On a possible limit to economic progress

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Economic output is shown to be related to population (N) and natural resources (R) by a simple power law. On the basis of the exponents for N and R, called, respectively, the "ingenuity index" (n) and the "technology index" (r), the regions of the world fall into three clusters: high n and high r (Western and Eastern Europe, South America, Australia, New Zealand, the USA and Canada); high n and low r (the USA, the Middle East); and low n and low r (Asia, Africa). Even the highest values (of n) barely exceed unity, however. n was found to be well-correlated with other independently obtained exponents characteristic of human ingenuity, such as those governing the number of telephone lines, patents, and the diversity of occupations. The analysis of r reveals that there are two kinds of capital: natural resources and technology, especially information technology. However, endogenous productivity-depressing factors appear to impose intrinsic limits on what ingenuity and technology can achieve.

1. Introduction

Despite remarkable, even exponential technical progress [1], overall economic progress appears to be much less spectacular; typically, economists assess most developed economies to grow annually by at best a few percent. At the same time, although one often encounters statements asserting that a worker, or the average US citizen, is ten times better off than his counterpart a century ago, comparison of purchasing power in terms of the number of hours that have to be worked in order to purchase a good reveal much greater differences (for example, Job and Proutat [2] comment that 40 000 hours of labour were required to purchase a 4 m^2 looking glass at the beginning of the eighteenth century, but only 200 h at the end of the twentieth), and at the same time the perception of the majority of the population is that their overall purchasing power is somehow pinned such that it remains effectively constant.

The purpose of this paper is to attempt to throw some light onto these apparent paradoxes. It might of course simply be that the quantities under discussion are ill-defined (Job and Proutat themselves point out that they are difficult to measure). We address this issue by taking a fresh, "first principles" look at the matter.

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An economy is a highly complex system in which measurable output results from the activity of people transforming resources. Here we seek to reduce it to its most essential features.

The most basic economic system is that of the sole hunter-gatherer. The output of two hunters is double that of one; the only way a superproportional output can be achieved is through ingenuity and technology; for example, by observing and generalizing patterns of behaviour, or by developing a system of traps, or by developing a system that delivers a high-speed projectile to the quarry. The leisure that is a precursor of scientific and technical progress [3] is more likely to emerge in a more settled community, permitting collective brainstorming, than among isolated hunter-gatherers.

The next most sophisticated economy is the subsistence level, consisting essentially of people independently cultivating individual pieces of terrain, and annual output $\mathcal{O}$ will be proportional to the product of the number N of people and the quantity R of resources. R can be made dimensionless by expressing it in units of R_1, which is that amount of land and other resources required to ensure the survival of one person, and $\mathcal{O}$ can be similarly normalized by expressing it in units of $\mathcal{O}_1$, the output of one person working with resources R_1 at subsistence level. In fact, since we are here concerned with scaling properties, the units of $\mathcal{O}$ and R are an important.

We first tentatively propose the relation $\mathcal{O} \sim NR$: doubling the number of people working on a piece of land should double the output; doubling the amount of seed (resources) given to a farmer should have the same effect. Clearly there is an upper limit to increasing output from a finite area of land in this way; hence the relation will ultimately have to be of the form $\mathcal{O} \sim \min\{N, R/R_1\}$—the expression $\mathcal{O} \sim (N\, R/R_1)/(N + R/R_1)$ has the required property, for example—but there are ranges of parameters over which the simple product is valid.

The farmer who acquires some capital equipment (technology) such as a tractor will considerably increase his effective resources, at least in the short term (it is implicit that the farmer also acquires the corresponding knowledge in order to effectively use the technology). To incorporate this idea, R should be raised by the power r, provisionally called the natural resources index. Similarly, a farmer who employs ingenuity (e.g., crop rotation, growing crops whose unmarketable portions can be eaten by his animals, better matching his crops to seasonal weather forecasts, etc.) will also be able to increase his output and, hence, N should be raised by the power n, representing a dimensionless measure of ingenuity, and called the ingenuity index. Our basic relation is therefore

$$\mathcal{O} \sim N^n R^r . \tag{1}$$

At first sight equation (1) somewhat resembles the so-called "production functions",

$$\mathcal{O}_{\max} \sim f(L, K, T, \ldots), \tag{2}$$

where L is labor, K capital, T terrain, etc., discussed by Turgot and Malthus in the eighteenth century, by Ricardo, von Thünen, Marshall and others in the nineteenth, and by Wicksell, and Cobb and Douglas (whose names were thereafter associated with these functions) in the twentieth [4]. They enjoy wide practical application in economics, both at the micro level (individual firms) and at the macro level (entire countries), usually in problems involving marginal productivity and the maximization of output. Wicksell, Cobb and Douglas specified the function f as having the form

$$\mathcal{O} \sim L^a K^{1-a} . \tag{3}$$

The fixed relation between the exponents of L and K is an expression of the marginal productivity theory of distribution. More recent literature has proposed including a time-dependent prefactor ($\sim e^t$) in order to capture the effect of exogenous technological progress. Despite some apparent empirical support, eqn (3) and its supposed theoretical basis have been severely criticized [5, 6]. As will become clear in the following discussion, our proposed equation (1) is essentially and fundamentally different from the "Cobb–Douglas" function (3).

2. Methods and results

Determination of *n*. In order to test the validity of eqn (1), we have plotted $\mathcal{O}$ against N and R. As a measure of output $\mathcal{O}$, we took gross domestic product (GDP), defined as export – import + private consumption + government consumption + gross fixed capital formation (FCF) + change in stocks. In order to determine the exponent n (the ingenuity index), we plotted log $\mathcal{O}$ vs log(population) for several dozen countries around the world (Fig. 1). There is no *a priori* reason to suppose that ingenuity is a globally common parameter, but it is likely to converge among countries sharing common historical, cultural and geographical features. Indeed, it was clear that different sets of countries, such as Western and Eastern Europe, South America, Asia, Africa, the Middle East, the USA divided into its constituent states, and the Dominions (Australia, Canada and New Zealand; in order to boost membership of this group we also included, as a single entity, the USA, which historically shares many common features with the others),[1] were grouped in separate clusters characterized by distinctly different trend lines. We found that good linear relationships exist for Western Europe, South America, the USA, and ANZUC, and less good ones for Eastern Europe, Asia, Africa, and the Middle East. The exponents and some statistical measures of goodness of fit are reported in Table 1.

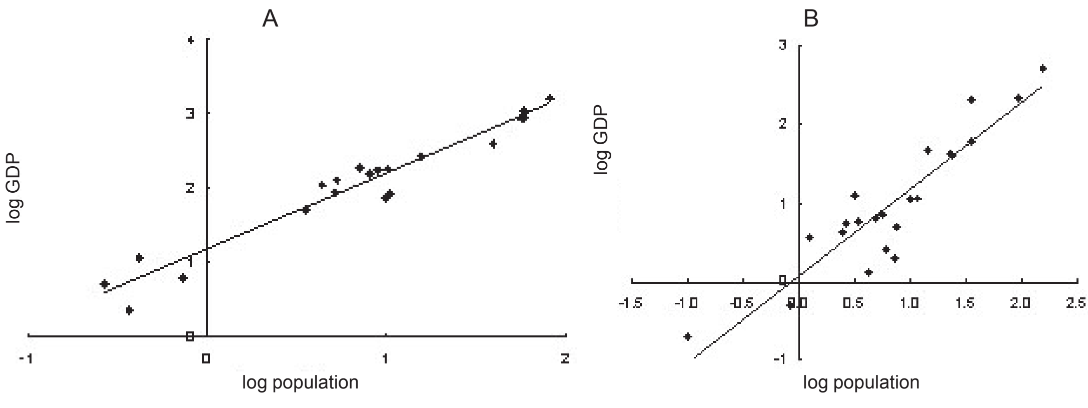

Figure 1. Representative plots of log $\mathcal{O}$ (GDP in units of special drawing rights (SDR) $\times 10^9$ [7]) vs log N (population in millions [7]. A, Western Europe; B, South America.

Determination of *r*. To a first approximation, the natural resources of a country are proportional to its total land area. Therefore, the exponent r (the resources index) can be determined by plotting log $\mathcal{O}$ vs log(area) for different countries, grouped as above into regions

[1] The combined grouping is called ANZUC.

Table 1. Exponents for eqn (1) and the diversity indices λ.

Region	v	n	$\mathcal{R}^2(n)$	r	$\mathcal{R}^2(r)$	l	$\mathcal{R}^2(l)$	λ
Africa	26	0.53 ± 0.26	0.43	0.30 ± 0.22	0.24	0.59 ± 0.50	0.22	0.23
America (S.)	22	1.11 ± 0.23	0.84	0.66 ± 0.24	0.63	0.92 ± 0.24	0.76	0.25
Asia[a]	14	0.81 ± 0.56	0.43	0.14 ± 0.58	0.02	–	–	0.43
ANZUC[b]	4	1.10 ± 0.06	1.00	0.85 ± 1.05	0.59	–	–	–
Europe (E.)	14	1.00 ± 0.51	0.58	0.61 ± 0.47	0.38	1.05 ± 0.32	0.82	0.32
Europe (W.)	20	1.02 ± 0.12	0.94	0.72 ± 0.31	0.56	0.99 ± 0.06	0.99	0.14
Middle East	10	0.90 ± 0.49	0.65	0.21 ± 0.99	0.02	0.75 ± 0.52	0.53	0.16
USA[c]	51	1.01 ± 0.05	0.98	0.14 ± 0.27	0.02	1.18 ± 0.17	0.81	0.047

v is the number of countries (states in the case of the USA). Quoted uncertainties are ± confidence intervals at the 5% significance level. $\mathcal{R}^2$ is the normalized sum of squares of the deviations between the observations and the regression line. If all the data for the whole world are treated together, we have the following parameters: $v = 110$, $n = 0.87 \pm 0.18$, $\mathcal{R}^2(n) = 0.45$, $r = 0.44 \pm 0.18$, and $\mathcal{R}^2(r) = 0.18$.

[a] Without Mongolia, which is distinctively different from all the other Asian countries, the data for Asia are: $v = 13$, $n = 0.56 \pm 0.62$, $\mathcal{R}^2(n) = 0.25$, $r = 0.27 \pm 0.46$, $\mathcal{R}^2(r) = 0.12$, and $l = 0.68 \pm 0.66$, $\mathcal{R}^2(l) = 0.29$. It might be argued that the Asian "tigers" (Hong Kong, South Korea, Singapore and Taiwan) are sufficiently different to warrant consideration as a separate group, at least until the Asian financial crisis of 1998, but very low r is also expected to be a feature of these countries, whose economies are probably less dependent on land than any other in the world, and they seem to retain a relatively inefficient division of labour—they achieve their dynamism by working longer and harder, but not necessarily more efficiently.

[b] Australia, Canada and New Zealand. The USA (which has a comparable historical legacy) is also included here as a single entity, as well as separately below, broken down into its constituent states.

[c] All US data is from ref. [15]. Since we had no access to telephone line data, l is derived from the number of patents issued in 1996, which may be considered as another measure of ingenuity.

sharing a common history or geography (Fig. 2). Again, the plots are reasonably linear, albeit more scattered than the corresponding ones for n (Fig. 1) The exponents are reported in Table 1.

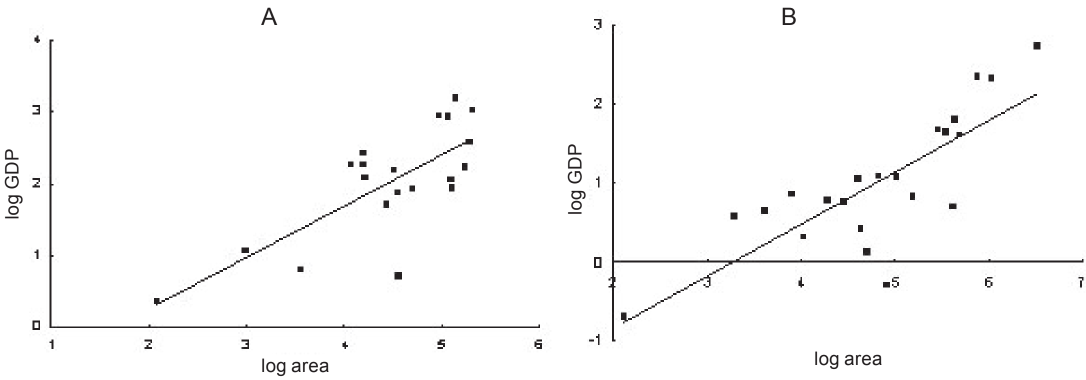

Figure 2. Plots of log $\mathcal{O}$ (GDP in units of SDR × 10^9 [7]) vs log R (land area in square miles [7]). A, Western Europe; B, South America.

3. Discussion

Robustness of the exponents. Is GDP an appropriate measure for output? If, instead of GDP, gross fixed capital formation (FCF) [7] is taken as the measure of output $\mathcal{O}$, the exponents barely change, and fall within the confidence limits of the GDP-based determination. Similarly, if the populations are weighted by the "activity rate" [8] (defined by the International Labour Organization (ILO) as the proportion of the population that is actively working), the exponents also barely change.

Is land area an appropriate measure of productive capital (natural resources)? The dramatically falling proportion of world trade in agricultural goods, dwindling from 47% in 1950 to 12% in 1996, whereas over the same period trade in manufactured goods increased from 38% to 77% [9], might lead one to question whether R can reliably be identified with land area. Heuristically, however, a correlation does exist between $\mathcal{O}$ and R, and it is plausible to argue that agricultural wealth accumulated during centuries provided a solid basis for financing industrial installations, and the recent relative decline in the importance of agriculture has not yet effaced the correlation between land area and productive capital. Besides, land is also needed for quarrying, brickmaking, transport infrastructure (airports, railway marshalling yards, roads), factories, etc. Moreover, we have the examples of Switzerland, which exploits its "unproductive" mountains for tourism, and mountainous Japan has the compensation of a long marine coastline and consequently an active fishing industry. Using land as a proxy for natural resources is the only practicable way we can determine differences between regions according to the terms of eqn (1).

Can the values of the exponents be checked independently? One of the principle results of ingenuity acting on human society is the division of labour [10]. Very small populations cannot well exploit this possibility, since there may be more essential occupations than individuals in a community, but as the number of citizens grows, the number D of distinct occupations should also grow. We posit a similar allometric relationship as for output, i.e.

$$D \sim N^d. \tag{4}$$

We ascertained the number of different types of activity by counting the numbers of commercial rubrics per commune in the Swiss telephone directory (considering Switzerland as a microcosm of Western Europe) and plotting these numbers against commune population N_C (Fig. 3). Good agreement with eqn (4) was found, with an exponents $d = 0.85 \pm 0.05$, which is the same as the average n for the four most developed regions—South America, Eastern Europe, Western Europe and the Middle East.[2]

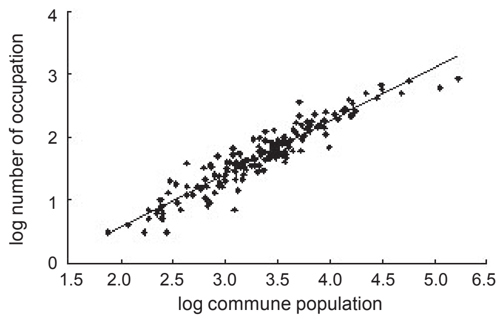

Figure 3. Log-log plot of the number of occupations (commercial rubrics) vs population for 162 Swiss communes. The exponent is 0.85, with 5% confidence limits of ±0.05 and $\mathcal{R}^2 = 0.89$.

[2] By way of contrast, if D is the number of species found in a terrain of area N, d is 0.25 [11].

Another measure of ingenuity is the number of telephone lines L in a community: ingeneous people wish to communicate with each other. Hence one might expect a relationship

$$L \sim N^{l} \,. \tag{5}$$

Eqn (5) describes the data [12] well, and in some cases, notably W. Europe (see Fig. 4), extraordinarily well (exponents etc. are reported in Table 1). Furthermore, l is so well correlated with n for all the regions, we may reasonably equate l with n.

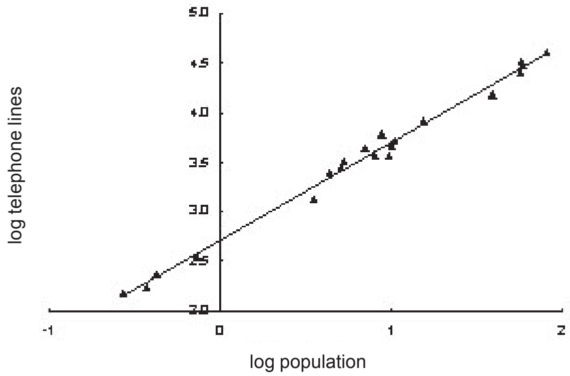

Figure 4. Log-log plot of the number of telephone lines (thousands [12]) vs population (millions [7]) for Western Europe.

Comments on the relative values of *n* and *r*. The regions of the world fall into three distinct groups, characterized respectively by:

1. High n and high r (Western and Eastern Europe, South America, ANZUC);
2. High n and low r (the USA, the Middle East);
3. Low n and low r (Asia, Africa).

Furthermore, for all regions, r is consistently lower than n.

Intuitively, one would expect the exponents n and r to be related: ingenuity should lead to the accumulation of capital assets and one would expect a positive correlation. Inspection of the data (Table 1) reveals that this only applies to group 1, however, suggesting that the economies of the other two groups are fundamentally different in nature.

The extraordinarily low value of r for the USA actually suggests that there is a possible gap in our argument so far, since it is hard to accept that the USA has a less well-developed economy than the group 1 regions. The presence of the Middle East together with the USA in group 2 provides an important clue to this apparent discrepancy: its wealth depends on oil, which requires hardly any land for its exploitation (certainly much less than the exploitation of other major natural resources). This is clearly not sufficient as an explanation, however, since even if oil was the basis of the wealth of the USA at a certain period in its history, it is no longer true today. The US economy today is characterized above all by the extensive use of information technology (IT). In order to reconcile these facts, we must recognize that there is a “hidden element” in capital.

Productive capital c is formally a measure of productivity P, defined as output per capita, viz.,

$$P = \mathcal{O}/N \tag{6}$$

(hence a subsistence economy has a productivity of unity, with $\mathcal{O}$ expressed in units of $\mathcal{O}_1$). At constant N,

$$(\partial P/\partial R)_N = c \tag{7}$$

where P and R have been suitably normalized (made dimensionless). As a first guess $r \approx c$, but plotting P against R according to eqn (7) for all our data reveals that, either for the entire dataset considered together or grouped according to regions, P and R are either uncorrelated, or $c = 0$ (with considerable scatter) (Fig. 5). Hence, it is more reasonable to propose that

$$r = c_1 + c_2 \tag{8}$$

where c_1 is the capital from natural wealth, and c_2 is a measure of the "hidden" capital embodied in technology, especially IT. We can call c_1 "tangible capital" and c_2 "intangible capital", but not in the sense of land vs human capital, an apposition frequently found in economics textbooks: rather, c_2 is an *outcome* of human activity; that is, in economic terms, infrastructure, for the provision of which technology is required. In today's world c_2 is dominated by technology (IT) and trade, which is itself increasingly heavily dependent on IT (indeed trade is an excellent illustration of activity that seeks to maximize output while minimizing land use, as strikingly exemplified by Hong Kong and Singapore). Without c_2 we would be forced to conclude that even the most sophisticated economies in the world are less efficient at exploiting resources than a simple subsistence farmer! The relation (8) allows us to predict the value of c_2 from the empirical estimates of c_1 using eqn (1) (i.e., the exponents r in Table 1 are to be equated with c_1) and a conservative "first principles" estimate of $r = 1$ for "healthy" economies (let us say groups 1 and 2).

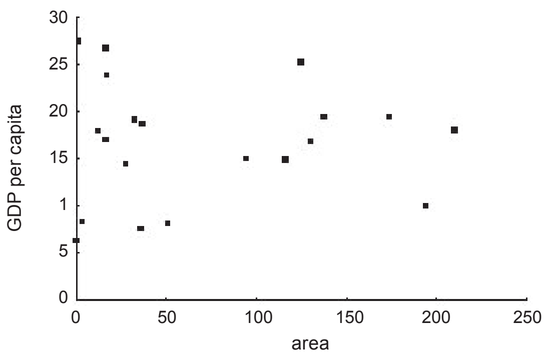

Figure 5. Plot of P (productivity, i.e. output (in units of SDR $\times 10^3$ [7]) per capita vs natural resources R (land area in square miles $\times 10^3$ [7]), for Western Europe.

A crucial aspect of the economic significance of IT—which is also reflected in the provision of telephone lines—is its facilitation of the division of labour. Although Asia and Africa have huge tracts of unproductive land, this is only part of the reason for their low r. Of greater significance is the fact that the division of labour is relatively inefficient in these continents and, hence, they are unable to make good the deficiencies in their utilization of natural resources, which is in principle possible by exercising extraordinary ingenuity (c_2).

If is assumed that each region forms a homogeneous trading bloc, a measure of diversity is the parameter λ [13], defined in our notation as

$$\lambda = \sum_i^v (\mathcal{O}_i/\mathcal{O})^2 \tag{9}$$

where $\mathcal{O}_i$ is the output in the ith country and $\mathcal{O}$ the total output. λ has a maximum value of unity (no diversity, all output originates from one country in the region), and a minimum value of $1/v$ (maximum diversity). Calculated values of λ are given in Table 1. They strikingly reinforce the idea that the USA has a strong economy because of highly efficient division of labour, resulting in such features as practically all fruit being supplied from California and Florida, all cheese from Wisconsin, all timber from Maine, etc.,[3] whereas the converse applies to some of Asia and much of Africa.

An alternative explanation for the discrepancy between r estimated from eqn (1) and the "first principles" estimate of $r = 1$ could be that sophisticated economies squander resources by nonproductive items of expenditure, such as health, social security and welfare. Table 2 shows the exponents (subscripted "soc") of these expenditures [14] plotted against N and R. Both the n_{soc} and the r_{soc} exponents are reasonably positively correlated with the n and r (Table 1), hinting that in reality these expenditures may act to maintain an efficient economy, rather than squandering wealth; in other words, "unproductive" inhabitants who need special care increase opportunities for output by their economically active compatriots.

Table 2. Exponents for eqn (1), based on expenditures for health, social security and welfare [14]. See notes to Table 1 for the definition of $\mathcal{R}^2$.

Region	v	n_{soc}	$\mathcal{R}^2(n_{soc})$	r_{soc}	$\mathcal{R}^2(r_{soc})$
Africa	12	0.18	0.09	0.05	0.02
America (S.)	14	0.98	0.69	0.65	0.64
Asia	10	0.33	0.06	–0.24	0.07
Europe (E.)	9	0.91	0.70	0.46	0.36
Europe (W.)	17	1.03	0.74	0.70	0.44
Middle East	9	0.42	0.43	0.30	0.27

Comments on the absolute values of *n* and *r*. The data strikingly reveal that only the ingenuity of South Americans and the inhabitants of ANZUC exceed that of a subsistence farmer, whose ingenuity index n is unity. It might be tempting to ascribe this to "productivity-depressing factors", which negate the achievements of ingenuity and resources in the long-established developed regions of the world. Many candidate examples of these "productivity-depressing factors" come to mind. The internet expands both in bandwidth and geographical extent, but so do computer viruses and unsolicited advertising ("spam"). Air travel becomes cheaper, hence ever more widely used, and the network of commercial routes expands, but so does the threat of terrorism and the corresponding inconveniences imposed on passengers. More indirectly, in the UK more people can afford to buy a personal motor car, but the closure of railways and village shops compels more people to use a motor car; a higher tonnage of crops can be harvested per acre, but concomitant population growth keeps the ratio of food per capita

[3] The question of quality is neglected in this analysis. Most people would assert that the tomatoes bought cheaply, albeit seasonally, at a local farmers' market in, say, New Jersey are better than the somewhat insipid produce from California and Florida available all the year round in shopping malls.

roughly constant; better medical care may be a consequence of prosperity, but so may dietary and (lack of) exercise habits that are deleterious to health. Many of these examples can readily be transformed from anecdote to evidence-based assertions; another example at a very different scale is provided by the weakening of the body's defences against bacteria by administering drugs against a viral infection [16]. The existence of these "productivity-depressing factors" is perhaps a typical manifestation of a complex system, in which it might be considered to be almost inevitable.

In order to test this proposition, let us look at the index characterizing the development of "pure" technology, untrammelled by being embedded in a complex society. Fig. 6 plots the "output" of technology (transportation in the example chosen, hence a reasonable measure of output is the product of speed and the number of passengers carried) versus its cost as an aggregate measure of the resources consumed to fabricate that technology. The exponent is 0.80. We have used average operational speed; taking the maximum speed (e.g., of a motor car, it may be 180 km/h, although it can hardly ever be driven at that speed) raises the exponent to 0.82. We have neglected the required infrastructure (roads, railways, airports), whose portion of costs ascribable to the moving units will, of course, depend on the numbers using the infrastructure (i.e., we are assuming that the slope is not significantly distorted by that neglect). A similar comparison for ships (dinghy, luxury yacht, cruise liner, supertanker), plotting displacement against cost, gives an exponent of 1.0.

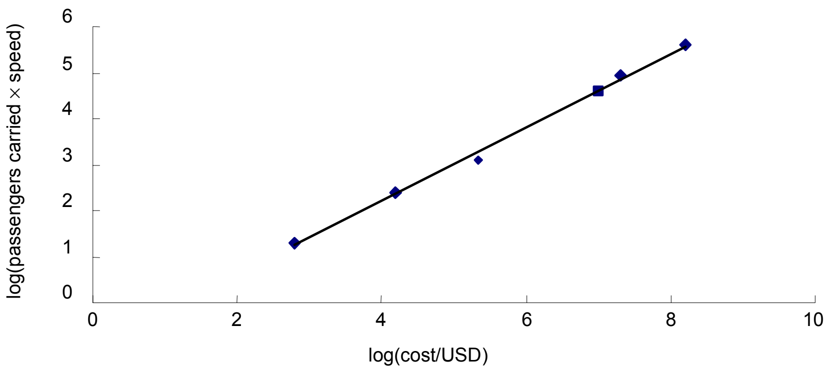

Figure 6. Plot of a "technology index" (here, the number of passengers transported multiplied by the average operating speed (in km/h) of the conveyance) vs the cost (in USD) of purchasing the conveyance. From lower left to upper right the symbols represent, successively, bicycle, motor car, light aircraft, suburban electric multiple unit train, high speed train, intercontinental airliner.

This result is surprising, contradicting intuition (unquestioned perception). It suggests that the introduction of technology cannot be explained on rational grounds, hence some other reason, such as a vague allure, must be sought. Furthermore, it shows that there is no need to introduce "productivity-depressing factors": even the raw technology is not able to yield "more for less", contrary to widely-held belief. This conclusion may also place sharp limits on the ultimate economic benefits of nanotechnology, widely held to have the potential to usher in an age of universal prosperity [17].

4. Summary and conclusions

According to the values of these two exponents, the world can be divided into three zones: a "European" one, characterized by intensive and rather uniform ("traditional") land use (as can be corroborated by anyone flying at a reasonable height over Europe on a clear day), high diversity (efficient division of labour) and a high level of technology; a "US" one, in which land has almost totally lost its significance as a contributor to wealth generation, and (information) technology is decisive and preponderant, making up the "*r*-gap", and in which the division of labour is extremely efficient (largely thanks to IT); and an Afro–Asian one, characterized by uneven land use, inefficient division of labour, and a relatively low level of technology, which renders these countries unable to compensate for the unavailability of large tracts of land.[4]

The arguments presented here throw light on the economic laggardness of the "South"—its real problem is the combination of low n and low r together; while Europe may take some heart from the fact that its economic system, characterized by high n and r, is presumably the most robust, even though at present Europe has lost the ability to price assets, an essential ingredient for economic dominance, which is now exercised globally by the USA.[5]

Perhaps the conclusion of greatest significance lies not in the relative values of the exponents, but in the fact that their absolute values barely exceed unity, in sharp contrast to almost universal perception. Probably the most apt remark bearing on this state of affairs is "All is vanity" [18]. It might be fruitful to examine whether there is some kind of pinning phenomenon in operation here, the deeper cause of which still requires elucidation.

Acknowledgments

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[4] Given the current rapidity of transformation of the economy of the Peoples' Republic of China, it will be worth re-examining their situation in a few years hence.

[5] The ability to price assets is crucial and particularly pertinent in the current debate on trade globalization, for trade (which comprises the exchange of any assets, including foreign exchange, stock, debt, as well as commodities and manufactured goods) is essentially an asset pricing phenomenon, and trade growth—seventeenfold over the last 50 years, compared with a "mere" sevenfold increase in manufacturing GDP—depends even more on technology, especially information technology, than on liberalization measures.

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