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The golden rule of material stock accumulation

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ABSTRACT

According to the key function of material stock, it constitutes valuable service infrastructure for society; however, it is also a driver for resource use, an object of technological lock-in, and a challenging waste management issue of the future. In this article, the golden rule of material accumulation is defined by confronting the ability of society to process materials–as the benefit of the capital, with the physical investments–as the cost of the process. Except for two countries with specific conditions (Japan and Switzerland), the level of assets in the analyzed economies performs under the golden rule quantity of capital per worker in material terms. Thus, there is no incentive present to reduce the material stock accumulation in the future under the current economic conditions, neither in emerging nor in developed countries.

1. Introduction

During the transition of the socio-economic system in the last decades, material stock accumulation became the primary driver of natural resource use. The ratio of stock building materials has risen globally from 20% to 58% of the domestic extraction between 1900 and 2010 (Krausmann et al., 2017). Material stock accumulation is strongly correlated with GHG emissions (Lin et al., 2016). Buildings and other infrastructures constitute the dominant part of energy consumption and carbon emissions, as 55% of all GHG emissions are related to buildings, transportation, and energy systems (Ellen MacArthur Foundation, 2019). Buildings exclusively are responsible for one-third of global energy consumption and carbon emissions; however, it may double when carbon footprint in life cycle approach is accounted for as well (Resch et al., 2020). In the United States of America, investments evoked 15% of carbon and 44% of material footprint in 2012 (Berill et al., 2019).

Therefore, together with infrastructures supporting production and consumption processes (e.g., roads, vehicles, productive capital), material stock accumulation determines resource use and environmental impacts. Consequently, the material stock constitutes not only valuable service infrastructure for the society (dwelling, mobility, production, and consumption), but also a key driver for resource use, an object of technological lock-in, and a challenging waste management problem in the future (Weisz et al., 2015; Haberl et al., 2017; Lanau et al., 2019). Carmona et al. (2020) argue that the quality of services delivered to society is frequently dependent on the material stock rather than flows alone. Furthermore, several construction materials are scarce as well, as shortages in supply and adverse environmental effects of sand production were recently reported, for instance (Torres et al., 2017; Bendixen et al., 2019). To that end, the key role of material stock, as infrastructure, is recently emphasized with particular regard to future emissions and resource use (Haberl et al., 2019).

Additionally, there is a rising awareness of the trade-off between material and energy efficiency and material stock accumulation. It is plausible both technologically (Whiting et al., 2020) and structurally in economic terms (Dombi, 2018, 2019). Material efficiency improves in line with technological progress and a higher share of services in the economy; although, the same technological progress

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List of abbreviations

Y	economic output
y	output per worker
L	labor
K	capital
k	capital per worker
s	savings rate
s_p	private savings per worker
c	consumption per worker
I	investments
S	savings
d	depreciation rate
n	rate of growth of labor
z	technological progress
k^{*g}	golden rule quantity of capital per worker
CFC	consumption of fixed capital
DE	domestic extraction
DMC	domestic material consumption

calls for excess growth of stock due to the evolving complexity of the infrastructure (Luderer et al., 2019; Chester et al., 2020).

According to the Solow model of economic growth, an optimal level of capital accumulation exists, which is referred to as the golden rule of capital accumulation, maximizing the consumption of society (Phelps, 1961, 1965). In theory, this exceptional level of capital per worker refers to the optimal resource allocation over time among the actual consumption and the savings for the future. By maintaining the golden rule, society utilizes the highest gains of investments. Since operationalization of the original golden rule is problematic based on the available macroeconomic data, the test of 'dynamic efficiency' was utilized in this study, as it was proposed firstly by (Phelps, 1965). Dynamic efficiency of several countries was proven indeed, e.g., in Abel et al. (1989); Ahn (2003); Lee et al. (2012). While the golden rule assigns one particular amount of assets, various ranges of capital endowments can be dynamically efficient for the same economy.

One may hypothesize the physical amount of capital accumulation (dynamics of material stock) to be dependent on the monetary capital accumulation. The question is whether optimization in the monetary dimension provokes over-accumulation of the physical capital, in contrast to its services provided for the society. In this article, I intend to define the golden rule of material accumulation by confronting the ability of society to process materials–as the benefit of the capital, with the physical investments–as the cost of the process. A group of 15 countries was assessed, which represents 50% of the global population, and 65% of the GDP.

The sample represents a large variety of the development status, as a spectrum of developed, transition, and developing countries are assessed, with each group represented by at least three economically significant states. With regard to the regional distribution of material stock, Lanau et al. (2019) reported in a literature review recently on 5–7 times higher amount of the per capita stock in developed countries of Europe, North-America, as well as Japan; in relation to those developing countries in Asia. In 2015, the highest in-use cement stocks were observable in Europe (25 t/cap), followed by China (20 t/cap) after its rapid ascendence in accumulation after the '80s (Cao et al., 2017). According to Haberl et al. (2019), high-income countries are endowed with 50–250 tones of concrete per capita, in contrast to the assets of low-income countries, where the stock hardly reaches 20 tones per capita.

Towards an assessment of the interconnectedness between the investments and their resource hinterland, the dynamic efficiency in monetary and material terms should be defined. Dynamic efficiency operationalizes the golden rule of capital accumulation, which is originated in the Solow model of economic growth, introduced by Robert M. Solow in (1956). While the dynamic efficiency in monetary terms was defined and applied in economics for decades, the material dynamic efficiency test is a novel contribution of this work.

1.1. Background – the basic model

The Solow model of economic growth is a valuable and straightforward description of the bonds between economic growth, capital endowment, population, and technological progress. Although the Solow model is popular in economic analysis, it has several shortcomings. It does not acknowledge where the technological changes come from, and it aggregates all the types of capital (e.g., human and physical). Furthermore, it is insensible to natural resource boundaries (Van den Berg, 2017). The latter one was addressed to by Robert M. Solow himself (1978) and by Brock and Taylor (2010); Arbex and Perobelli (2010) later on, for instance. Hao and Wei (2015) applied a modified Solow-model to analyze carbon dioxide emissions in China; however, the model has been applied for empirical analyses in environmental economics infrequently.

The basic Solow model describes the output Y as a function of production factors labor (L) and capital (K). Constant return to scale is assumed, i.e., the output rises with the factors proportionally.

$$Y = F(K, L) \quad (1)$$

$$\frac{Y}{L} = F\left(\frac{K}{L}, 1\right) \quad (2)$$

$$y = f(k) \quad (3)$$

where y is the output per worker, a function of capital per worker. Savings rate s in the simplest way is assumed to be a fixed portion of the output (per worker), and savings equal to investment since the economy is assumed to operate by perfect competition, which guarantees the equilibrium in the long run:

$$s_p = sy = sf(k) \quad (4)$$

$$c = (1 - s)y \quad (5)$$

$$I = S \quad (6)$$

where s_p is the private savings per worker, k is the capital per worker, I is the total investments, S is the total savings, and c, s are the rates of consumption and savings, respectively. Investment and depreciation of capital determine the changes in the capital in time.

$$\Delta k = i - dk \quad (7)$$

where i denotes investment per worker, and d is a constant depreciation rate, i.e., the portion of the capital being demolished each year. The variables tend to a stable equilibrium (k^*, y^*), where investments replace all the depreciated capital–it is the steady-state of the model. To conclude, the increasing level of capital per worker leads society to a steady-state, where economic growth stops. According to the Solow model, therefore, changes in savings rate s cause periodic growth exclusively; thus, permanent economic growth addresses other conditions, i.e., population and technological change. If these factors are included as well, (7) can be improved as:

$$\Delta k = i - dk - nk - zk = sf(k) - (d + n + z)k \quad (8)$$

where n is the constant rate of growth of the labor force, and z is the rate of labor-augmenting technological change, which affects labor efficiency positively.

1.2. Background – golden rule of accumulation and dynamic efficiency

Society is assumed to maximize consumption. Since the steady-state variation in the capital is zero, the consumption per worker in a steady-state c^* is:

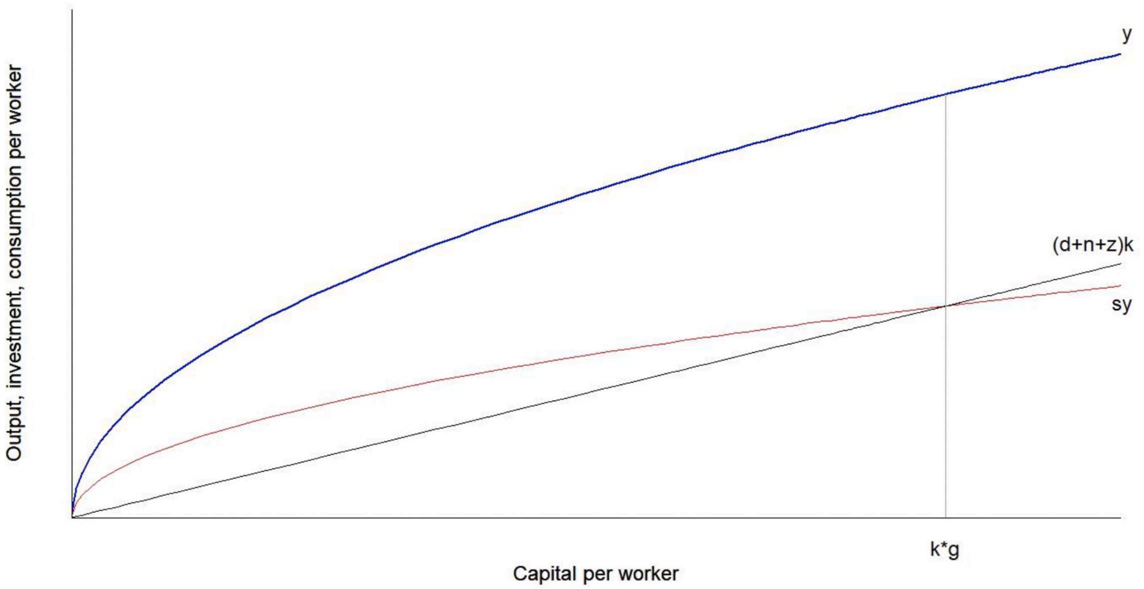

Fig. 1. The golden rule quantity of capital per worker. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

$$c^* = f(k) - (d + n + z)k \tag{9}$$

The specific steady-state savings rate, which maximizes c^*, derives the golden rule quantity of capital per worker (k^{*g}) (Fig. 1). At this particular level of capital endowment, the marginal product of capital (MP_K), i.e., the partial change in the output resulted in the changes in capital, equals the sum of the rate of depreciation, population, and technological change. Any other savings rate results in a lower level of consumption per worker.

$$MP_K = d + n + z \tag{10}$$

The sound conclusion of the golden rule quantity of capital per worker (k^{*g}) (Phelps, 1961) confronts severe limitation, i.e., estimation of a macroscale marginal product of capital is extremely complicated and uncertain (Ahn, 2003). Therefore, Abel et al. (1989) proposed a dynamic efficiency test based on a net cash flow criterion. They generalized the original golden rule as follows. An economy is dynamically efficient if the return to capital (the cash flows provided by production after the payment of wages) exceeds the investments. Thus, capital accumulation contributes to the level of consumption in dynamically effective economies and narrows it in inefficient ones (Abel et al., 1898). One may calculate the cash flow criterion of dynamic efficiency as follows (Ahn, 2003).

$$\begin{aligned} &Gross\ capital\ income = domestic\ factor\ income + capital\ consumption\ allowances - employee\ compensation \\ &\quad - proprietor's\ labor\ income \end{aligned} \tag{11}$$

$$Gross\ investment = gross\ domestic\ fixed\ capital\ formation + increases\ in\ inventory \tag{12}$$

$$Dynamic\ efficiency\ test = \frac{Gross\ capital\ income - Gross\ investment}{Gross\ capital\ income} \tag{13}$$

Ahn (2003) warns that there are two sources of potential overestimation with regard to gross capital income, namely, monopoly profits and land rent. While the former one is difficult to assess, the author shows that the latter one may constitute up to 5% of the factor income, and it plausibly does not bias the judgment on dynamic efficiency. Also, the proprietor's labor income is not indicated directly in national accounts. Based on the literature, Ahn (2003) proposed to assume it at the level of two-third of the operating surplus.

The result of the test in (13) is zero in the case of the equity of the gross capital income (11) and gross investments (12). At this level, capital income covers all the investments, as this particular value reports. Also, it reports that the golden rule quantity of capital per worker (golden rule path) was achieved; hence any changes in savings rate would result in either overinvestment or capital shortages, manifested in moderated consumption per worker (see the proof in Appendix).

2. Materials and methods

The criterion introduced above is thus a helpful tool to assess the dynamic efficiency of an economy in monetary terms. However, this study aims to evaluate the physical dimension of the capital endowment; whether the services of the accumulated capital pay off the natural resources utilized for its establishment. This section describes the concept of the golden rule path henceforth–in material terms.

2.1. The concept of the golden rule of material accumulation

Towards an analysis of both the benefits gained by society and the turnover in the physical dimension, the concept of socio-economic metabolism is a superior theoretical frame. Studies of socio-economic metabolism focus on the exchange of energy, matter, and information between Nature and society, facilitated by material flows and stocks (see. e.g., Fischer-Kowalski and Hüttler, 1998; Pauliuk and Hertwich, 2016). Terms, indicators, and databases of socio-economic metabolism research alike provide a suitable framework and also tools for the analysis described below.

During the 'metabolic' process, society utilizes resources to provide services and products. Meanwhile, either consumption, i.e., immediate utilization in the form of nutrients, packaging, heat, etc., or accumulation of natural resources occurs. In the end, all the resources are transformed into a useful service accompanied by a waste component as outputs to water, air, soil, or landfills. In the case of consumption, this process is significantly faster than that of accumulation, which builds up material stock (Baccini and Brunner, 1991; Fischer-Kowalski and Haberl, 1997).

Through the lens of economics, all types of capital, i.e., assets or land, do create value, which is received by the resource owners afterward. Factor income is thus compensation for the ability the usage of the resource in production processes. Value added cumulates factor income along the whole supply chain. To implement the concept of dynamic efficiency in material terms correctly, one may take a look at the physical representation of this very process. In line with economic value creation, production factors (labor, land, capital) are deployed in distinct stages of production, which deduct the original form, energy content, and mass of the natural resource. Considering the primary biomass as a source of human nutrition, since solar radiation directly does not provide essential nutrients for the human organism, the mass of all original natural resources undergoes deduction to become a useful service without any mass or a product with significantly reduced mass. Emerging waste generation accompanies economic value creation and mass deduction in our current socio-economic system. This pathway of the flow of natural resources from the extraction stage to the consumer characterizes any supply chain.

In essence, economically, the value added is the ability the destruction of the raw material; thus, the value added mirrors the material deducted to deliver a product or provide a service for final use. Consequently, if factor income in monetary terms refers to the value added, it addresses the deducted part of the original natural resource in material terms.

In that sense, the dynamic efficiency in material terms is conceptualized as follows. Society is in the state of material dynamic efficiency if the mass of natural resources deducted by capital (material gains of capital) exceeds the mass of material that is required to maintain and improve the ability of this deduction process (investments).

Therefore, the dynamic efficiency criterion is applied for the material dimension as follows.

$$\textit{Mass of deducted material} = \textit{domestic extraction of raw materials} + \textit{Mass of imported materials} - \textit{mass of final used material} \quad (14)$$

$$\textit{Material gains ofcapital} = \textit{mass of deducted material} - \textit{mass of material deducted by labor} \quad (15)$$

$$\textit{The material requirement of investment} = \textit{mass of gross domestic fixed capital formation} + \textit{mass of increases in inventory} \quad (16)$$

$$\textit{Dynamic efficiency test (material)} = \frac{\textit{Material gains of capital} - \textit{Material requirement of investment}}{\textit{Material gains of capital}} \quad (17)$$

Regarding the monetary dynamic efficiency calculation, accounting for the proprietor's labor income constitutes a methodological issue. In material terms, however, material gains of capital and labor are complicated to divide generally. To that end, forms of capital and labor force in the process described above were considered as media of the material deduction. The question is, therefore, what amount of material is deducted with the help of capital (machinery, buildings, computers, etc.) and human workload. There is no perfect method to answer this question; however, energy consumption might be a good proxy for useful work. The energy required for human work in the form of additional caloric intake is negligible in contrast to the energy consumption of the industrial, transportation, and service sector. The ratio of labor energy demand stays below one percent of the non-residential energy use even if the highest estimate of additional nutritional energy intake is considered (2700 kcal daily), both in developed and developing countries.

Mass of material deducted by labor was therefore assumed to be 1% of total deducted material in (15). One should, however, not underestimate the role of human work. Although its quantitative share in the processing of materials is extremely low, it is still elementary in qualitative terms, as human labor operates, controls, and develops machinery, IT, and other infrastructures.

Besides, this approach reveals a tremendous property of material dynamic efficiency, as it is worth investing almost as much material into the economy as its gains weigh. At this point, if one sets monetary and material dynamic efficiency criteria against each other, the results of the test in material terms apparently exceed those of monetary ones. If the result of the dynamic efficiency test equals zero, the golden rule path is found, as it was introduced at the end of the previous sub-section. Therefore, if a society succeeds in matching the s delivering the capital endowment k^{*g} in monetary terms, underinvestment in material terms is likely.

2.2. Data

The primary source of the data was the Eora26 database, constituting symmetric input-output tables of 190 countries as well as the rest of the world regions (Lenzen et al., 2012, 2013). Total factor income was considered as the sum of operating surplus and mixed income, while capital allowances were represented by the consumption of fixed capital (CFC). Investments involve dwelling stocks of households, capital stock, and other infrastructures established by enterprises.

The physical amount of domestic extraction (DE) and import are intensely used indicators in socio-economic metabolism studies; additionally, they are reported worldwide by statistical offices and several institutions in four groups of materials, namely biomass, non-metallic minerals, metal ores, and fossil fuels. For the purposes of this current research, UN Environment International Resource Panel (UN IRP) Global Material Flows Database was used, with further disaggregation of material groups to 13 categories.

Material consumption indicators, like domestic material consumption (DMC), though, are unable to describe final consumption in (14); hence they still contain fractions of materials object to further processing, e.g., primary biomass, which will be used in the economic system as fodder, or metal ores instead of the pure metal content. Therefore, the final use indicator was compiled as follows. Food consumption and wood usage were considered among biomass DMC. The database of FAO food balance sheets (FBS) provided country-level data on food consumption globally, while the category 'wood' in the UN IRP database corresponds to the wood final use. Ferrous and non-ferrous ores categories of UN IRP data were considered at the level of 47% and 15% ore grade particularly, in accordance with guidelines of EUROSTAT (2013) and Krausmann et al. (2015). Non-metallic minerals consist mainly of construction materials. Since there is a negligible loss before the final use, the construction materials category of the DMC was entirely accounted for as final use. In contrast, fossil fuels are consumed perfectly with regard to their mass during the production and consumption processes.

The material dimension of gross investments in (16) was calculated by the Eora26 as well. Since the mass of deducted materials in (14) corresponds to materials processed inside a country, inland needs for material accumulation were considered among the material requirements of investments in a country as well to maintain the coherence between the two sides of the efficiency test. Eora26 is an input-output database with environmental extensions, of which one type of additional dataset is row material input (see the details in Appendix).

3. Results and discussion

3.1. Dynamic efficiency

The results of the monetary and material dynamic efficiency tests are presented in Fig. 2. First of all, two of fifteen countries have been reported as inefficient (South Korea and China) in monetary terms due to overinvestment throughout the whole analyzed period, while the United States of America shows inefficiency for a long time. In Hungary, the years after 2000 perform as an intensive upward trend shift in CFC and operating surplus (OS), with annual increments above 10%. At the same time, investments have been slowed (0–10%). As CFC and OS accounted for 2.5 times higher amount that times, the Hungarian economy turned into a monetary efficient

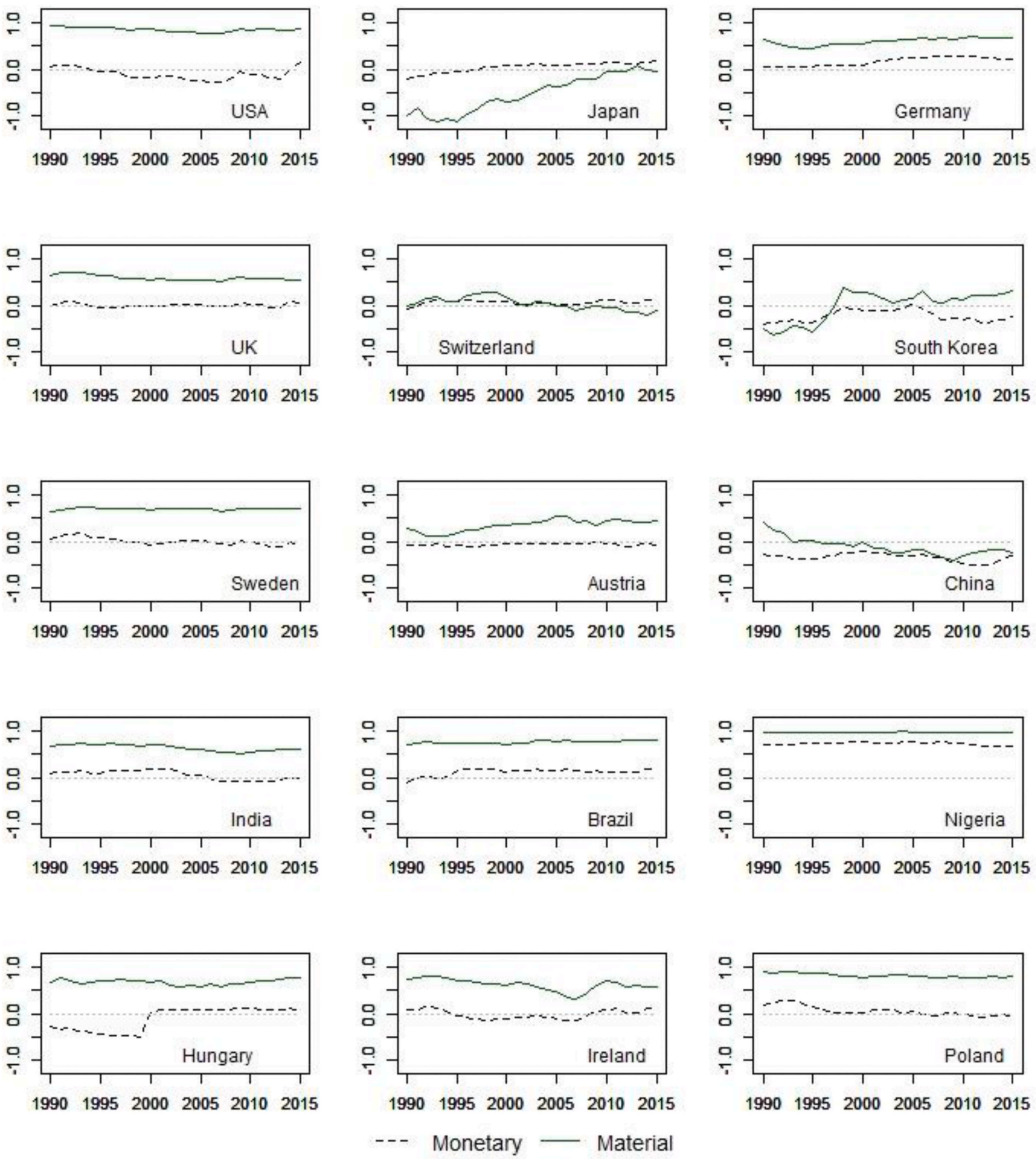

Fig. 2. Dynamic efficiency of 15 countries.

one during a relatively short time period of two years.

Several countries passed shorter periods of inefficiency (up to 10 years). With the exception of Nigeria as a special case discussed later, by all means, monetary dynamic efficiency varies in a narrow range. The ramble of the results of the monetary dynamic efficiency test around zero suggests that the majority of the countries maintain the golden rule quantity for capital per worker (k^{*g}); thus, the consumption is permanently maximized by maintaining the optimal steady-state capital level.

Dynamic efficiency in material terms is strongly coupled with that in monetary terms. Furthermore, with the exception of Japan and Switzerland, material efficiency exceeds the monetary dimension's efficiency significantly. It implies that societies gain more from investments in material terms than financially. Several countries operate with an excess level of material requirement of investment per capita, i.e., Japan, China, Switzerland, South Korea, Sweden, Austria, and Ireland (Table 1.). Except for Japan, these countries have increased their per capita resource use of investments between 1990 and 2015. The majority of this very country group shares a common development path, as will be discussed later.

The final use per input ratio is higher in those inefficient countries (China, Japan) and in Switzerland. According to two sides of the dynamic efficiency test in (17), inefficiency occurs when the accumulated material does not contribute to deduction of at least the same amount of material, or in other words, the participation of the invested material is limited with regard to the final consumption processes of the society. The high ratio of final use per input, and also the low ratio of deducted per final use, reports on the higher portion of minerals relative to other final use materials (food, wood, metals), as the mass of this material category is considered to be utilized entirely in final use. Considering, however, the low variability of the ratio of minerals in final use; the difference rather originates from the level of deducted materials.

Countries reporting significant gains in deducted material between 1990 and 2015 are grouped with special regard to the source of the improvement as follows. Brazil, Nigeria, and India have observed the fastest population growth, resulting in a 'demand-driven' increment in material gains. These countries utilize minerals at a low level in comparison to their final use (Table 1); however, the deduction of biomass is a significant process here (Food per biomass input). Despite the rapid growth, investment per capita still lags

Table 1
Structural analysis of the material dynamic efficiency test results.

	Final use per input (mean)	Deducted per final use (mean)	Food per biomass input (mean)	Minerals per final use (mean)	Investments per capita (t/cap), 2015
Austria	0.54	0.84	0.37	0.84	5.52
Brazil	0.31	2.25	0.09	0.63	2.66
China	0.69	0.44	0.34	0.86	7.34
Germany	0.46	1.18	0.42	0.81	2.88
Hungary	0.47	1.15	0.22	0.79	1.99
India	0.51	0.94	0.24	0.68	0.94
Ireland	0.41	1.49	0.19	0.78	4.19
Japan	0.56	0.80	0.56	0.81	5.11
Nigeria	0.34	1.93	0.27	0.29	0.06
Poland	0.39	1.62	0.27	0.74	2.03
Republic of Korea	0.60	0.69	0.53	0.86	7.21
Sweden	0.40	1.59	0.50	0.75	4.24
Switzerland	0.71	0.41	0.54	0.84	4.09
United Kingdom	0.51	0.95	0.52	0.80	2.39
United States of America	0.50	1.01	0.29	0.83	2.06

behind the developed countries remarkably. Consequently, food production and energy supply are suspected to be primary deduction processes here. If one considers the dynamic efficiency test exclusively, this group performs similarly to developed or transition countries (Hungary, Poland, Ireland) in the sample. Nevertheless, according to the deeper analysis above, complete with the well-known differences in economic welfare and standard of living, a prolonged development process is foreseen.

The remarkable rise of material gains is also recorded in China, Austria, and South Korea. The population growth, however, is significantly slower in these countries. At the same time, invested material per capita is the highest, and the dynamics of the investments are remarkable as well: 500% in China, 30% in South Korea, and 38% in Austria in 2015 as compared to 1990. South Korea shifted its material inefficiency into efficiency between 1995 and 2000 due to the rapid doubling of material gains. The marginal product of capital is probably already lower than in other countries. These emerging material gains of the 'investment-oriented' path keep monetary and material efficiency performance close to each other and near the golden rule path according to both dimensions.

Countries outside these two very groups are developed countries, sharing a common history of industrialized countries. One may, though, assume without any doubt that none of the development paths are sustainable regarding socio-economic conditions and the ecosystem boundaries, as the 'investment-oriented' development calls for an excessive amount of natural resources, the 'demand-driven' path may conserve social inequality and poverty, while the developed countries are the major resource users already at the global scale.

According to the clustering effort above, Nigeria reports a large operating surplus compared to its level of investments. Although investments are still extremely low, the improvement was twelve-fold during the time period 1990–2015, which indicates a high pace of capital accumulation in contrast to up to four-fold increment in other countries. Nigeria thus represents a sort of a low base effect, while China permanently overinvests both in terms of monetary and material efficiency; investments per capita have increased six-fold compared to 1990.

Switzerland and Japan, though, introduce two different cases with policy relevance. Japan's efficiency improvement is a result of a drop in investments per capita by 40%, in line with a stable population and a 15% improvement in deducted material. Japan proceeded successfully towards material efficiency last decades; however, a significant country-specific factor, namely the preference for new housing, will probably not allow the society to become dynamically efficient in the near future (Wyjts et al., 2019).

The final use per input ratio is the highest in Switzerland among the analyzed countries due to excess imports. Heeren and Hellweg (2019) forecast further increment by one-fourth of the existing stock until 2055. A high level of investments in Switzerland, therefore, does not translate to the deduction of the material. Energy intensity (MJ/USD 2011, World Bank database) in Switzerland and Ireland is far the lowest among analyzed countries, 2.19 and 1.95, respectively. Ireland, however, deducts a large amount of biomass for domestic consumption and export purposes. The Swiss society, thus, accumulates a large amount of material and imports the majority of the final use at the same time. Also, achievements in energy efficiency, together with a high ratio of renewable energy use in total primary energy supply (TPES) (25%), allow maintaining the same standard of living by a moderate amount of deduced energy carriers. Furthermore, the share of services in Switzerland is high (72%) even in European comparison, while services probably require a relatively high amount of material stocks for operation (Dombi, 2018, 2019). Therefore, this may forecast the future of developed countries as an 'end point' of a succession of a socio-economic system, considering an ecological analogy, where succession refers to a directional, predictable change in a plant community structure over time. The case of Switzerland, therefore, supports the arguments of the existence of a trade-off between economic and technological efficiency and intense material accumulation.

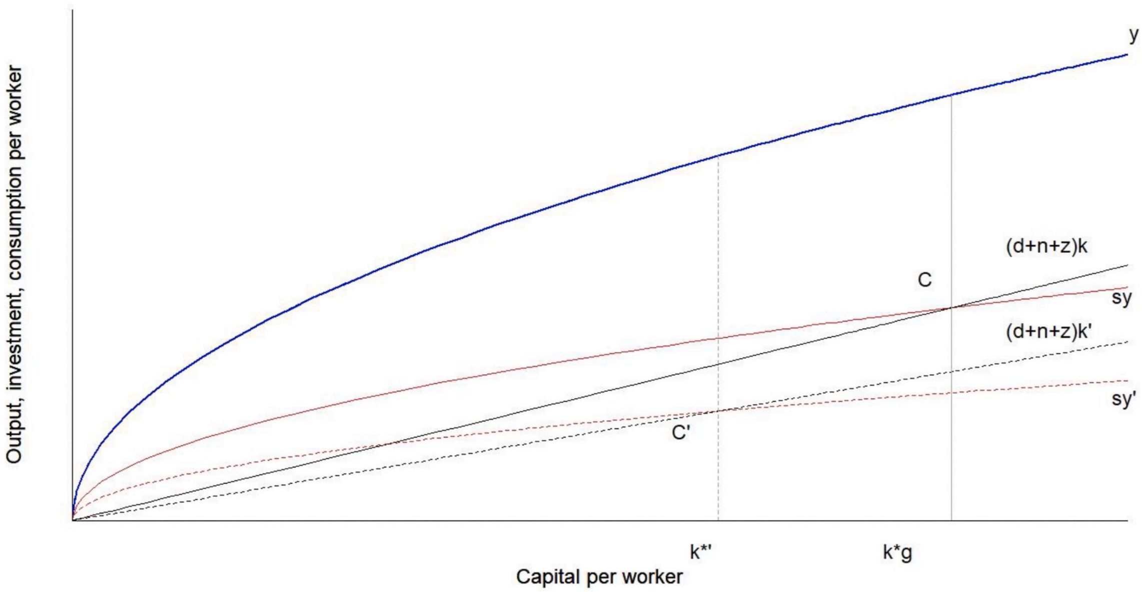

Fig. 3. Capital per worker under a stock-centered environmental policy.

Since material stock accumulation is the primary factor of demand for natural resources and evokes an excess of GHG emissions, rapid policy intervention is required to change the development path, which is presented above. Under this trajectory, a country establishes and maintains an enormous level of capital, being efficient under economic conditions continuously; furthermore, even inefficiency pays off as a mature economy in material terms. Additionally, the example of the economic models of Switzerland and developing countries (e.g., Nigeria) above raises questions of environmental justice and resource inequality as well, which are intensely discussed adverse effects of the economic status quo, resulting in resource flows into the direction of affluent societies (Schaffartzik et al., 2019; Wu et al., 2019).

Generally, there is no incentive to reduce the material stock accumulation in the future under the current economic conditions, neither in emerging nor in developed countries, as long as dynamic efficiency in monetary terms applies. Therefore, a sound policy should aim at lower savings and/or investment rates, which still correspond to the (monetary) golden rule accumulation rate.

3.2. Policy implications

Bearing in mind the limited ability of the Solow model to draw policy conclusions, one may theoretically construct a mix of policy means, resulting in positive environmental outcomes. Since the output (Y) in the model is determined by the available resources and technology represented by the production function in (1); changes in other parameters, i.e., savings rate, depreciation, and labor force, assign golden rule quantity of capital per worker (k^{*g}), which is probable to reach in monetary dimension with regard to the results of this study. Fig. 3 represents the effects of a policy intervention towards lowering the savings rate and depreciation rate at the same time by unaltered population growth rate, production recipe, and technological progress. As modified investments (sy') and depreciation with other factors $(d+n+z)k'$ define a new level of capital worker (k^{*}') (dashed lines in the figure refer to modified parameters), the output and the investment drop. At the same time, consumption rises as the distance on the vertical lines between the y function and points C, C' clearly shows.

Note that this policy excludes the availability of a new golden rule of stock accumulation since reduced depreciation rate constitutes maximized level of consumption by decreased marginal product exclusively, as it is stated in eq. (10). Consequently, there is no golden rule quantity of capital per worker in the case of decreasing d and s at the same time, i.e., on the left side of the k*g in Fig. 3. Still, society would witness an economic setting described by dynamic efficiency, as MPK exceeds $(d+n+z)k'$. In conclusion, this policy allows to operate the economy by reduced environmental pressures, emerged consumption, and net yielding investments at the same time. This option may provide a politically and socially acceptable policy towards reduced environmental impacts. The set of interventions, obviously, still may incorporate a resource or carbon tax intended to restructuring consumption and stimulate innovations. Additionally, reduced savings are considered recently as a key to tackle economic inequalities recently (Hartley et al., 2020).

A recent literature review by Krogstrup and Oman (2019) suggests that fiscal policy tools, like taxes, subsidies, and public investments, will probably play a vital role in the future; however, the optimal policy mix is still unexplored. Nevertheless, there is little doubt in the professional and public debate on the required policy measures, as they are supposed to affect consumption through carbon or resource pricing principally. Several studies, however, report on promising tools of fiscal policy with an effect on capital accumulation. Guttiérez (2008) modeled dynamic efficiency by the involvement of externalities of production. In the model, emissions are a function of capital accumulation, so the agents are able to reduce pollution by reducing savings and capital accumulation exclusively. The author found that if externalities of pollution (coupled to capital) are considered, the economy will turn into a dynamically inefficient one. The optimal tax scheme consists of transfers to consumers and taxes of producers in case of taxes on production (Pigovian tax), and the total amount of tax paid by the agents is lower in this case than in a tax scheme on wages and capital income. Dao and Dávila (2013) concluded by their model that for societies paying more taxes by young generations than the transfers elderly receive, taxes on capital income offer the best policy with regard to all of the agents. Kennedy (2020) recently proved the trade-off between the depreciation of capital and the efficiency of resource usage in the United Kingdom from 1850 to the present.

However, prices of non-renewable resources have limited effects on the whole economy, as their constant ratio in the 20th century (Solow, 1978) suggested. Therefore, there is a risk that the economy fails to change the production recipe in spite of the increasing resource prices, despite promising modeled (Diestelkamp et al., 2010; Tang et al., 2015) and observed achievements of resource taxation (Bahn-Walkowiak et al., 2012). In addition to economic efficiency, again, Krogstrup and Oman (2019) emphasize the 'political and social feasibility' as a deciding factor towards successful climate mitigation.

3.3. Limitation and further research directions

There are several sources of biases with regard to this investigation of investment into the capital stock and its services derived. Given that the Eora26 and IRP data are well-established and often used research tools, two major systematic issues remain to harm the estimation with uncertainty, i.e., the excluded part of the material accumulation and the accounting of renewable energy sources.

Among all types of capital utilized by the society, the results presented above involve residential dwelling stock, infrastructures, and capital stock; while, human capital and durables of the households are excluded. From the viewpoint of socio-economic metabolism, assets which are the object of political decisions are essential with regard to function and amount. A significant part of the infrastructures supplying the society with essential services like mobility, waste management, freshwater availability is frequently financed by the state budget. It is uncertain whether this type of investment will intensify in the future. On the one hand, unfortunately, climate change mitigation will probably evoke additional demand for construction, as citizen's protection against intensifying rainfall, storms, and floods will require new infrastructures, e.g., the new dam system of Venice. A sustainable energy transition also calls for new, essential investments. On the other hand, urbanization harnessed with opportunities of the 'smart city' concept may ensure reduced resource needs of mobility, and electricity supply, for instance. Analysis of the amount and dynamics of these material stocks in further research is crucial.

The special case of Switzerland indicates that in line with the increasing role of renewable energy sources in the energy supply, the measurement of material gains based on deducted material becomes imperfect since these energy sources do not translate into materials at all. The concept of exergy would be able to incorporate these energy sources into the material dynamic efficiency test. Current results, however, are not critically biased by the zero mass of renewables; the extremely low amount of deducted material in Switzerland led to a loss of 11% of the deducted material by a high, 25% of renewable's share.

4. Conclusions

In this article, a novel test of material dynamic efficiency was proposed. It was suggested conceptually that considering the unilateral share of labor and capital in material deduction, society is better off by investing the amount of natural resources nearly equal to the amount of deducted material.

The results of the study reveal, unsurprisingly, though, that the material accumulation is depending on the investments optimized economically. Thirteen countries out of fifteen in the sample were dynamically efficient considering the time period 1990–2015, and the majority of them follow a golden rule path of capital accumulation. Except for two specific countries with specific conditions (Japan and Switzerland), the level of assets in the analyzed economies is under the golden rule quantity of capital per worker in material terms. Thus, there is no incentive present to reduce the material stock accumulation in the future under the current economic conditions, neither in emerging nor in developed countries.

By identifying several country groups, namely demand-driven, investment-oriented, and industrialized countries, together with Switzerland, an entire development panorama was presented. Unfortunately, though, all the stages along the development are characterized by excess and unlimited material accumulation.

The declining real material productivity (Krausmann et al., 2017; IRP et al., 2019) is apparently originated in the path dependency with regard to material stock. Considering the limits of the basic Solow model of economic growth, a socially and politically feasible resource policy was outlined in this article as well by proposing efforts towards lower savings rates and reduced depreciation of capital. A decreased incentive for depreciate capital, and declining available savings may enforce business innovations promoted by the idea of the circular economy. Shared use, product as service, modular design, and enlarged lifespan offer an opportunity to reduce the environmental impacts of the elements of material stock, like buildings or vehicles.

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.

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Appendix

The results of the dynamic efficiency test and the golden rule path

$$\textit{Dynamic efficiency test} = \frac{\textit{Gross capital income} - \textit{Gross investment}}{\textit{Gross capital income}} = 1 - \frac{\textit{Gross investment}}{\textit{Gross capital income}} \tag{A.1}$$

$$1 - \frac{sf(k^*)}{f'(k^*)k^*} = 1 - \frac{sf(k^*)}{MP_K k^*} \tag{A.2}$$

Since in steady-state, the Δk equals zero (8),

$$sf(k^*) = (d + n + z)k^* \tag{A.3}$$

$$1 - \frac{d + n + z}{MP_K} \tag{A.4}$$

$$\textit{If } 1 - \frac{d + n + z}{MP_K} = 0; \Rightarrow MP_K = d + n + z \tag{A.5}$$

Calculation of the gross fixed capital formation (material) An environmentally extended input-output table (IOT) performs as an extension of the classical IOT, and it provides a description of the physical basis required for economic processes.

$$x = (I - A)^{-1} * y \tag{A.6}$$

$$M = L(DE) * y_i \tag{A.7}$$

where: x is the output, I is an identity matrix, A is the coefficient form of the IOT describing the direct connections between the sectors, and y_i is a final demand category, i.e., consumption, gross fixed capital formation, governmental expenditures, changes in inventories, and exports. The inverse matrix in the equation above is the Leontief inverse (*L*), which now covers all direct and indirect monetary flows of a specific sector into another one. In the next step, the material requirement of the final demand categories (*M*) is given by the involvement of the array of used domestic extraction (*DE*), raw material input, or any specific material type of it (e.g., biomass, metals, construction materials, fossil fuels) into *L* and then multiplying it with the final demand (Steen-Olsen et al., 2016; Schaffartzik et al., 2014).

Author's contributions

Mihály Dombi, designed the work, interpreted the results, and prepared the manuscript.

Availability of data and materials

The datasets analyzed during the current study are available in the Eora, FAO, and UN IPR repository, https://worldmrio.com/eora26/; http://www.fao.org/faostat/en/#data/FBSH; https://www.resourcepanel.org/global-material-flows-database. Processing of the data is included in this published article and its supplementary information files.

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