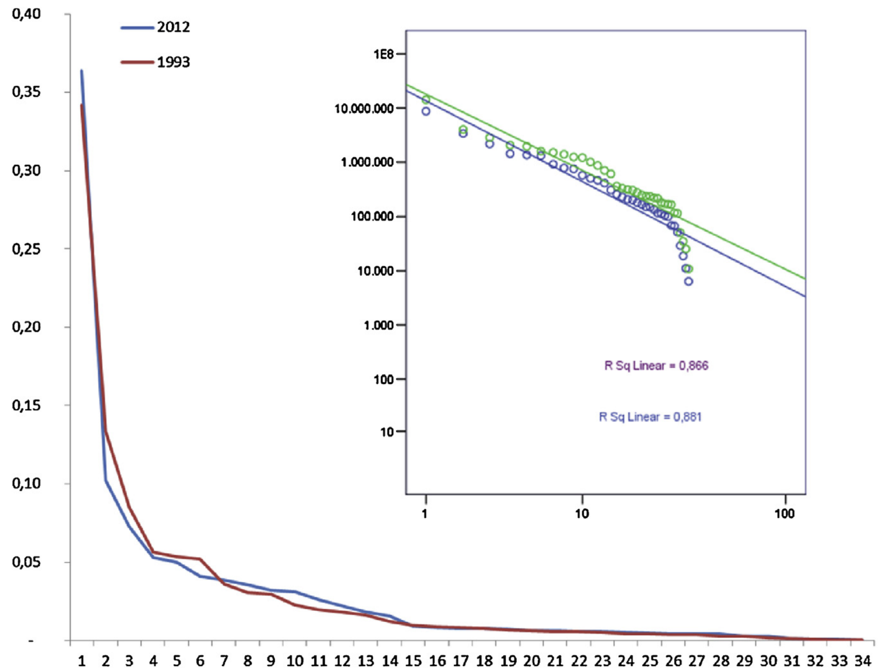

Fig. 6. GDP rank size distribution: OECD 1993 and 2012.
Note: Countries GDP data are ranked top-down and then normalized as a percentage of total: the red curve refers to 1993 and the blue curve 2012 year. The inset figure shows original data on a log–log plot with linear trends: blue dots denote 1993 and green dots 2012 year. The 1993 is the earliest year with data fully comparable with 2012 year. Data Source: OECD.Stat http://stats.oecd.org/, extracted on 02 Feb 2014.

manufacturing process, the industrial sector is unlikely to shrink below 20%. Therefore, we infer on these grounds that the general structure of economic output and employment in the core economies and in the OECD group may have acquired its definitive shape.

3.3. Stability and resilience

Regarding "*internal stability and capacity to recover from perturbations*" we look firstly at recessions as a characteristic endogenous perturbation of the capitalist socioeconomic system. Empirical findings from a large number of market economies show that size and duration of recessions follow power-law distribution (Ormerod and Mounfield, 2001; Ausloos et al., 2004; Matutinović, 2006). Because smaller size events in power-law distribution predominate, the social and economic costs are relatively low and recovery time is rather fast in most of the cases. Institutional mitigation instruments like automatic stabilizers and welfare state that developed during the past seventy years have been helping the socioeconomic system get through the large recessions as well. Such a capacity for resilience could have been observed recently in the OECD group, which went through the largest postwar recession 2007–2009 without major socioeconomic disruptions. We note, however, that energy prices and availability of natural resources have been so far supportive of fast recoveries. Considering natural disasters, the OECD group has been resilient to earthquakes, hurricanes, floods, droughts, and wildfires, not the least thanks to stable climate and abundant and relatively cheap energy. We conclude, therefore, that stability and resilience in the OECD group is adequate to the mature stage of development.

3.4. Negative feedbacks

Now we turn to three different types of negative feedback that tend to suppress autocatalytic growth: (1) finite rate of supply, (2) planetary biophysical boundaries, and (3) attenuation of feedback among the constituents of the autocatalytic system. We will address (1) and (2) at the planetary level as national economies source their material requirements globally while (3) will be discussed at the level of the core group of countries, at the OECD level, and globally.

3.4.1. Finite rate of supply of critical resources

We consider the finite rates of supply of resources that are critical for sustaining complex socioeconomic systems like, but not limited to, primary energy supply, fertile agricultural land, and fresh water (Meadows et al., 2004, 67–72, 147–149; Burger et al., 2012).

With a share of 78.4% in final global energy consumption (REN21, 2014), non-renewable energy sources still represent our major energy source. Their peak-production may have already happened or will do so in the near future (Heinberg and Friedley, 2010; Patzek and Croft, 2010; Murray and King, 2012). Regardless of the correct estimates of the remaining fossil fuels reserves, the fact is that the efficiency of supply of free energy to the economic system has been already declining for some time: the world's most important fossil fuels, oil and gas, have declining EROI (energy return on investment) values, while coal, although abundant, is very unevenly distributed, has large environmental impacts and has an EROI that depends greatly on the region mined (Murphy and Hall, 2010; Lambert et al., 2012; Hall et al., 2014). Because fossil fuels represent still vast majority of total global energy use and renewable energy sources have currently very low EROI – ranging from 2.1 for biofuels to 18:1 for wind (Lambert et al., 2012) – declining EROI of the total energy supply is likely to represent the major constraint on future growth (Hall et al., 2014). There is yet another important reason that should affect, via self-imposed restrictions, future rates of supply of fossil fuels: about one third of oil reserves, half of gas reserves and over 80% of current coal reserves should remain unused from 2010 to 2050 in order to meet the target of 2 °C global warming (McGlade and Ekins, 2015). Relaying only on renewables to close impending fossil energy gaps, physical or self-

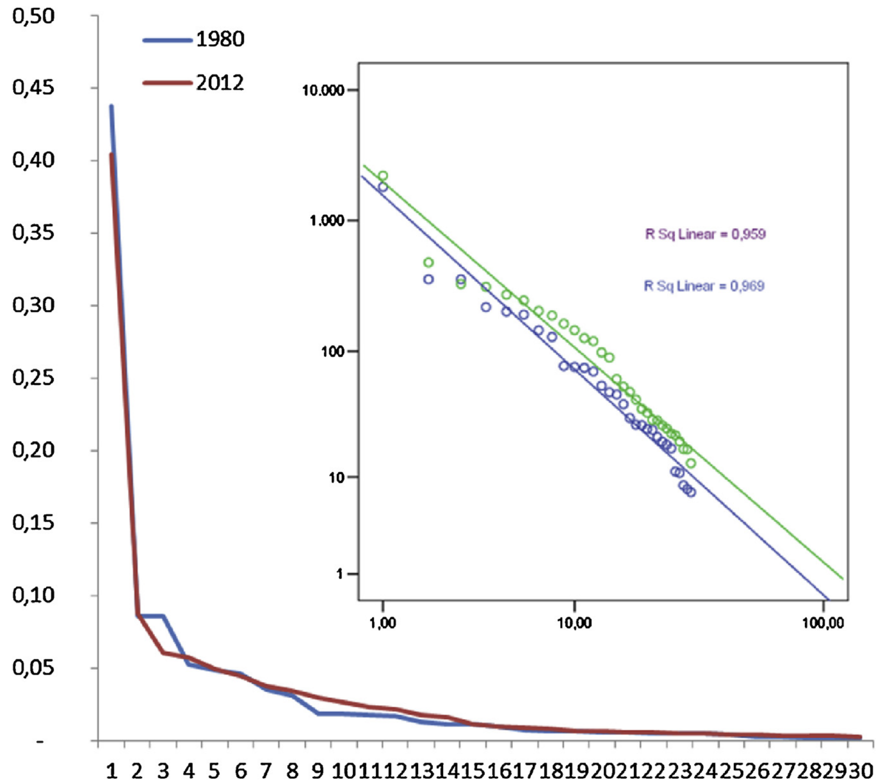

Fig. 7. Energy consumption rank size distribution: OECD 1980 and 2012.
Note: Countries total energy consumption data are ranked top-down and then normalized as a percentage of total: the blue curve refers to 1980 and the red curve 2012 year. The inset figure shows original data on a log–log plot with linear trends: blue dots denote 1980 and green dots 2012 year. Data Source: BP Statistical Review of World Energy June 2012.

imposed, appears unviable in a foreseeable time because their high dispersion and low EROI makes them extremely land-intensive: as MacKay (2010) demonstrated on the example of UK, "for any renewable facility to make an appreciable contribution – a contribution at all comparable to our current consumption – it has to be country-sized".

Rising costs of energy extraction will transfer into higher energy prices and that will increase the proportion of the household budget to be spent on energy, and, consequently reduce the part destined for consumer goods and services with a negative impact on economic growth. Eventually, the declining rate of free energy supply will act as a physical deterrent to economic growth as more and more energy will be spent in the extraction process and less will be available for economic uses. We conjecture, that the decreasing EROI and rising costs of fossil fuels[7] would likely mark the mature capitalist society, which in its later, senescent, stage may depend prevalently on low-EROI renewable energy thus implying a substantial reduction in per capita energy consumption (MacKay, 2010; Lambert et al., 2012) and in the standard of living (Lambert et al., 2013; Tainter et al., 2003).

Global per capita agricultural land and freshwater withdrawals have a long-term declining trend that started in the sixties and in the eighties of the 20th century, respectively (Burger et al., 2012). It is estimated that up to 40% of global croplands may be experiencing some degree of soil erosion, reduced fertility or overgrazing (Foley et al., 2005). While dry and poor regions of the world are the most affected, loss of soil functions due to urban land take and land degradation due to soil erosion and land intensification has been increasing in the EU as well (EEA, 2005). The overall effect of land degradation is reduced productivity of land and, consequently, lower yields, higher prices or both. We can reasonably expect that decreases in per capita fresh water availability – mostly used for irrigation purposes (Caldecot, 2008, 191) – combined with land degradation will be shrinking the output potential in the food sector with likely increases in global food prices.[8] Potential economic growth will be reduced directly via output reduction in the food sector, and indirectly, by reducing the proportion of the consumer budget available for non-food products because of the higher food prices.

3.4.2. *Approaching planetary biophysical boundaries*

Human planetary expansion and application of technology to convert land and transform natural resources into products for human use have been transforming the biosphere ever since the Neolithic (Ruddiman et al., 2015). This millennial process has brought humanity to appropriate currently 38% of global net primary production (NPP) and it is estimated that only 10% of NPP is available for additional future use by humans (Running, 2012)—a close proximity to the key biophysical boundary. In the context of approaching the limits of human NPP appropriation, biodiversity conservation policies already tend to prevent additional land conversion and habitat destruction on the global scale, which limit the

[7] The remarkable drop in oil prices that started in August 2014 and bottomed in January 2016, has been caused by a combination of three major factors: supply glut arising from shale oil "revolution" in the US; weakening of global growth rates and especially in China; and a tactical decision of the major spare capacity player – Saudi Arabia – to keep its market share and squeeze-out marginal oil suppliers outside the OPEC. This is most likely to be a temporary phenomenon with the most immediate effect of disinvestment in new oil wells by major oil companies that is likely to produce supply shortages in the future and, consequently, new price hikes.

[8] FAO Food Price Index shows an increasing trendline in real food prices since the 1987 year ($R^2 = 0.66$) that is congruent with the above mentioned trends. See data set at FAO http://www.fao.org/worldfoodsituation/foodpricesindex/en/http://www.fao.org/worldfoodsituation/foodpricesindex/en/ (accessed 26.03.15.).

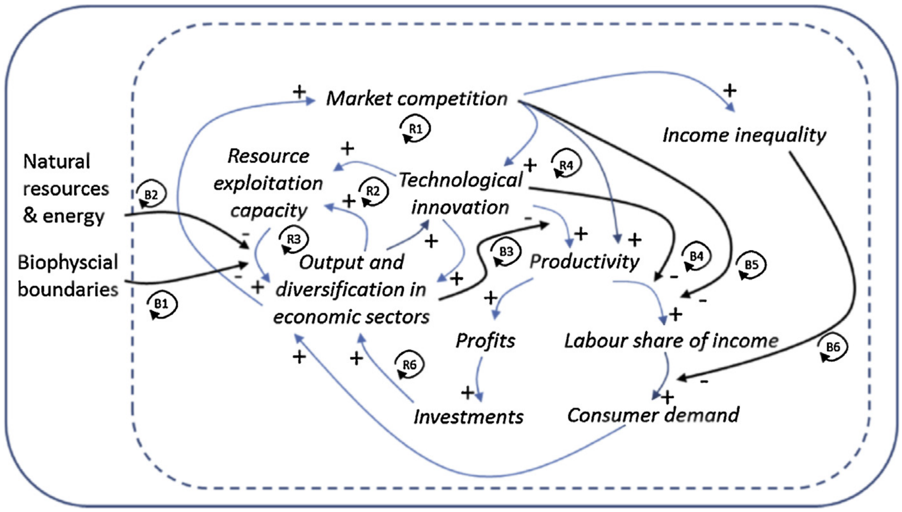

Fig. 8. Negative feedbacks to autocatalytic process of growth and development.
Notes: Symbol B identifies negative or balancing feedback loop. (B1) refers to biophysical boundaries like, for example, NPP for human appropriation, the rate of biodiversity loss, and climate; (B2) refers to finite rate of supply of renewable and non-renewable energy sources, fresh water reservoirs, and fertile land. B1 and B2 act as constraints from a higher hierarchical level - that of natural environment and biosphere. Negative feedbacks B3-B6 are generated at the level of economic system - they are a product of autocatalytic process itself. The impact of (B4) on corporate profits and via investments on economic output and innovations (the reinforcing loops (R5) and (R6) shown in Fig. 3) has been omitted for figure's clarity.

expansion of economic activities and thus reduces the potential for material economic growth. On the other hand, failure of conservation policies and continuing loss of biodiversity will further reduce the capacity of ecosystems to provide provisioning and regulating critical services to human societies, with likely negative economic impacts in many areas (Cardinale, 2012). Therefore, whichever the direction we look at, negative feedbacks on economic growth seem to be unavoidable.

Among the ten planetary boundaries identified by Rockström et al. (2009a,b), climate change presents unique challenge for humanity. The negative effects of climate change on economic growth arise from both physical and institutional domains. On the physical side, bad harvests resulting from extreme weather conditions will be occasionally reducing the contribution of agricultural sector to GDP. Food price increases due to crop failures will shrink disposable income that would be otherwise spent elsewhere, thus reducing aggregate demand. Droughts will reduce output of hydroelectric power plants and push the energy prices up with the negative effect on disposable income and consumer goods demand. On the institutional side, new restraints on economic activities will be likely imposed in order to prevent undesirable future states like crossing the safe bound of 2 °C global average temperature rise above pre-industrial times, as stated in the COP21 Agreement (FCCC, 2015). For example, introduction of carbon taxes, banning exploitation of new coal mines, and protecting remaining world forest from exploitation will likely have negative impact on economic growth. Future rises of carbon price together with mandatory CO_2 abatement technologies in industry will increase production costs in many sectors like energy, transportation, construction, and manufacturing. Eventually, these costs will be transferred into higher prices that will likely reduce demand for many goods and services.

Approaching planetary biophysical limits produces stresses which signals are perceived in a socioeconomic systems via rising prices of resources, increased investments to extract a resource, and discovery of new damages that have to be dealt with—all of which act as a negative feedback to economic growth (Meadows et al., 2004, 147–148). While the market system response to these signs has been reactive, we can expect that societal responses in the near future will be increasingly anticipatory, as in the case of climate change. The number of reactive and anticipatory negative feedbacks on growth is more likely than not to increase in the future.

3.4.3. Attenuation of feedback among the constituents

There are signs that positive feedbacks among some of the key components of the autocatalytic cycle shown in Fig. 3 may be attenuating. The most important and far-reaching of these concerns the nexus between market competition, technological innovation, and productivity growth.

Although the past fifty years have seen an outburst in global competition and technological innovation, the rates of labour productivity growth have been declining from the seventies onwards in Canada, Japan, Germany, France, Italy, UK, US, (Chancel et al., 2013; Diaz et al., 2014a; Schmelzer, 2015), and in the world as a whole (Randers, 2012). The major reason for this negative trend is most likely developmental: as economies mature most of the workforce ends up in the service sector (see Table 3) where productivity increases are more difficult to obtain than in manufacturing and agriculture (Randers, 2012). This causes lower growth of personal income and corporate profits.

However, even the productivity gains obtained in manufacturing do not contribute to increases in personal income and corporate profits as obtained before. A greater share of technology-enabled productivity gains in manufacturing and especially in the information and communication industry creates "consumer surplus without raising either profits or consumer purchasing power" (Manyika et al., 2015). This is because a larger share of productivity improvements is passed on to consumers in the form of higher-quality products and less in the form of lower prices while lower entry barriers and higher competition are eroding company profits (Brynjolfsson, 1996; Manyika et al., 2015). Eroding company profits are weakening the investment capacity of the private sector while stagnating purchasing power exerts less pressure on demand for consumer goods thus contributing together to the slowing down of economic growth.

It is not only that less of productivity growth is now passed on to consumer in form of lower prices but also less of it is transferred to wages than was the case couple of decades ago. Technically, when the real wage grows at a slower pace than labour productivity, the labour income share shows a decline, and vice versa (European

Commission, 2007, 243).[9] Labour share in national income has been declining at all levels since the 1980s: globally (Karabarbounis and Neiman, 2013), in OECD (Stockhammer, 2013), in most of the EU-15 countries (European Commission, 2007, 237–260), and in all of the "core economies", except for Belgium (Guerriero, 2012).[10] Productivity growth that does not transfer to growth of wages – an income component that tends to have a high propensity for spending and generating demand elsewhere (Manyika et al., 2015)—attenuates its contribution to economic growth. According to empirical research (Stockhammer, 2013), the major reasons for declining of wage share in national income are globalization, financialisation, reduction in welfare state generosity, and technological change. While the impact of the latter on wages share is straightforward,[11] we see the impact of the first three variables as different aspects of *growing competition* on the world marketplace: fast and deregulated movement of capital, relocation of manufacturing facilities to low-wage economies, and pressure on national governments to relax welfare-state costs in order to stay competitive. In that way global market competition has been attenuating the impact of productivity growth on labour share of income.

Declining wage share in national income is closely related to rising income inequality (Stockhammer, 2013), which is an expected phenomenon in autocatalytic systems (see Section 2.2). Income inequality increased in a large majority of OECD countries over the past 2–3 decades (Förster, 2013). World income inequality has been rising since the outset of the industrial revolution: in the early 19th century the global Gini coefficient had a value 0.50, at the eve of World War I it rose to 0.61 (Bourguignon and Morrisson, 2002), then in 1964 to 0.70, and in the 1999 year it reached almost 0.80 (Butler, 2000). Because "higher-income individuals tend to save more of their income, therefore a larger share of productivity gains goes to intermediated financing rather than to demand for goods and services" (Manyika et al., 2015). We thus infer that global competition, by increasing income inequality (the centripetality effect of the autocatalytic process) tends to weaken overall consumer demand with a negative impact on economic growth. This negative impact of income inequality on economic growth has been statistically confirmed in OECD economies (OECD, 2014).[12]

To wrap all this up, we extend the system model of autocatalytic growth with a new variable—"income inequality" and introduce endogenous and exogenous negative feedbacks (Fig. 8). The model shows an open economic system that receives material and energy inputs from a closed biophysical system. We identify six main negative feedbacks (B1-B6) that tend to attenuate or neutralize the self-reinforcing loops in a global economy. Biophysical boundaries (B1) and finite rate of supply of natural resources and energy (B2) exert attenuating effect on a positive feedback link (R3) from the resource exploitation capacity to output and diversification in the economic sectors. This means that even if our capacity to exploit natural resources increases, the feedback to economic growth is weakened because EROI of fossil fuels has decreased, reservoirs of fresh water are being depleted, conservation policies prevent new land conversion to economic uses, and land degraded by application of industrial agriculture becomes less productive. Similarly, the very notion that a third of oil reserves, half of gas reserves and over 80 per cent of current coal reserves should remain unused from 2010 to 2050 in order to meet the target of 2 °C global warming (McGlade and Ekins, 2015) is likely to act as a psychological deterrent to our capacity to exploit fossil fuels reserves to their maximum.

Inside the economic system, negative feedback (B3) represents the impact of economic maturity where predominance of the service sector attenuates the positive influence of technological innovation on productivity. The reinforcing loop (R4) that links market competition, productivity, income share of labor, and consumer demand to output has been attenuated by two negative feedbacks which act on the link that connects productivity to labor share of income: (B4) that arises from technological innovation and (B5), which originates at market competition. As explained earlier, (B4) also reduces corporate profits, and, consequently investments, which, along reinforcing loops (R5) and (R6), impact negatively on economic output and innovations. Finally, income inequality (B6), arising from market competition, attenuates the link between labor share of income and consumer demand. The final, stabilizing impact of these negative feedbacks is on consumer demand, and to a lesser extent on corporate investment, which both influence negatively on the rate of economic growth.

Eventually, exogenous and endogenous negative feedbacks put an end to autocatalytic growth and stabilize the economic system at a given level of output. If the growth happens to end at a level of output that cannot be supported by biophysical and energetic constraints (temporary overshoot), negative feedbacks may trigger the process of economic shrinking (Schneider et al., 2010) and, eventually, stabilization at a lower level.

Although this model is far from being exhaustive, this interplay of endogenous and exogenous negative feedbacks may be the key cause of a change in the slope of theoretic developmental curve in Fig. 1—from exponential to zero growth. It contributes also a systemic explanation of empirical slackening-off in output growth rates in most developed countries since the seventies[13] (Chancel et al., 2013; Diaz et al., 2014a; Schmelzer, 2015).

4. Discussion

Both systems science (Salthe, 2011) and economics (e.g. Herrick and Kindleberger, 1983; Nafziger, 2006) agree that developing systems will grow,[14] but we know that no natural (e.g. living) system can do so indefinitely. Therefore, capitalism, while growing, is

[9] Labour share of income is conventionally calculated by dividing total compensation of employees by national income and it includes not only wages but also other forms of non-wage compensation like employers' contributions to social security programs, pension schemes etc... (Guerriero, 2012).

[10] Comparison of trends in the labor share of income for individual countries from different sources, like European Commission (2007) and Guerriero (2012), shows differences resulting probably from different methodologies and time series used. However, the overall picture in both studies is that of a declining trend.

[11] Efficiency gains in capital producing sectors, often attributed to advances in information technology and the computer age, induced firms to shift away from labor and toward capital to such a large extent that the labor share of income declined (Karabarbounis and Neiman, 2013)

[12] "Rising inequality by 3 Gini points, that is the average increase recorded in the OECD over the past two decades, would drag down economic growth by 0.35% point per year for 25 years: a cumulated loss in GDP at the end of the period of 8.5%" (OECD, 2014).

[13] Chancel et al. (2013) identify three main "suspects" to explain this slowdown: lesser benefits from innovation, the tertiarisation of the economy and the environmental constraint.

[14] Note that economic growth is not an exclusive feature of industrial societies—the world has experienced many "economic efflorescences" in a variety of regions throughout much of history (Grabowski et al., 2007, 291). Goldstone (2002) distinguishes three types of economic growth - "Extensive", "Smithian", and "Schumpeterian". Preindustrial societies experienced only "Extensive growth" wherein a society's total output grows, but only because population and/or territory increases—e.g. territorial spreading of hunting & gathering tribes via splitting after a band exceeds a certain size and, later, more complex patterns of population growth and territorial expansion of early agricultural societies. All complex societies experienced temporary productivity gains from the division of labor and occasional technological advancements that enabled them to increase not only the total output but also their income per capita ("Smithian" growth). Only capitalist societies achieved "Schumpeterian growth" where both income per capita and total output increase rapidly in a self-sustained manner, driven by accelerating technological progress (Goldstone, 2002).

by definition an immature, developing system. According to the naturalistic perspective based on dissipative structures, immature stages are invariably followed by mature and senescent stages and our empirical results suggest that at least some of the capitalist countries that belong to the OECD group may have entered the mature stage. In his analysis of the growth paradigm, Schmelzer (2015) concludes:

> "In the long term, economic growth might just not develop in the form of the hockey stick we are used to imagining—being stagnant for most of human's history and then speeding up very rapidly into an almost vertical rise following a J-curve. Rather, those regions that kicked off capitalist industrialization first seem to have been transitioning into a development more adequately described as an S-curve, in which rapid acceleration slows down and eventually comes to a halt. In the long term, the fast economic growth of Western societies from 1760–1970 might prove to be a historical exception."

Our model in Fig. 8, however, does not imply an automatic and smooth adjustment of economic activity with a given global environmental constraints at any observed level. It only suggests that certain exogenous and endogenous negative feedbacks are being operative, and that capitalist economic system has the propensity to stabilize in its mature stage of development. We are aware that political action may consciously work in a direction of neutralizing endogenous balancing forces. Also, leading world polities may choose continuing with environmental degradation, intensive exploitation of fossil fuels, and disregarding of climate change risks. This scenario would likely result in an "overshoot" or breaking through the biophysical boundaries with potentially disastrous and irreversible negative consequences for humanity (Rockström et al., 2009a,b). If the overshoot size and duration happens within the resilience capacity of the natural system, the global economic subsystem may recover at the lower level of material throughput; otherwise it is likely to collapse (Meadows et al., 2004, 158).

4.1. Major implications of the mature stage

There are clearly many important implications of the transition to the mature stage and addressing them all is beyond the scope of this work. We will, therefore, focus only on two: declining per capita energy consumption and zero or negative economic growth.

4.1.1. Declining per capita energy consumption

We do not discuss the impact of population dynamics on p.c. energy consumption: in our perspective it is irrelevant if p.c. energy availability declines because it lags behind the population growth, or because energy sources vanish and the population remains stable or declines. In the context of the transition to maturity, it is the declining energy density throughput that counts as a signifier of change. Per capita consumption can also decline because of rising energy prices,[15] changing life styles, and technological improvements that may work in concert, like switching from personal to mass transportation with contemporary increase in fuel efficiency. In our theoretical perspective this would happen as a result of negative feedbacks discussed before, and, therefore, pertain to the transition to maturity. We checked the possible impact of the "pollution haven hypothesis" on our findings and did not find support that this phenomenon could account for observed trends in the decline in p.c. energy consumption in the core countries and in the OECD group. Empirical studies show little evidence of widespread pollution havens on the North-South trade routes (Cole, 2004) and while there is some positive evidence for trade of energy intensive goods (Cave and Blomquist, 2008) it is far from bearing on the observed trends in our samples.

The process of increasing efficiency in per capita energy use is characteristic of transition from high-gain to low-gain extraction systems and implies that overall consumption may, nevertheless, continue to grow (Tainter et al., 2003) before leveling-off. Energy availability per capita will anyway fall in absolute terms because of the trend of decline in the EROI of fossil fuels and, eventually, because of their fast depletion, once the peak of extraction has been crossed. Apart the issue of energy scarcity, there is a pressing urgency to restrain the extraction of fossil fuels in order to meet the target of 2 °C global warming (McGlade and Ekins, 2015). Therefore, we expect that per capita energy use will be definitely falling under these diverse pressures.

Although energy availability is highly correlated with societal well-being (Lambert et al., 2013), having to live at lower energy per capita levels should not represent a major problem for advanced economies: they already enjoy high levels of consumption and there is a room for considerable savings that would not affect negatively their extant quality of life. Lambert et al. (2013) found that improvement in societal well-being levels-off at energy uses greater than 200 GJ/capita per year. The values in our group of 10 core countries for the 2012 year range from 114 GJ (Italy) to 294 GJ (US) with the average of 212 GJ. Given the subjective and objective measures of quality of life (Costanza et al., 2007) it is difficult to imagine that these cannot be attained at the level of Italy or somewhat below. Latouche (2007, 84–93), for example, suggested that the level of material consumption of the 1960s–70 s in the Western Europe may be ecologically viable and socially acceptable.

4.1.2. Zero or negative economic growth

Using less energy per capita, beyond certain threshold of efficiency gains, implies also a reduction in per capita material consumption, although not in linear way. Panel data analysis on 82 countries over 30 years found bi-directional positive feedback relationship between economic growth and energy consumption in per capita terms (Huang et al., 2008). Recent analysis for 220 countries over 24 years period showed that, on average, a growth of p.c. GDP of 1% requires a growth in p.c. energy consumption of 0.76% (Brown et al., 2011). With such a close statistical relationship we logically infer that the mature stage will be eventually marked by a decline in real p.c. GDP.

For advanced countries a declining p.c. GDP will represent a major political challenge as our societies have become addicted to growth and have yet to learn how to accommodate to a non-growing or materially shrinking economy. In the past few decades a vast literature developed around this issue proposing a variety of solutions (Daly, 1996; Victor, 2008; Jackson, 2009; Dietz and O'Neill, 2013; Odum and Odum, 2001; Latouche, 2007; Lawn, 2011; Kallis et al., 2012) so we will not discuss it here.

Regarding developing countries, we conjecture that China, India and the rest of countries outside the OECD group will likely never get close to the present average per capita energy consumption in the Western economies as this would exceed by far the available energy gradients (Brown, 2011; Brown et al., 2011). For example, raising the current global population to the standard of living in the United States would require a nearly fivefold increase in the rate of energy consumption, from 17 to 77 terawatts (Brown et al., 2011). Besides that, the end of growth in the OECD group is likely to negatively impact on economic growth in the South. Consequently, long-term projections of GDP per capita growth in OECD and elsewhere in the world (e.g. OECD, 2012) may be entirely unwarranted and illusory.

[15] The period after the year 2000 was marked by an historic hike in fossil fuel prices led by crude oil and it very likely acted as a non-linear negative feedback on consumption.

4.2. Senescence and afterwards

As mentioned in Section 2.1, three coincident processes – decreasing energy availability per capita, accumulated deforming marks in the material and natural domains, and diminishing returns on societal investment in complexity – would, eventually, make the system rigid, brittle, and unable to respond to external and internal stresses. The resilience capacity to large-scale recessions will, as before, depend on the availability of energy and natural resources to be cheaply and quickly harnessed into the economic process and failing that will make capitalist socioeconomic systems increasingly brittle. Regarding external stresses like natural disasters, the societal capacity to adapt and mitigate may decrease substantially if we cross the threshold of 2 °C global warming. In such a precarious state, reaching energy levels that are barely compatible with sustaining civilization[16] would mean risking a classic case of societal collapse (Diamond, 2004).

Reorganization may, however, happen at an entropy production level that is still supportive of a less dissipative variant of Western civilization and in that case it would refer primarily to restructuring in the institutional sphere. The urge for major institutional change may come from a prolonged environmental stress which is socially mediated by a change in a dominant worldview while the material infrastructure and technology will just bear the consequences of the changes in the institutional sphere (Matutinović, 2007a,b). Changes in the institutional sphere will likely cause a cascade of transformations in the patterns of production and consumption, a process similar to that which happened in the former East European communist block after the collapse of the Berlin Wall and in China after the institutional reforms initiated by Deng Xiaoping in the eighties. In that case a socioeconomic system would evolve into something novel but, nevertheless, genealogically close to capitalism.

Finally, we cannot rule out the possibility that, as a response to environmental stress, a higher-level institutional system – global governance – may emerge and harness capitalist dynamics under its particular goals. Reorganization and recycling thus does not necessarily mean the collapse of the industrial civilization or the "revolution" in a sense that it acquired throughout the 20th century.

4.3. A note on human ingenuity, knowledge, and technology

At this point one may ask can we rely on human ingenuity in developing needed solutions, based on a sustained increase in knowledge and technological innovation, to respond to challenges arising from planetary biophysical limits and energy constraints, and thus to continue to drive economic growth and development.

There are several reasons why we adopt a "prudent skepticism" (Costanza et al., 2015, 172–175) with regard to the role of knowledge and technology in its practical application to resource and energy problems. First, history teaches us that technology, by solving one problem creates others, often unanticipated (Diamond, 2004, 504–505; Victor, 2008, 107–111). Second, human ingenuity cannot replicate or replace some services that nature provides if they are lost or damaged (Victor, 2008, 108) (e.g. regulation of climate, pollination of crops by insects, extinct species, etc.). Third, due to the so called "rebound effect", technological advancement does not necessarily lead to overall reduction in resource or energy use and often the final outcome is quite the opposite Victor (2008, 110–111). Fourth, in a market economy technological change is mostly price and profit driven. Because, markets are not conveying accurate and reliable information about resource scarcity and environmental impacts (Victor, 2008, 108; Matutinović, 2010) the desired outcome of technological change remains uncertain. Fifth, even if competitive markets do provide a sustained push to innovations, there is no assurance that needed technologies will appear and diffuse on time to resolve major environmental, energy, and resource issues. For example, Hall et al. (2014), empirical study concludes that "The decline in EROI among major fossil fuels suggests that in the race between technological advances and depletion, depletion is winning". Recent study of Germany, Denmark, and Spain finds: (1) no indications of a shift to green growth, (2) relatively clean sectors do not seem to be more productive than dirtier ones, and, (3) they don't show higher productivity growth (Gazheli et al., 2016). Finally, investments in research and development may exhibit diminishing returns, measured either as declining patenting per inventor (since mid-70s) or as patents per $100M of investment in R&D as, for example, in the US (Strumsky et al., 2010), meaning that the pace of human ingenuity may have its own limits. To conclude, by quoting Ludwig et al. (1993): "But by and large the scientific community has helped to perpetuate the illusion of sustainable development through scientific and technological progress. Resource problems are not really environmental problems. They are human problems that we have created at many times and in many places, under a variety of political, social, and economic systems".

We shall, anyway, need a lot of human ingenuity, knowledge, and technological advancement to work out something like a "Prosperous way down" (Odum and Odum, 2001) to bring the world economic system's energy and material flows in alignment with bearing biophysical limits.

5. Conclusions

We investigated the possibility that early capitalist economies – those that industrialized first, and indeed the whole OECD group – may be reaching the growth plateau naturally, in a similar way to other complex systems in nature. Based on general developmental stages for dissipative systems, we identified likely variables that would uniquely mark the transition to maturity: p.c. energy consumption, GDP and energy consumption distribution, and sector composition of labor and GDP. Empirical findings suggest that the observed groups of capitalist countries may have terminated their historic phase of intensive economic growth and are entering the mature stage. When we look at fossil fuels, most of the accessible gradients with the highest EROI have been already used during the growth stage. We count decreasing EROI as additional evidence that capitalism is entering the mature stage.

In the system model of autocatalytic economic growth we introduced a set of four endogenous and two exogenous variables that provide negative feedbacks, which account for a change in the slope of theoretic developmental curve. It also offers a tentative explanation of the slowing down of long-run rates of GDP growth in the G7 economies (Diaz et al., 2014a,b; Schmelzer, 2015) and in Western Europe (Chancel et al., 2013).

The conjecture that the observed groups of capitalist countries may have terminated their historic phase of intensive economic growth and are entering the mature stage is intriguing for several reasons. From the theoretical perspective, it places a capitalist system to the class of dissipative systems that have the propensity to reach a growth plateau spontaneously. On the practical side, it questions the usefulness of pursuing active growth policies in the North: forcing economic growth and, consequently, extending the exploitation of fossil fuels into the unconventional oil and gas reserves will only postpone the problem for a few decades as

[16] An EROI value of at least 14:1 is needed to provide the performing arts and other social amenities that we associate with complex societies (Lambert et al., 2012). In other words, to have a modern civilization, one needs not simply surplus energy but lots of it, and that requires either a high EROI or a massive source of moderate EROI fuels (Hall et al., 2009; Lambert et al., 2012).

well as creating multiple adverse environmental and climate consequences. Instead, a more reasonable political agenda would be devising "post growth" institutional solutions (Odum and Odum, 2001; Victor, 2008; Jackson, 2009; Lawn, 2011) to help work our way through the maturity stage.

Acknowledgements

We thank Joseph A. Tainter for his comments on the earlier version of the text and two anonymous reviewers for their questions and suggestions, which contributed to the clarity of the text.

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