Ecological Economics 190 (2021) 107183

Contents lists available at ScienceDirect

Ecological Economics

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

Methodological and Ideological Options

The profile of time allocation in the metabolic pattern of society: An internal biophysical limit to economic growth

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ARTICLE INFO

Keywords:
Human activity
Societal metabolism
Energy
Social practices
MuSIASEM
Sustainable production and consumption
Sustainability

ABSTRACT

We show that shortage of human activity may represent an internal constraint to economic growth as relevant as external resource and sink constraints. Human time is required, both inside and outside the market, to produce and consume the goods and services needed to sustain societal metabolism. The time allocation profile is therefore an emergent property of the societal metabolic pattern. When most time is invested in services and final consumption rather than supplying the inputs required by the metabolic process, further growth is constrained. This problem may be temporarily overcome by three strategies: (i) increasing capital investment to boost labor productivity in the productive sectors; (ii) externalizing the requirement of working hours through imports of goods and services; (iii) importing economically active population through immigration. Each strategy is illustrated with an empirical example: (i) a comparison of the evolution of the profile of time and capital allocation between China and the EU; (ii) an assessment of the labor hours embodied in EU imports; (iii) an analysis of demographic changes in response to immigration in Spain. While these strategies can temporarily overcome constraints to economic growth at the national level, they do not represent a long-term solution at the global level.

1. Introduction

The famous quote of Kenneth Boulding (United States-Congress-House, 1973) "anyone who believes exponential growth can go on forever in a finite world is either a madman or an economist" typifies current discussions about the (un)sustainability of continuous economic growth. These discussions are systemically concerned with an expected shortage of external resources, i.e., the Malthusian trap. Indeed, the limits to growth (Meadows et al., 1972) are currently understood to be exclusively external. Several methods have been used to quantify these external limits, both on the supply side – e.g. the availability of net primary productivity (Vitousek et al., 1997a, 1997b), water (Hoekstra, 2017), land (Giljum et al., 2013), materials (Wiedmann et al., 2015), oil (Kerr, 2011) and other fossil fuels (Heinberg, 2007) – and on the sink side – e.g., GHG emissions in the atmosphere (Pachauri and Meyer, 2014), pollution and destruction of habitats and biodiversity (Brondizio et al., 2019). In all these studies, society is invariably seen as a black box and the environment as the factor limiting its expansion by constraining the availability of resources and environmental services. Not surprisingly, policy-makers are obsessed with technical innovations and business models that are expected to decouple economic growth from natural resource requirements. The bio-economy, circular economy, and net-zero carbon transitions are examples par excellence (Giampietro, 2019; Giampietro and Funtowicz, 2020; Parrique et al., 2019).

However, economic growth can also be limited by *internal biophysical* constraints. Current analyses of sustainability tend to overlook the existence of these internal constraints because they are observable only by looking at the social practices taking place *inside* the black box. This neglect is surprising because, for example, in the field of human metabolism it is well known that growth is not only determined by food (external factor). Age (internal factor) also limits the growth of individuals by changing the characteristics of the metabolic system. This suggests that the analysis of the growth of any metabolic system should address both external and internal constraints. In this paper, we seek to

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https://doi.org/10.1016/j.ecolecon.2021.107183
Received 1 November 2020; Received in revised form 22 June 2021; Accepted 5 August 2021

fill this gap. We analyze the factors that determine the profile of human time allocation in contemporary society and explain how forced relations between time and energy allocation can generate a phenomenon of senescence in the metabolic pattern. We illustrate our arguments with practical examples.

The paper is organized as follows: Section 2 summarizes past research relevant for the semantic framing of our analysis. Section 3 presents the conceptual framework for analyzing the impredicative constraints between the profile of human time allocation and the organization of energy end-uses (metabolic pattern) inside society. Section 4 illustrates the relevance of the results with three practical examples: a comparison of time allocation and labor productivity between the EU and China, the role of trade in easing internal biophysical constraints, and the effects of immigration. Section 5 concludes.

2. The profile of human activity as a limiting factor of growth

Spanning several scientific disciplines, the literature on societal metabolism and human time allocation is abundant. In this section, we exclusively focus on previous research relevant for the semantic framing of our analysis. For a broader overview of the literature on societal metabolism, see (Gerber and Scheidel, 2018; Giampietro et al., 2012; Haberl and Fisher-Kowalski, 2007; de Manuel and Toledo, 2014). For previous research on social practices and human time allocation in the field of ecological economics, see (Druckman et al., 2012; Jalas and Juntunen, 2015; Røpke, 2009; Schatzki, 2010; Shove et al., 2012; Smetschka et al., 2019; Yu et al., 2020). Other entry points for the analysis of human time allocation have been explored (e.g., gender, race, class) by, among others, (Carrasco and Mayordomo, 2005; Fisher and Robinson, 2011; Folbre and Bittman, 2004).

As early as 1941, Zipf (1941) analyzed in a holistic way the concept of human time allocation at the level of society. He was the first to suggest that the diversity of socio-economic activities is a key factor in shaping the emergent property of a 'bio-social organism'. Reflecting on the roots of the Great Depression that hit the USA from 1929 to 39, Zipf associated the onset of the economic crisis with the saturation of its 'consumptive capacity'. He pointed at the insurgence of an internal constraint to economic growth determined by the existing profile of human time allocation. For the US economy to continue growing, Zipf argued that its existing economic structure had to give way to a radically new one, in which more hours could be allocated to consumption:

"‥ in 1929 the United States discovered a new "raw material": leisure time, which in a way is just as much a "raw material" as coal, oil, steel or anything else, because for many types of human activity, leisure time is an essential prerequisite [...], any change in kind or amount of goods or of processes within a social-economy will necessitate a restriation within a social-economy itself" (Zipf, 1941, p.324).

With the term 'restriation', Zipf intended a different pattern of allocation of human activity, matter and energy flows – that is to say, a new set of social practices inside and outside the paid-work sector – in order to generate a different pattern of societal organization and metabolism. Zipf's insight is fundamental to our argument: in order for a society to produce more (economic growth), it has to consume more. When a society has access to new resources, it has to get out of the structural lock-in and move human activity from the primary sectors to services and final consumption.

Along this same line, Meier (writing in 1959) proposed that the enlargement of the option space of possible human activities represents an indicator of economic growth:

"Thus, if it can be shown that more people are choosing to use their time for a wider range of activities, one has as significant an indicator of socioeconomic growth as increased per capita income [...] A steady growth of per capita income over the long run does imply wider choice in time allocation: and the inverse is equally true" (Meier, 1959, p.29–30).

Indeed, an expansion of the diversity of social practices associated with modern life styles is a powerful driver for the creation of new labor roles, especially in the service sector. The continuous generation of new activities for consumers boosts the GDP. According to this rationale, economic growth is directly related to the diversity of activities expressed. However, as the overall amount of human time at the level of society is given (8760 h/year per capita), a larger fraction of human activity invested in consumption and a concomitant larger demand for services is likely to entail a reduction of the workforce in the productive sectors (we have a zero-sum game at societal level in closed systems).

Cipolla (1978) confirmed the latter hypothesis through a historic analysis of structural changes of the economy. He used the percentage of the active population employed in agriculture as a proxy of the level of industrialization of societies between 1750 and 1950. The percentage was more than 40% at the beginning of the industrial revolution, between 21 and 40% during its expansion, and less than 20% in its consolidation phase (Cipolla, 1978). In developed countries, the active population employed in agriculture has dropped further, to less than 5%, and in most of them to even less than 2% (Arizpe et al., 2011; Giampietro, 1997). Thus, the dramatic reduction in the share of the workforce employed in agriculture provides a robust indicator for characterizing the evolutionary pattern of the industrial revolution, one of the most remarkable events in human history (Cipolla, 1978; Smil, 2017). The existence of this trajectory of structural change has been confirmed by the analysis provided by (Giampietro et al., 2012).

However, (Tainter, 1988) pointed out that a perpetual complexification of society can also be 'too good a thing'. Too much growth of final consumption and services can lead to a collapse of the productive sectors, as was the case in the Roman Empire. Tainter documents several examples of past empires collapsing due to a systemic excessive complexification. The continuous swelling of the final consumption and service sector, associated with the reinforcement of the identity of the empire, ended up strangling the primary sectors of these economies (i.e., farmers and rural communities) through a continuous increase of taxation. At a certain point, farmers simply could not produce enough surplus for appropriation by the tertiary sector.

The idea of the existence of internal constraints to a perpetual complexification has also been explored in conceptual terms in the field of infodynamics – the study of the evolutionary patterns of complex adaptive systems – from the perspective of information theory and thermodynamics (for an overview, see (Salthe, 2003)). The phenomenon of senescence is here explained in terms of an information overload, i.e., a growing fraction of resources invested as overhead in the building of adaptive capacity leads to a progressive reduction of the internal investment in the primary productive sectors. Maturity is reached when the vast majority of available human activity is needed to *control* the process of self-organization in the consumptive or anabolic part of the metabolic process rather than to produce the inputs required by the productive or catabolic part of the metabolic process.

This mechanism has been neatly illustrated in theoretical ecology by (Ulanowicz, 1997, 1986) in his seminal work on the evolutionary pattern of ecosystems. The limits to ecosystem growth are determined by the relative sizes of the dissipative compartment (detritus feeders, herbivores and carnivores) providing control and the hypercyclic compartment (primary producers) generating a net surplus of resources for the system. In mature ecosystems, the dissipative compartment limits the activity of the compartment generating the surplus. The balance between the activity and the relative size of the dissipative (anabolic) and hypercyclic (catabolic) compartments is determined by the closure of nutrients in the ecosystems (the balance between what is produced and what is consumed internally).

In this paper, we frame the analysis of the phenomenon of senescence in the realm of human society and argue that post-industrial societies have outgrown the solution described by Zipf, and are approaching the situation described by Tainter. The time invested in the dissipative compartments of society (consumption and control) has passed from being "too little" to becoming "too much" to sustain economic growth.

Post-industrial societies are therefore steadily heading toward senescence: the growing requirement of goods and services has to be produced by a continuously shrinking work force in the productive sectors. The approach presented in this paper is original in that we use Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) to establish a coherent representation of the entanglement between patterns of human time allocation and exosomatic[1] energy end-uses across the various structural and functional components of society.

3. The entailment between time allocation, energy metabolism and societal organization

The perspective of societal metabolism permits us to view a given profile of human time allocation as a specific combination of social practices both inside and outside the paid work sector within a given option space (Giampietro et al., 2012; Renner et al., 2021). This bundle of social practices is expressed simultaneously across different levels of societal organization and can only be 'observed' using an analytical framework that integrates the different factors shaping the social life. The idea that the stability of the metabolic pattern is determined by a dynamic equilibrium between the supply and the requirement of energy carriers (and material and technology) as well as human time, is at the core of the concept of *metabolic pattern* of social-ecological systems (Giampietro et al., 2013, 2012). Indeed, the entanglement between the time requirements in social practices inside and outside the paid work sector is exactly what generates an internal constraint, i.e., the biophysical opportunity cost of human time at the societal level.

To study the profile of human time allocation, we need a categorization of the functions expressed by the social practices inside and outside the paid work sector, as well as a characterization of the socio-economic and demographic structure (e.g., types and sizes of socio-economic sectors) in relation to the expression of these functions. The various functions and structures must then be associated with different typologies of energy end-uses. The quantity of exosomatic energy used per hour of human activity will depend on: (i) the nature of the task (function) to be expressed; and (ii) the technology and the power available to express the task. The coupling of the profile of allocation of human activity and that of exosomatic energy end-uses gives rise to the energy metabolic rates of the metabolic elements in society. More specifically, the energy metabolic rate of a structural or functional element is defined as the amount of exosomatic energy throughput in the element i (ET_i) divided by the hours of human activity in that element i (HA_i), according to the relation $EMR_i = ET_i/HA_i$ (measured in MJ/h).

Both the economic process and the demographic structure are described at the level of society, which is above the level at which we observe the agency of individuals. Hence, in the analysis of the societal metabolic pattern, individual choices are 'invisible'. We can only discern *patterns* of time allocation describing social practices at the level of functional elements of society (average amounts over categories). Nonetheless, individual choices are important in that they shape the pattern. Individuals can decide whether or not to supply their time to certain jobs or how to invest their time outside of paid work. This is relevant for the stability of the metabolic pattern. In fact, in the paid work sector the activity of individuals is required for the realization of specific functions (associated with 'jobs' i.e., social practices inside the paid work sector), while outside the paid work sector it is essential for the reproduction of the agency of human beings. Thus, the allocation of human activity across the various compartments of society represents an *expected* pattern that has to be expressed by instances of structural types of citizens.

3.1. The time allocation pattern in society

Fig. 1 represents the taxonomy of human time allocation in relation to the societal organization in the form of a dendrogram. The Total Human Activity available in society (THA) – observed at level n – is limited and amounts to: "population size × 8760 h/y" (24 h/d × 365 d/y). If expressed per capita, the THA_n is simply 8760 h/y. At the level *n-1*, we split the human activity between: (i) the hours allocated to social practices inside the paid work sector of the economy ('job roles') – indicated by the label 'Paid Work' (PW), and (ii) the hours allocated to social practices outside the paid work sector – indicated by the label 'Societal Overhead' (SO). The label 'societal overhead' reflects that this is the amount of human time society requires for making available the required net supply of human activity (hours of human time) for the paid work sector. Most post-industrial societies will manifest a time allocation pattern similar to that of Spain, shown in Fig. 1: less than 10% of the total human time is allocated to paid work, i.e., between 650 and 800 h per capita per year. Note that for each level of the dendrogram, the allocation of human activity to the selected set of categories must be mutually exclusive (time can only be accounted in one activity at the time) and exhaustive (all time must be accounted for), in order to provide closure in the accounting. Thus, at every level i, the following relation must be observed: $THA_i = [\sum HA_i]$.

A second split in the dendrogram, at level *n-2*, allows a more detailed analysis of the profile of time allocation (see Fig. 1), both for the societal overhead and the paid work sector. As regards the societal overhead (left side of Fig. 1), we distinguish between disposable time (DT) and non-disposable time (NDT). Disposable time refers to the activities carried out by people currently not requiring nurture and care within the option space shaped by socio-cultural and economic constraints (such as income). Time allocation within this category is not strictly forced on individuals by their context, but at the same time it does not only depend on their 'attitudes, behavior or choices' (Shove, 2010). Cultural traditions, income, education and the demographic characteristics of the household do affect the choices determining the formation of standardized typologies of social practices. The disposable time (DT) is further divided (at level *n-3*) into 'household chores and commuting' (R&M – Residential and Mobility) and 'leisure, culture and study' (LCS). Note that the former includes unpaid household work. As for the non-disposable time, this includes the physiological overhead of all individuals (PO) – i.e., sleeping and personal care – and the remaining time of the population Requiring Nurture and Care (RNC) (at level *n-3)*. Note that the largest share of the available time (about 50% at societal level), goes in sleeping and personal care (PO). Note that in this taxonomy work is defined both inside (PW) and outside the paid work sector (R&M).

On the side of the paid work sector, we adopt the standard accounting categories used in statistics. In the example given in Fig. 1, we see that around 25% of the hours in paid work go to the 'primary and secondary production sectors' (P&S) and 75% to the 'service and government sector' (SG). At a lower level (*n-3*), the tertiary sector SG is subdivided into 'transport and distribution' (T&D) and 'other services' (SER), whereas the primary and secondary sectors are split into the secondary sector 'manufacturing and construction' (MC) and the primary sectors 'agriculture, forestry and fisheries' and 'energy & mining' (PS**)**. Note that only 5% of the time allocated to paid work (less than 50 h per capita per year) is allocated to the primary sectors of the economy and about 19% (less than 200 h per capita per year) to the secondary sector.

While data on time allocation for the paid work sector is readily available from national and international statistics, this is not the case for the societal overhead. The time allocated to the sub-categories of societal overhead in Fig. 1 has been estimated from available data from surveys on time use. Classification, data sources and calculations are

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[1] Exosomatic means outside the body. Exosomatic energy metabolism refers to energy conversions by power sources outside the human body but operated under human control, such as machine or animal power. Endosomatic means inside the body. Endosomatic energy metabolism refers to the conversions of food energy taking place inside the human body.

Box 1
List of acronyms.

Acronym	Explanation
BEP	Bio-Economic Pressure: the amount of energy carriers *consumed* by society per hour of paid work in the primary and secondary sectors
DT	Disposable Time of the 'population currently not requiring nurture and care' (for more details, see Appendix)
EMR$_i$	'Energy Metabolic Rate': the exosomatic energy throughput per hour of human activity of the metabolic element *i* of society
ET$_i$	'Energy Throughput': the exosomatic energy metabolized by the metabolic element *i* of society
GDP	Gross Domestic Product
HA$_i$	Human Activity: time allocated to the metabolic element *i* of society
LCS	'Leisure, Culture and Study' (for more details, see Appendix)
MC	'Manufacturing and Construction', subcategory of Primary & Secondary sectors (P&S)
NDT	Non-Disposable Time – the combination of physiological overhead of the entire population and the time of population requiring nurture and care
P&S	'Primary & Secondary' sectors: comprehensive of economic activities with the purpose of producing goods.
PO	Physiological Overhead: personal care and sleeping
PS	Primary Sectors: agriculture, forestry, fisheries, mining and energy sectors, subsector of Primary & Secondary sectors (P&S)
PW	Paid Work: time spent on paid work
R&M	Residential & Mobility: household chores and commuting (for more details, see Appendix)
RNC	Time of the population Requiring Nurture and Care
SEH	Strength of the Exosomatic Hypercycle: the amount of energy carriers *supplied* to society per hour of paid work in the primary and secondary sectors
SER	Other services: subcategory of Service and Government sector (SG)
SG	Services and Government sector: comprehensive of all typologies of societal and economic services, administration and institutional activities
SO	Societal Overhead: the time spent outside paid work
T&D	Transport & Distribution: subcategory of Service and Government sector (SG)
TET	Total Energy Throughput: total exosomatic energy metabolized at the level of society on a year basis
THA	Total Human Activity available in society on a year basis

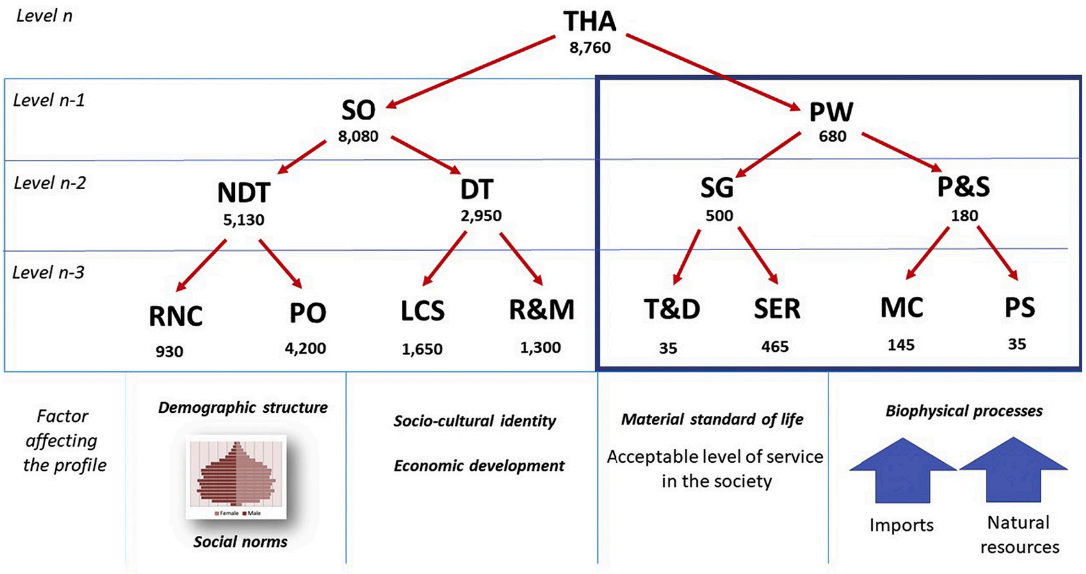


Fig. 1. Dendrogram characterizing the profile of time allocation (in h per capita per y) associated with the expression of a given metabolic pattern (Spain, year 2012). For abbreviations, see Box 1; for data sources and calculations see Appendix.

detailed in the Appendix. Time use in the informal economy (also known as shadow economy) has not been considered in Fig. 1.

Fig. 1 conveys an important (implicit) message: the overall profile of human time allocation is affected by four main factors (illustrated in the bottom row of the figure):

1. The demographic structure of the population – This factor determines the percentage of dependent population, i.e., the population under 15 years and over 65 years. For instance, in the example of Spain (Fig. 1), it is about 32% (Table 1).
2. The socio-cultural identity of society – This factor shapes the social practices outside the paid work sector and determines the participation of women in the formal economy, the, the size of the

Table 1

Population, demographic structure, time allocation, workload, average societal energy metabolic rate (EMRAS) and bio-economic pressure (BEP) for the EU, China and 12 European countries for 2012. Values for time allocation and workload are expressed on a per capita and per year basis. Data sources: “Population on 1 January by broad age group and sex”, “Population on 1 January by age and sex” (Eurostat, 2018a, 2018b) and Tabulation on the 2010 Population Census of the P.R.C. (NBSC, 2018) for total population and demographic structure; “National accounts employment data by industry”, “Full-time and part-time employment by sex and economic activity” (Eurostat, 2018c, 2018d) and China Labor Statistical Yearbook (NBSC, 2019a) for time allocation in paid work; Energy Balances for the EU (Eurostat, 2019) and for China (NBSC, 2019b). EMR and BEP sources: our calculations.

2012	Population	Demographic structure			Time allocation							
		Adults	<15	>64	Societal overhead		Paid work		P&S sector	Workload	EMR$_{AS}$	BEP
	millions	*%*	*%*	*%*	*h*	*%*	*h*	*%*	*h*	*h*	*MJ/h*	*MJ/h*
Bulgaria	7.3	68	13	19	7990	91	770	9	328	1920	12	317
Czechia	10.5	69	15	16	7900	90	860	10	338	1840	20	513
Finland	5.4	66	16	18	7995	91	765	9	235	1665	31	1144
France	65.3	64	19	17	8120	93	640	7	141	1620	19	1174
Germany	80.3	66	13	21	8025	92	735	8	202	1515	19	820
Greece	11.1	65	15	20	8000	91	760	9	196	2290	12	532
Italy	59.4	65	14	21	8040	92	720	8	214	1900	13	546
Netherlands	16.7	67	17	16	8015	91	745	9	154	1495	23	1308
Romania	20.1	68	16	16	7980	91	780	9	428	1820	8	172
Spain	46.8	68	15	17	8080	92	680	8	161	1760	13	711
Sweden	9.5	64	17	19	7985	91	775	9	198	1580	25	1110
UK	63.5	65	18	17	7985	91	775	9	155	1670	15	867
EU	504	67	15	18	8030	92	730	8	207	1710	16	669
China	1350	75	15	10	7460	85	1300	15	814	2295	9	97

households, the accessibility of higher education, the legal working and retirement age, etc.

3. The level of economic development of society – This factor determines the demand for services in society. The expectations about a minimum standard of living defines a certain bio-economic pressure, i.e., the need for investing a certain fraction of the work force and energy carriers in the SG sector of society. This mechanism is explained in detail in the following section (Section 3.2).
4. The boundary conditions – This factor determine the productivity of the biophysical processes taking place in the primary and secondary sectors. The boundary conditions reflect both: (a) the amount and the quality of the natural resources available for exploitation by the primary sectors (agriculture, energy and mining); and (b) the option of importing resources and goods. The latter option saves on the requirement of resources and the human activity needed for their exploitation.

Note that, within this analytical framework, numerical relations over the categories of time allocation are expressed on a per capita basis. This makes the population size an ‘invisible’ attribute. What matters in this set of relations is a change in any of the four factors listed above (demographic structure, socio-cultural identity, standard of living, boundary conditions). Indeed, with an increasing standard of living and life expectancy, less work hours are available in the market economy (less time in PW in Fig. 1), whereas more work hours are needed in the service sector (more time in SG) and more goods are consumed. This leads to a progressive shortage of labor in the productive sectors (less time in P&S). In such a situation, developed countries have only three options to avoid a stagnation in their economy: (i) (further) increasing the use of energy and machines to boost the labor productivity in the productive sectors, provided resources are available; (ii) externalizing the production of goods by exploiting the (temporary) availability of labor surplus in other countries, thus overcoming internal shortages of labor in the primary and secondary sectors; and (iii) using immigrant workers to (temporary) increase the relative size of the workforce (compared to the dependent population) in society.

These three options are further analyzed in the form of examples in Section 4. The conceptual framework explaining the mechanisms underlying these three solutions is described in the following sub-section (Section 3.2).

3.2. *Entanglement of human time and energy allocation patterns*

The previous section (Section 3.1) focused on the taxonomy of human time allocation according to functional categories. In this section, we address the implications of the need for energy carriers in the expression of those different activities. Indeed, the performance of a task invariably involves the realization of an energy end-use and requires a specific mix of human activity, energy carriers and power capacity (technology). Therefore, we couple the dendrogram of human time allocation to that of exosomatic energy allocation (Fig. 2). On the right-hand side of Fig. 2, the total energy throughput (TET) of society is subdivided over the same set of accounting categories, thus describing the profile of allocation of energy carriers at lower-level nodes (ET$_i$). Also in the case of energy end-uses, closure of the accounting is required at each level i of the dendrogram: $\text{TET}_i = [\sum \text{ET}_i]$.

The representation in Fig. 2 allows us to characterize, in an indirect way, the level of technical capitalization of the activities. The level of technical capitalization is a proxy of power capacity and refers to the quantity of technical devices used for the expression of a given activity. It can be approximated by the value of the energy metabolic rate (EMR$_i$) for that activity. Thus, the EMR$_i$‘s measure the specific rate at which exosomatic energy is used per hour of human activity in the various social practices inside and outside the paid work sector, i.e., the end-uses of energy. They represent important benchmark values for the study of the societal metabolism (Velasco-Fernández et al., 2018).

The coupled dendograms of time and energy allocation, shown in Fig. 2, permit the analyst to identify forced patterns of time allocation in relation to the feasibility, viability, desirability and security (openness) of the metabolic pattern of society (Giampietro et al., 2021). Particularly useful in this regard is the concept of Bio-Economic Pressure (BEP), a biophysical indicator of economic development (Giampietro et al., 2012; Giampietro and Mayumi, 2000). BEP is defined as the required (or desired) total energy throughput (TET in J) of a society (used for the production and consumption of good and services) divided by the total hours of human activity allocated to the primary and secondary sectors of its economy (HA$_{P\&S}$ in h), both expressed on a year basis (see Eq. (1)). It can be calculated from the set of relations shown in Fig. 2, and is measured in MJ/h. BEP is considered a ‘pressure’ because it reflects the amount of energy and materials that must be made available by the productive sectors of the society (P&S) to meet the desired standard of living. BEP can also be expressed in terms of the average energy use in

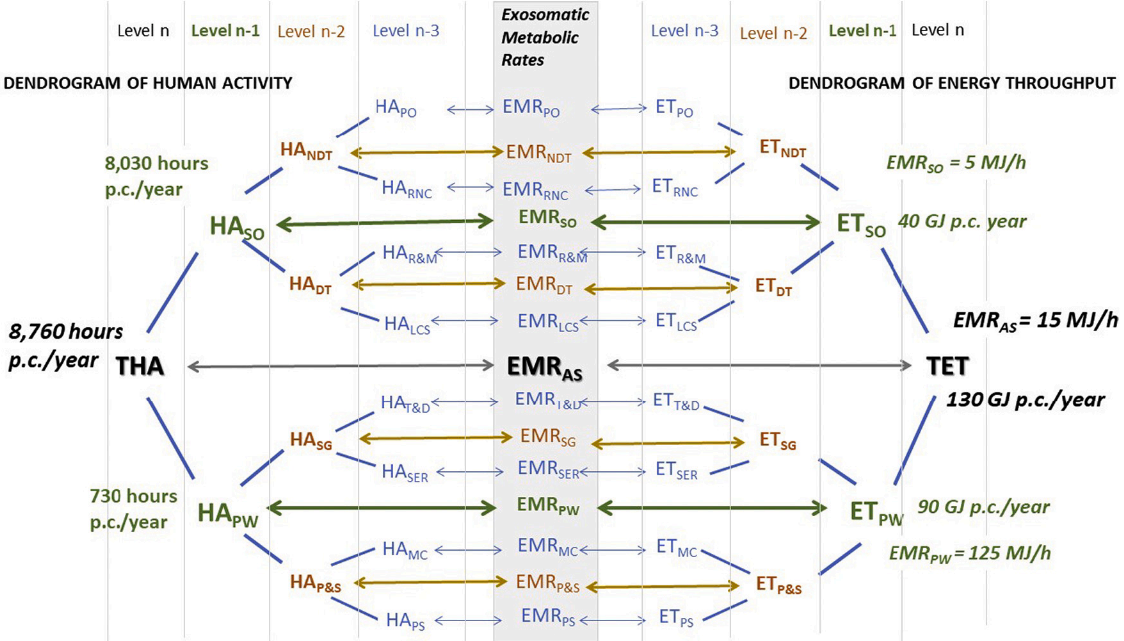


Fig. 2. Coupled dendrograms of human activity (HA) (left) and energy throughput (ET) (right) for the EU. Subscript abbreviations are explained in Box 1. Data from (Velasco-Fernández et al., 2020).

society (EMR_{AS} in MJ/h) and the time (in h) allocated to the consumptive (dissipative) compartments ($HA_{NDT} + HA_{DT} + HA_{SG}$) (see Eq. (1)). The larger is the value of BEP, the higher the material standard of living. It has been empirically proven (Giampietro et al., 2012; Pastore et al., 2000) that BEP correlates well with conventional indicators of development and material standard of living. This confirms that economic development entails an increase in societal energy use, coupled to a simultaneous increase in the share of human time invested in its consumptive (dissipative) compartments.

$$\mathrm{BEP} = (\mathrm{TET}/\mathrm{HA}_{\mathrm{P\&S}})_{\mathrm{required}}$$
$$= \mathrm{EMR}_{\mathrm{AS}} \times \mathrm{THA} \Big/ [\mathrm{THA}-(\mathrm{HA}_{\mathrm{NDT}} + \mathrm{HA}_{\mathrm{DT}} + \mathrm{HA}_{\mathrm{SG}})] \tag{1}$$

The surplus required by society from the primary and secondary sectors to meet the BEP must be consistent with what the primary and secondary sectors can possibly supply. We refer to the latter capacity as the Strength of the Exosomatic Hypercycle (SEH) (see Eq. (2)). SEH mirrors BEP and is also expressed in MJ/h. It depends on the available resources (boundary conditions), technology and imports. The dynamic equilibrium between SEH and BEP (Eq. (3)) entails a constraint over the relations of the coupled dendrograms shown in Fig. 2, which is formalized by Eq. (4). Note that in Eq. (4), the EMR_{AS} on the left is defined as the average rate of *supply* of energy carriers to society (TET per year), whereas the EMR_{AS} on the right side refers to the average rate of *consumption* of energy carriers (TET per year). Any discrepancy between internal supply and consumption must be compensated by trade.

$$\mathrm{SEH} = (\mathrm{TET}/\mathrm{HA}_{\mathrm{P\&S}})_{\mathrm{supplied}} = \mathrm{EMR}_{\mathrm{AS}} \times \mathrm{THA} \Big/ (\mathrm{HA}_{\mathrm{P\&S}}) \tag{2}$$

$$\mathrm{SEH} \leftrightarrow \mathrm{BEP} \tag{3}$$

$$\mathrm{EMR}_{\mathrm{AS}} \times \mathrm{THA}/(\mathrm{HA}_{\mathrm{P\&S}}) \leftrightarrow \mathrm{EMR}_{\mathrm{AS}} \times \mathrm{THA}/[\mathrm{THA}-(\mathrm{HA}_{\mathrm{NDT}} + \mathrm{HA}_{\mathrm{DT}} + \mathrm{HA}_{\mathrm{SG}})] \tag{4}$$

Eq. (4) is useful to study the conditions of congruence required for achieving a dynamic equilibrium between SEH and BEP. These conditions will define the feasibility, viability and desirability of a given profile of human time allocation, and, importantly, the extent of openness of the system (Giampietro et al., 2012; Pérez-Sánchez et al., 2021). Note that, even if formally identical, SEH and BEP are defined over different scales and using non-equivalent descriptive domains. BEP is concerned with the internal viability of the distribution profiles of energy throughputs and human activity among societal components; it can be assessed by looking at the characteristics of the purely dissipative compartment of society in relation to the characteristics of the whole (EMR_i per hour across levels). SEH is related to the labor productivity in productive sectors, guaranteeing the feasibility of the metabolic pattern; it depends on boundary conditions (external primary energy sources) and technological capital and know-how (TET of the whole society and $HA_{P\&S}$).

4. Applications

4.1. Comparing changes in time allocation between the EU and China

In this first example, we show the existence of an attractor in the evolution of the metabolic pattern of societies. The presence of such attractor was first suggested by (Giampietro et al., 2012) in a longitudinal analysis of the metabolic pattern of EU countries, in which the energy metabolic rates (EMR_i) of the various sub-sectors of the paid work compartment were plotted against the corresponding sub-sectoral gross domestic product (GDP_i, calculated per hour) for the period 1992–2005. In the example presented here (see Fig. 3), we examine how the various compartments of the paid work sector of China (left pane) and the EU (right pane) changed during the period 2000–2016. Fig. 3 also shows the difference between China and the EU for the selected economic sectors at the different points in time. In this example, changes are represented in a purely biophysical Cartesian plane (no monetary indicators). The sectoral EMR_i are represented on the vertical axis (in MJ/h, averaged over one year), the sectoral HA_i on the horizontal axis (in h per capita per year). The energy throughput per capita ($ET_{i\ pc}$) of the different economic sub-sectors are represented by the relative size of the bubbles. The scope of this example is to show that economic development entails: (i) an increase in the EMR_i of the primary and secondary sector; and (ii) an increase in the HA_i allocated to the service & government sector.

A comparison of the two graphs in Fig. 3 shows that sectoral EMR_i values for China are consistently lower than those of the EU, the

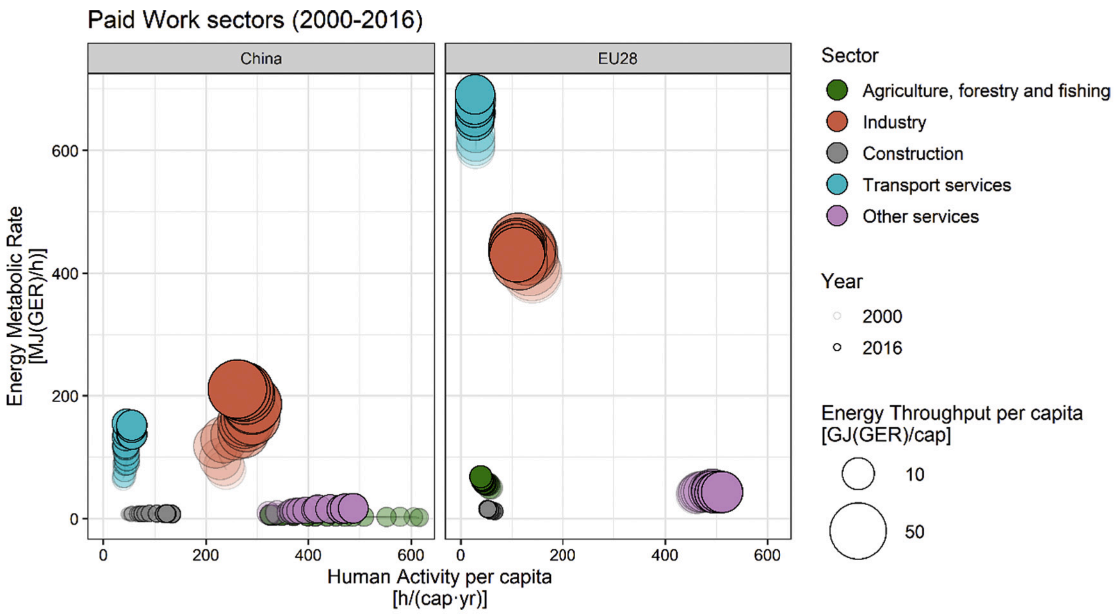


Fig. 3. A diachronic analysis of the metabolic pattern of China and the EU over the period 2000–2016, after (Velasco-Fernández et al., 2020).

difference being most marked for the sectors of transportation, industry and agriculture. In the EU, the level of technical capitalization appears to be stable (with the exception of the transport sector, whose EMR_i is still increasing in time), thus indicating a situation of maturity. For China, on the other hand, values are steadily heading toward the EMR_i levels recorded for the EU. This pattern is especially evident for the transportation and industry sectors.

Important differences between China and the EU also exist for the investment of human time in the various economic subsectors (HA_i) (Fig. 3). The number of hours per capita allocated to the 'other services' sector has been rapidly increasing in China over the past 20 years (the purple bubbles move to the right with time) and is approaching EU values. This development originates from China's modernization process that has implied a progressive and steady reduction of farmers (the green bubbles moving to the left, partly covered by the purple bubbles). This pattern confirms the existence of an attractor in the evolution of the time allocation profile and the hypothesis of Zipf, Meier, and Cipolla (discussed in Section 2) that economic progress leads to a progressive

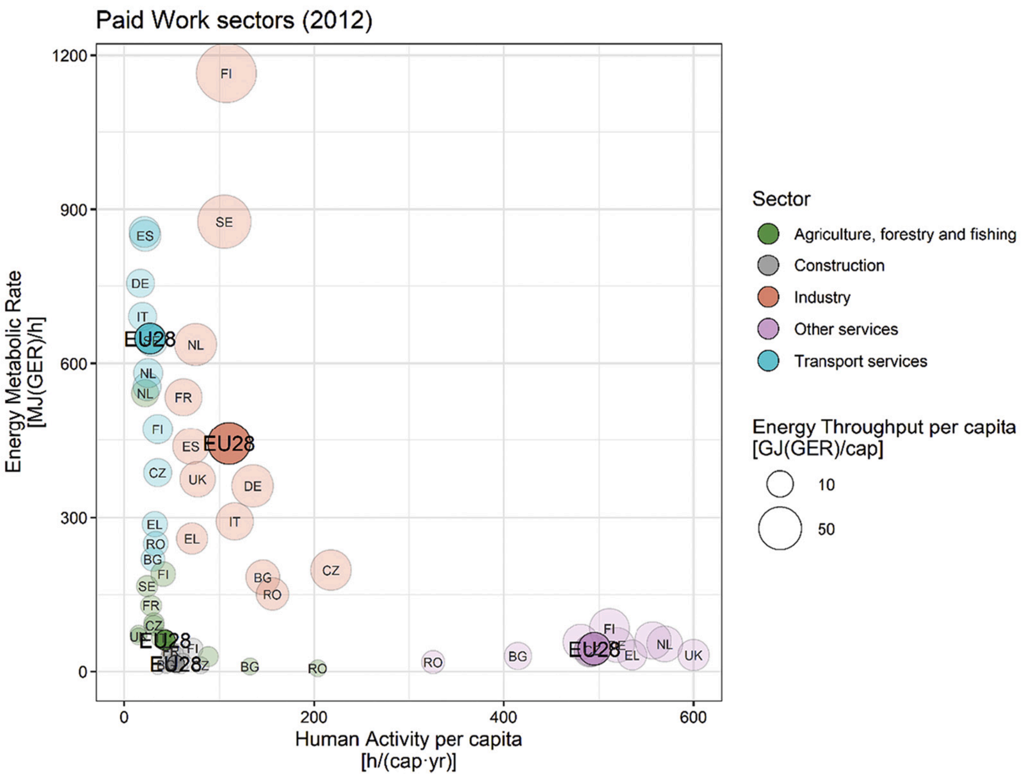


Fig. 4. A synchronic analysis of the metabolic pattern of a sample of 12 European countries in 2012. Data are from the same study reported in Fig. 3 (Velasco-Fernández et al., 2020).

reduction in time allocated to agriculture and a simultaneous increase in time allocated to final consumption. Nonetheless, China has not yet reached the 'maturity' observed for the EU: although the time invested by China in the agricultural sector declined, in 2016 it still was about 10 times that of the EU. For the industrial sector, the Chinese time investment in 2016 was more than twice (almost triple) that of the EU (Velasco-Fernández et al., 2020).

Note that the low investment of human time in the EU agricultural sector is achieved not only through technical capitalization (boosting the labor productivity of farmers) but also through a massive import of agricultural commodities (mainly feed for animal production) (Cadillo-Benalcazar et al., 2020; Renner et al., 2020). Such a solution is currently out of reach for China, as capitalization is still focused on industry and urbanization. It is also questionable whether enough agricultural commodities would be available in the global market to cover a significant amount of China's enormous food requirement. Another interesting feature of China's metabolic pattern is the rapidly growing investment of hours in its construction sector. This reflects its incredible pace of urbanization: China consumed in 3 years (2011−2013) more cement than the USA in one century (1901–2000) (Smil, 2014).

In Fig. 4, we zoom in on the EU for the year 2012, adopting the same plane as in Fig. 3, but a different scale. For the sake of visualization, we represent a heterogeneous sample of 12 European countries only (Spain, Greece, Bulgaria, Italy, France, Sweden, UK, Finland, Czech Republic, Romania, Netherlands and Germany). As can be seen from Fig. 4, the industrial sectors of these countries exhibit markedly different EMR_i values, depending on the industrial production processes performed. For instance, the high EMR of the industrial sectors of Finland and Sweden can be attributed to the relative importance of their energy-intensive pulp and paper industry (Velasco-Fernández et al., 2019). On the other hand, time allocation to the industrial sector (i.e., the HA_i values) is fairly similar among the selected EU countries. The same applies to the agricultural sector. This chart confirms that there is an evolutionary attractor toward reducing the time investment in the productive sectors. Eventual mismatches between the demand and supply of industrial and agricultural products are solved through trade, rather than domestic production, when too high an investment of human time is required (see Section 4.2). The variation in time allocation observed for the SG sectors of these EU countries reflects small gradients in their economic development and their different reliance on imports.

Table 1 shows time allocation for China, the EU, and the 12 individual European countries from Fig. 4, along with dependent population, workload, average energy metabolic rate and BEP. Obviously, values reported are necessarily approximated. As can be seen from this table, the ratio between the societal overhead and the time allocated to the paid work sector is markedly different between China (6/1) and the EU (11/1). This difference is explained by (i) the lower percentage of elderly (over 65 years) in the population of China, i.e., 10% compared to 18% in the EU, and (ii) a higher workload per worker (almost 2300 h/worker/y in China versus 1710 h/worker/y in the EU). Note that the labor force participation rate in China of the population 15y + is higher than that in the EU for both males and females, the difference being more marked for male than female workers (The World Bank, 2021). Thus, the assessment of time allocation on a per capita basis clearly illustrates that the larger amount of HA_{PW} in China (1300 h p.c./y) is basically due to its demographic structure and workload regulations. The higher percentage of adults in the population gives China an important (temporal) economic advantage over the EU.

Studies on the time invested in the paid work sector (the formal economy) in other countries report values closer to that of the EU (730 h p.c./year) than that of China (1300 h p.c./year), suggesting the situation in China is unique. For example, (Eisenmenger et al., 2007) report 990 h for Brazil, 870 h for Chile, and 870 h for Venezuela, all values referring to 2000. (Velasco-Fernández et al., 2015) found a stable value of around 880 h for India between 1990 and 2010. Similar values have been reported for Australia (790 h in 1990 and 870 h in 2010), Canada (700 h in 1990 and 830 h in 2010, the increase in time probably due to immigration), as well as the USA (880 h in 1990 and 2008) (Chinbuah, 2010). Other EU countries, not included in our sample, have values like those reported in Table 1. For example, Hungary 670 h and Poland 740 h (Iorgulescu and Polimeni, 2009). All values reported as hours per capita per year.

The unique situation of China is also reflected in the relatively low value of its bioeconomic pressure. In 2012, the BEP of the EU was 669 MJ/h compared to 97 MJ/h for China – a difference of more than 6-fold. In that same year, the EMR_{AS} of the EU was 16 MJ/h while that of China was only 9 MJ/h (a difference of less than 2/1). Note that these values represent the average metabolic rate for the whole society, calculated over the mix of energy carriers across end-uses and are expressed in Gross Energy Thermal equivalent (Velasco-Fernández et al., 2020). The ratio between the THA and $HA_{P\&S}$ in China was 11/1, whereas that of the EU was 42/1 – a difference of almost 4 times (recall that the value of BEP depends not only on the level of energy use in society, but also on the profile of time allocation – see Eqs. (1) to (4) in Section 3.2). Hence the difference in the value of BEP between China and EU cannot be explained only by the observed increase in labor productivity in the primary sectors of the EU (larger values of EMR_i). To explain the discrepancy, it is essential to consider the effect that global trade has on the requirement of paid work in the different economic sectors (changes in the values of $HA_{P\&S}$). This analysis is illustrated in the next example.

4.2. The effect of global trade on time allocation patterns

The second example is based on an analysis of (Pérez-Sánchez et al., 2021) on the externalization of labor time requirements associated with international trade. We use the findings of this study to illustrate the relevance of considering simultaneously intensive variables (the profile of human time allocation inside the society, expressed as a fraction of the total – a qualitative attribute) and extensive variables (the size of the population, expressed as the actual number of people) to check the effects of (and the limits to) the externalization of requirements of human labor through trade.

In Fig. 5 we summarize again the main factors determining the supply of working hours for the EU and China: (i) population size; (ii) demographic structure; and (iii) the yearly workload. Immediately below, the time allocated to the entire paid work sector, and to the service sector in particular, are shown for the EU and China. The latter figures make it evident that in absolute terms the time investments in the service sector are similar for the two societies. However, the relative investment of working hours in the service sector (as % of the total HA_{PW}) in the EU (68%) is much larger than in China (34%) and leaves little room for time investments in the other economic sectors.

In the bottom part of Fig. 5, the flows of embodied hours of work associated with trade are shown. According to the data of (Pérez-Sánchez et al., 2021), the EU imports 566 h p.c./year and exports 101 h p.c./year, whereas China exports 158 h p.c./year and imports 88 h p.c./year. In order to make sense of these data, they need to be contextualized in relation to the characteristics of these two societies and the size of the global market.

In the EU, the exported working time concerns the manufacturing of products with high added value, while the imported working time is associated with lower value chains. In this way, the EU can boost its internal work supply by 78%, using the equivalent of an inflow of more than 167 million workers (calculation based on EU workload). If this work were to be achieved with 167 million immigrant workers, it would entail, in the long term, a signficant increase in the size of its dependent population associated time requirements of nurture and care (Fig. 1). From the data reported in Fig. 5, it is evident that Europe is importing goods also from other countries, besides China. On the contrary, China has a slightly negative net trade of working hours per capita (−5% in relation to its paid work sector), exporting more hours than it imports. All the same, given its huge workforce (and workload), China is a large

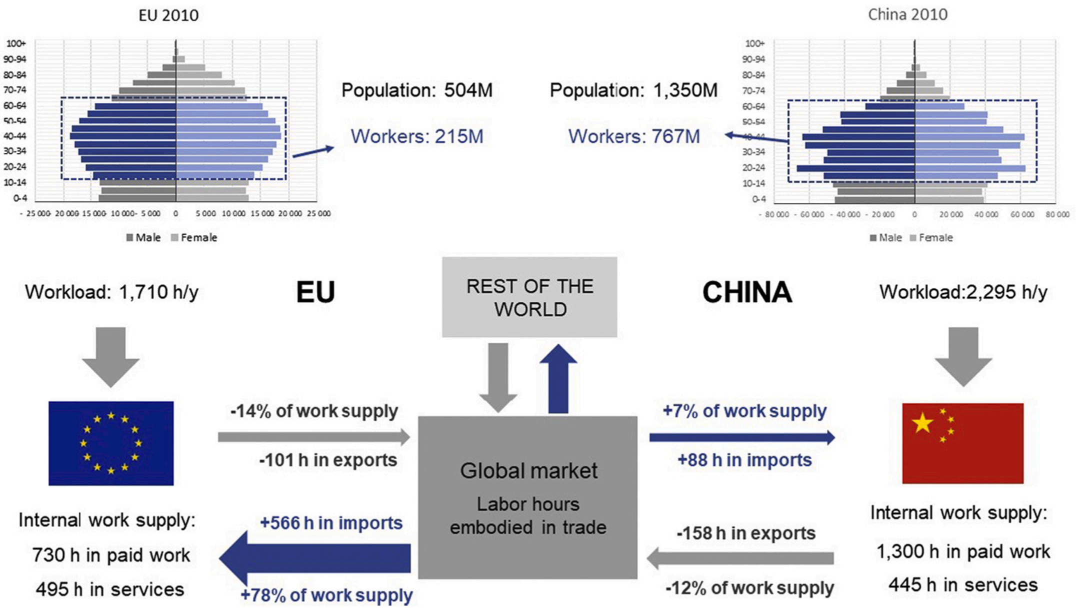


Fig. 5. The pattern of time allocation at the societal level for China and the EU, using extensive and intensive variables. All values for time allocation, work load, and import and export of labor time are expressed on a per capita and per year basis. Year of reference: 2011 Data from (Pérez-Sánchez et al., 2021).

supplier of human time to the rest of the world.

In relation to the global market, this analysis casts doubt on the possibility of extending the pattern of economic growth adopted by the EU (and the USA) to population giants such as China, India and Brazil. If the latter countries would adopt the strategy of sustaining their increasing BEP by externalizing the labor requirements of the productive sectors (manufacturing, agriculture, energy and mining) to other countries – reaching a level of dependence on imported labor similar to that of the EU and USA – we would run into a problem of planetary boundaries. Besides the problem of scarcity of primary resources (an external limit), there would not be, at the global level, sufficient surplus of labor hours, nor technical capital, infrastructure, skilled workers etc. (internal limits). Moreover, a systemic externalization of work by rich countries to poor countries would impede an increase in the material standard of living of the poor countries playing the role of net exporters of paid work hours. This solution would lock them into an economy based on primary sector activities, with diminishing returns (Reinert, 2007). Needless to say, that at a global level the solution of externalizing labor requirement to "others" does not exist. The given budget of human time entails a "zero sum game" at the global level. This internal constraint at the global level determines the option space of the profile of human time allocation of individual societes. Thus, the openness of the metabolic pattern of post-industrial societies requires an enlargement of scale of the analysis, to the global level and weaken the control on their own metabolic pattern of trading societies. In relation to this point, Ulanowicz (1997, 1986) explicitly addressed the relevance of considering the level of openness of the metabolic pattern of ecosystems. Ecosystems that rely on nutrients derived from 'outside', have a weaker "metabolic identity". In fact, the stability of their metabolic pattern depends on the stability of their boundary conditions which are determined by their context. This observation points at the importance of considering the "metabolic security" of modern economies.

4.3. Can immigration ease internal labor constraints?

In this section we look at the effects of immigration on internal labor constraints through an alteration of the demographic structure of the population. We refer to the time allocation pattern presented in Fig. 1 and the BEP discussed in Section 3.2.

The age structure of the population of immigrants is known to markedly differ from that of the hosting population. This is shown in Fig. 6 for Spain for the period 2011–2012. We select Spain as a case because in the period 2002–2014, it had an accumulated immigration inflow of 7.3 million and a net flow of 4.1 million, making it the second-largest recipient of immigrants (in absolute terms) among OECD countries, after the USA. As a result, the total foreign population in Spain rose from 2% in 2000 to about 12% in 2011 (Romero, 2015).

The age structure of immigrants shown in Fig. 6 suggests that 79% of the immigrant population belongs to the work force, compared to 67% of the resident population. A similar figure (65-86%) has been found for the immigrant population in most other EU and OECD countries for 2011–12 (OECD, 2015a, Table 2.A1.1). This entails that the budget of human time of 1 million immigrants could potentially supply 1.35 billion hours per year of paid work for society (1710 × 0.79 × 1,000,000) – provided all immigrants find employment. In comparison, the average net supply of paid work hours of a same-sized population with the demographic structure of Spain (67% of the population in the workforce), would be 1.15 billion hours. Assuming the same workload, this makes on average 1350 paid work hours per capita per year for immigrants and 1150 for residents.

As is evident from the dendrogram of Fig. 1, the immigrant population has a lower per capita societal overhead because relatively little time is implied for the dependent population – children and dependent elderly (in the category 'Requiring Nurture and Care' in Fig. 1). By relying on immigrants to boost the available time in the PW sector, the overhead associated with their dependents (temporarily) remains in their country of origin, thus generating the so-called global care chains (Pérez-Orozco, 2016).

Immigration does not only lower the societal overhead of paid work (SO in Fig. 1), but tends to also reduce the labor demand in the service & government sector (S&G in Fig. 1). Compared to the hosting (native) population, immigrants in the EU have a relatively low income (OECD, 2015b), consume less goods and services (e.g., (Borch et al., 2019)) and are more likely to live in overcrowded homes (OECD, 2015c). This reduces the BEP at societal level, but represents evidently an undesirable situation.

Immigrants thus potentially provide an immediate relief on the pressure to maintain the dependent population by (temporary) increasing the relative proportion of working hours in society, while not always receiving in return the due amounts of public services. However,

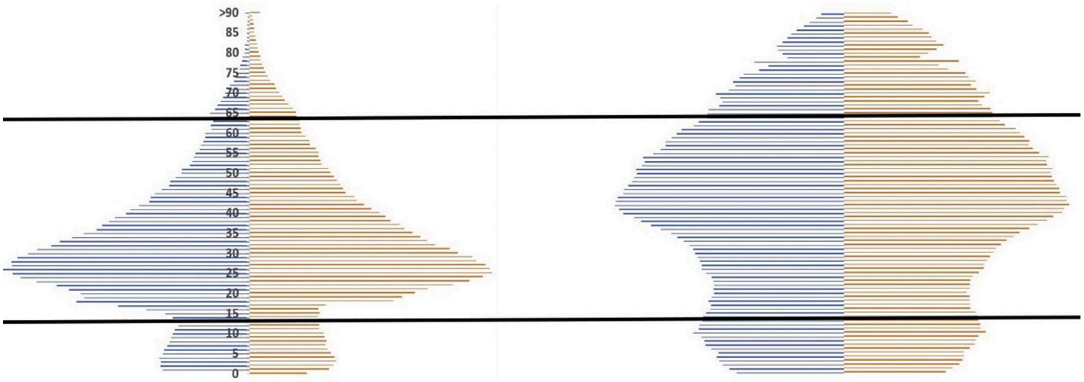


Fig. 6. Comparison of the demographic structure of the Spanish residents in 2012 (pyramid on the right) with that of immigrants coming to Spain (pyramid on the left) throughout 2011. Data from INE.
(https://www.ine.es/dynt3/inebase/index.htm?type=pcaxis&path=/t25/e447/a2009-2010/p02/&file=pcaxis&L=1).

what will happen in the long run?

The long-term effects of immigration depend on the differential in fertility rates between immigrant and native population, the stability of this differential in time and the integration of immigrants in society. In the period 2008–15, foreign births made up on average 20% of total births in Spain, while immigrants made up about 11% of the total Spanish population during this period (data from INE). The younger age and relatively high fertility rates of the settled immigrants counteract the aging process of the Spanish population, but also increase the human time in the category "Requiring Nurture and Care". Moreover, immigrants will eventually retire. At that point, the initially positive effect of the original injection of immigrants, in terms of hours of labor supply versus societal overhead, may be largely nullified (Giampietro et al., 2012, p.33–36).

The potential solution of immigration to the relative shortage of labor hours has received much attention in recent years. In 2001, the United Nations (UN) published an influential study on 'replacement migration' in response to increasing concerns about the effects of population aging in developed countries (United Nations, 2001). The report presented estimates of the replacement migration needed by developed countries to: (a) maintain the size of the total population, (b) maintain the size of the working-age population (aged 15 to 64), and (c) uphold the potential support ratio (PSR), defined as the ratio of persons aged 15–64 / 65+ (the inverse of the old age dependency ratio). An inevitable diminution in the potential support ratio emerged from the study, with a plausible number of migrations unable to halt (or revert) this progression. Many variants of the study have been published since. Notably the use of a more dynamic definition of the labor force participation and/or a more elaborated definition of the support ratio have resulted in more nuanced estimates and conclusions (e.g., Bijak et al., 2007; Craveiro et al., 2019; Marois et al., 2020; Rees et al., 2013; Wu and Li, 2003, see also the Appendix). Surprisingly, most studies define the support (or dependency) ratio solely in relation to old age, only few (e.g., Marois et al., 2020; Wu and Li, 2003) also consider the need to support children (<15). Some studies factor in migrant education level in relation to labor productivity (Marois et al., 2020) or potential effects on the demand side through variables such as household size (Rees et al., 2013), albeit exclusively in monetary terms. Nonetheless, given the multitude of factors involved, projections about the effects of replacement migration on the support ratio in the host society have remained inconclusive.

Giampietro (1998) proposed that the stabilization of a given population size is linked to the establishment of a metastable equilibrium between BEP and SEH, building on the empirical knowledge that demographic changes are related to changes in the metabolic pattern of society as a whole. According to the classic theory of the demographic transition, in a situation of high fertility and high mortality rates, we may have a stable population size with BEP matching SEH at a low value. In this equilibrium, the majority of human time is invested in producing food and other primary inputs, an activity with low labor productivity. This limited production (supply) keeps the level of consumption low and prevents a further expansion of human activity (population size). In a transitional period, in which the value of SEH consistently exceeds that of BEP (e.g., in response to the industrial revolution), society experiences a simultaneous increase in the EMR_i in PW and the time allocated outside the P&S sectors (the expansion described by Zipf). Finally, a new equilibrium can be reached when BEP matches SEH at a higher value. This translates into a society with low fertility and low mortality rates, i.e., an aged society with a high productivity of labor, investing much of its time in consuming.

However, as observed by Giampietro (1998) the existence of this second metastable equilibrium does not necessarily solve the problem of Malthusian instability (potential problems generated by population growth) (Layzer, 1988). If a gradient in economic growth exists among different societies (different BEPs) with global economic transactions, the formation of "immigration pumps" is inevitable: human activity produced in countries with a lower BEP will move to countries where the SEH is stronger.

Note that the 'solution' of replacement immigration presupposes a surplus of active population at the global level. As is the case with the import of goods and services, such a solution therefore presumes that a gradient between 'poor' and 'rich' countries persists. The effects of international migration on the countries of origin of the migrants have been relatively poorly documented and focused on isolated aspects such as brain drain (e.g., (Remeikienė and Gasparėnienė, 2019), and short-term economic effects such as remittances and relief on unemployment rates (Asch and Reichman, 1994) rather than on the structural transition process to that of a developed economy.

In this paper, we have used data from time use surveys to study the nature of this phenomenon. We combined demographic statistics of Spain with data from the Spanish Time Use Survey 2009–2010 (Instituto Nacional de Estadistica (INE), 2011a), which is consistent with the methodology of reference in Europe and amenable to the categories of accounting shown in Fig. 1 (Instituto Nacional de Estadistica (INE), 2011b) (see Appendix for more details). Nonetheless, it remained difficult to relate these data in a systemic way to the conceptual framework proposed in Section 3, especially with regard to the distinction between: (i) the societal overhead and paid work at level *n-1*; and (ii) disposable and non-disposable time at level *n-2*. In Fig. 1, the closure of time allocation is based on a taxonomy of functional categories of time allocation, whereas the data in time surveys refers to a taxonomy of structural types of population (e.g., unemployed, student, part-time worker, men, women). It is therefore complicated to use these data to examine the relations over the different quantities of human time across the different functional compartments of society. The use of such data represents a challenge that needs further research.

5. Conclusions

We have provided a conceptual representation of the profile of human time allocation as an emergent property of the metabolic pattern of society. In this representation, the profile of time allocation is conceived as a specific combination of human activities capable of expressing an integrated set of functions that is needed to reproduce the functional and structural elements of the society across different hierarchical levels of organization. A set of formal relations has been proposed to identify the factors that shape the dynamic budget of human time in relation to society's resource (exosomatic energy) use. Two crucial benchmarks resulted from these formal relations: the bioeconomic pressure and the strength of the exosomatic hypercycle. The former is defined by the profile of time allocation and energy expenditure associated with the production and use of goods and services *expected* by society; the latter defines the biophysical limits to this pressure imposed by the productivity of labor in the primary and secondary sectors. As the available amount of human time is given for a defined population, the expansion of the consumptive sector (time allocated to the services and government sector plus time allocated outside the paid work sector) that typically comes with economic growth, translates into a dramatic increase in the pressure on the labor productivity of the primary and secondary production sector.

Three empirical applications of the conceptual framework have shown that: (1) with economic growth, the societal metabolic pattern evolves toward an increase in labor productivity in the primary and secondary production sectors associated with larger EMR_i, more working hours allocated to the service sector, and more time allocated outside the paid work sector and thus an increase in the societal overhead of paid work; (2) with the labor capitalization process saturated, the EU and its individual member countries currently overcome internal labor constraints through the massive use of working hours embodied in imported commodities, a solution that cannot be extended to the global level; (3) immigration can be a temporary solution to ease labor constraints, but is unlikely to solve the problem of senescence of developed societies in the long term.

History has shown that the time allocation in society is flexible and responsive to changing political, economic and environmental contexts. In crisis situations (e.g., war, famine, pandemic), the acceptability of consumption levels (EMR_i) and social roles inside and outside the paid work sector (profile of HA_i) is readily adjusted so as to guarantee the survival of society. The result is a 'forced' adaptation of the metabolic pattern. The sustainability crisis may represent in the near future one of these forcing phenomena. However, to improve the sustainability of the current metabolic pattern of developed societies, there is also the option of a planned gradual transition to a post-growth caring economy. Our findings suggest it will be no walk in the park either, as it will require radical changes in our social practices. To better inform such a transition, we need analytical tools that provide a richer understanding of the societal metabolism and how it relates to the choices we make in our social practices. This paper has made a contribution into this direction.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors thank Fabrizio Ciatti and two anonymous reviewers for their valuable comments and suggestions. MM and LPS gratefully acknowledge financial support from the Catalan administration/AGAUR (Grant number: 2018 FI_B 00313 and 2019 FI_B 01317). RVF and MG acknowledge support by the European Union's Horizon 2020 research and innovation programme under grant agreement no. 689669 (MAGIC). The Institute of Environmental Science and Technology (ICTA) has received financial support from the Spanish Ministry of Science, Innovation and Universities, through the "María de Maeztu" program for Units of Excellence (CEX2019-000940-M). This work reflects the authors' view only; the funding agencies cannot be held responsible for any use that may be made of the information it contains.

Appendix

A.1. An accounting methodology for human time allocation outside paid work

An important practical problem in the analysis of societal metabolism is to establish meaningful relations between the demographic structure of the population and the time allocation to the functional categories of a taxonomy of social practices not only inside but also *outside* paid work. In fact, in the official statistics these two features are dealt with separately. On the one hand, time use surveys provide profiles of social practices (functional categories) in relation to different typologies of individuals (structural categories), i.e., data on how employed/unemployed, active/inactive, students, housekeepers or retired people spend their time throughout the day. On the other hand, demographic statistics provide the population structure per age, sex, nationality, residence, etc. There is no obvious relation between the definition of these structural types of individuals – often defined ad hoc in relation to the purpose of the survey – and demographic statistics. This makes it difficult to obtain semantic and quantitative closure in the time accounting at societal level. Therefore, the following steps were performed to obtain the data for Fig. 1: (1) the definition of meaningful accounting categories of human activity (taxonomy); (2) the construction of the expected patterns of time use per structural type based on this taxonomy; and (3) the assessment of the distribution of the population over the various categories of structural types (scaling to societal level).

(1) A taxonomy of social practices outside the paid work sector is provided by the "Harmonized European Time Use Survey" (HETUS) 2008 Guidelines (which, in turn, is based on earlier experiences with the Multinational Comparative Time-Budget Research Project (Szalai, 1966)). HETUS is the European methodological reference for time use surveys. It proposes the following time allocation categories (see left column in Table A1): Personal Care; Employment; Study; Household & Family Care; Voluntary Work & Meetings; Social Life & Entertainment; Sports & Outdoor Activities; Hobbies & Computing; Mass Media; and Travel & Unspecified Time Use. Note that in the time allocation literature, the categories Voluntary Work & Meetings; Social Life & Entertainment; Sports & Outdoor Activities; Hobbies & Computing; and Mass Media are often grouped as "expressive activities" (Pentland et al., 2002), as they are activities that people choose to do during their free time and unrelated to productive or maintenance chores.

Some of the HETUS categories were too fine-grained for the purpose of our study, and some were irrelevant for certain typologies of individuals (i.

e., the population requiring nurture and care). Therefore, we merged and renamed some of the HETUS categories. The semantic bridge between our conceptual framework (used in Fig. 1) and the HETUS taxonomy is shown in Table A1. The categories 'Physiological overhead' (PO) and 'Requiring Nurture and Care' (RNC) represent non-disposable time (not subject to choice). The categories 'leisure, culture & study' (LCS) and 'residential & mobility' (R&M) represent disposable time (subject to choice: potentially available for paid and unpaid work).

Table A1
Correspondence between HETUS categories and the categories used in the present study for time allocation outside paid work.

	Present study	
HETUS categories	Adult population able to work	Dependent population
Paid work	Paid work	–
Personal care	Physiological overhead (PO) (non-disposable time)	Physiological overhead (PO) (non-disposable time)
Study Voluntary work & Meetings Social life & Entertainment Sports & Outdoor activities Hobbies & computing Mass media	Leisure, Culture & Study (LCS) (disposable time)	Requiring Nurture & Care (RNC) (non-disposable time)
Household chores & Family care Travel and unspecified time use	Residential & Mobility (R&M) (disposable time)	

(2) Time allocation patterns for different types of individuals were obtained from the Spanish Time Use Survey 2009–2010 (Instituto Nacional de Estadistica (INE), 2011a). This data is consistent with the HETUS methodology and amenable to our categories of accounting shown in Table A1 (Instituto Nacional de Estadistica (INE), 2011b). Implementing the correspondence between the HETUS classification and our taxonomy, the time allocation patterns shown in Fig. A1 were obtained. Note that 'students' are defined as individuals >15y old who are actively engaged in higher (post-secondary or tertiary) education; 'early retired' are people who receive 'anticipated old age pensions' or 'benefit from early retirement for labor market reasons'; 'others' match with INE's 'inactive people'. The following assumptions were made: for the category children <15y, PO was assumed equal to that of 'students', while the remainder of their time was classified as RNC.

In line with the criticism found in the literature (e.g., Marois et al., 2020) on the conventional age dependency ratio, in which the dependent population is simply defined as (0–14 plus >65), we adapted the concept of 'dependency' by accounting for the fact that a non-negligible part of the population > 65 is still 'active' (i.e., performing unpaid work, such as household chores and child care, and potentially available for paid work). Based on data of (Spijker and Zueras, 2020), we estimated this 'active' share at 20%. For the active elderly (>65), we assumed a time allocation profile equal to that of the 'early retired', while for the other elderly, we assigned the same time to PO, but allocated the remainder of their time to RNC (see Fig. A1). The 'unfit for work' aged 15–64 were included with the dependent population; their time was assumed to be divided equally between PO and RNC (50–50).

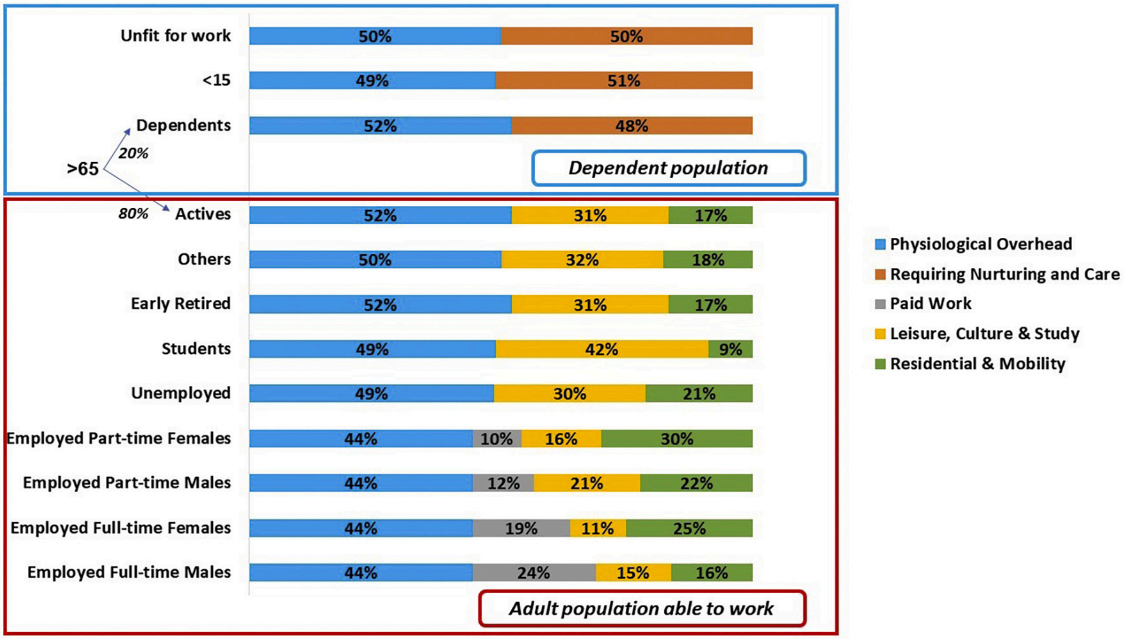
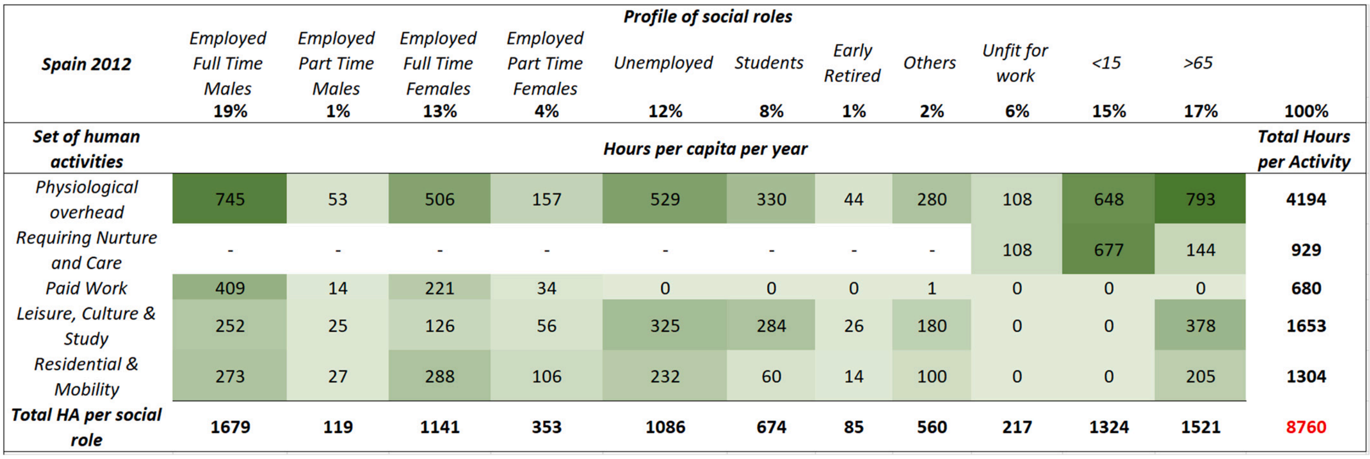


Fig. A1. Profile of time allocation for different typologies of individuals. Data elaborated from the 2009–2010 Time Use Survey for Spain (Instituto Nacional de Estadistica (INE), 2011a).

(3) In the next step, the time allocation patterns of these types of individuals were linked to the demographic structure of Spain, to scale data to the national (societal) level. The number of individuals per structural type was obtained from Eurostat. The scaling process is detailed in Table A2.

Table A2
Profile of time allocation by different types of individuals (in hours per capita).



	Profile of social roles											
Spain 2012	Employed Full Time Males **19%**	Employed Part Time Males **1%**	Employed Full Time Females **13%**	Employed Part Time Females **4%**	Unemployed **12%**	Students **8%**	Early Retired **1%**	Others **2%**	Unfit for work **6%**	<15 **15%**	>65 **17%**	**100%**
Set of human activities	**Hours per capita per year**											**Total Hours per Activity**
Physiological overhead	745	53	506	157	529	330	44	280	108	648	793	**4194**
Requiring Nurture and Care	-	-	-	-	-	-	-	-	108	677	144	**929**
Paid Work	409	14	221	34	0	0	0	1	0	0	0	**680**
Leisure, Culture & Study	252	25	126	56	325	284	26	180	0	0	378	**1653**
Residential & Mobility	273	27	288	106	232	60	14	100	0	0	205	**1304**
Total HA per social role	**1679**	**119**	**1141**	**353**	**1086**	**674**	**85**	**560**	**217**	**1324**	**1521**	**8760**

Time profiles are calculated per capita according to the following equation:

$$H_{i,j} = I_i * 8760 * A_{j,i} \big/ tot\_pop$$

where I is the array of percentual fractions of individuals belonging to m categories of structural types, 8760 is the annual quantity of hours per capita, $A_{j,\, i}$ is the matrix representing the percentual fractions of time allocated to activity j (summed over the set of n categories) of the structural type I (out of m structural categories), *tot_pop* is the country population (Spain 2012).

Closure of the accounting is verified if:

$$\sum_{i=1}^{m} \sum_{j=1}^{n} H_{i,j} = 8760$$

Note that the solution proposed here for the time accounting is of an exploratory nature. The ultimate purpose is to establish (and quantify) entanglements across demographic data referring to structural types and data referring to time allocation of typologies of individuals, in order to enable triangulations (sudoku effect) in studying the effect of possible changes in either demographic structure or social practices in the future. The reader should be aware that the information provided in Table A2 does not reflect the individual choices of time use (i.e., preferences associated with individual behaviors), but the expression of social practices at a higher level of analysis. Indeed, only a multi-level, metabolic analysis of the entanglement between exosomatic energy use and human activity – as proposed in this study and exemplified in Fig. 1 and Fig. 2 – allows an integrated study of the formation (historical lock-in or forced emergence) and the functional nature of social practices.

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