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Why we use more materials

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In this paper, we review the drivers for the high levels of material use in society, investigating both historical and current trends. We present recent national and global data by different material categories and accounting schemes, showing the correlations between materials use and different measures of human well-being. We also present a development narrative to accompany these observed trends, focusing on the strong role materials have played in economic development by industrialization and in the consumer economy. Finally, we speculate on how material efficiency might alter this pattern going forward and whether it is possible to de-couple well-being from material use.

This article is part of the themed issue 'Material demand reduction'.

1. Introduction

We will argue that increased material usage has gone along, hand in glove, with economic development. There are two parts to this dynamic. The first is about the role of materials in the economic development of developing nations. The second part is about the social/economic dynamic that sets up in developed countries. History has shown that the only way thus far discovered for large developing nations to advance to developed status is by industrialization, which means large-scale production of materials, in particular, cement and steel. For developed nations, as wealth grows, consumer spending dominates the economy and a new relationship develops between producers and consumers. This is the Consumer Economy that leads to the promotion of and the consumption of more and more goods. The result is economic growth, with potentially unhealthy side effects, and at the same time, increased material usage. To complicate matters, these two dynamics have become deeply intertwined, particularly in recent times as international trade has expanded. Now increased consumption in the developed world is coupled with increased production in the developing world.

Similarly, historical research that has looked at the nominal annual material intensity of different forms of human societies can also be used to suggest the magnitude of the increase in materials use. Their estimates are for hunter–gatherers 0.5–1 t per cap, agrarian society 3–6 t per cap and industrial society 15–25 t per cap [1]. The last transition from agrarian to industrial represents a material intensity increase from anywhere from 2.5 times to 8.3 times. Fridolin *et al*. [2] suggest a similar magnitude increase.

Many of our most basic needs—identified by Maslow [3] as physiological and safety needs—have material requirements. Freedom from violence and war, as well as access to water, food, clothing and shelter all require the use of materials in order to build necessary infrastructure and production capabilities, as well as the good themselves. At the same time Dasgupta [4], who is concerned with measuring human well-being, identifies the determinants of human well-being as the actual commodities needed to satisfy human needs both physical products and services, such as food, clothing, potable water, shelter, access to knowledge and information and resources devoted to national security. Of course, well-being is more than just access to materials, among other things it requires the institutions that allow for the creation and equitable distribution of these goods and services. But there is wide agreement from diverse fields on the significant physical components needed to deliver improvements in human well-being.

However, in addition, people's needs go far beyond these utilitarian needs. Not only do materials provide for basic human needs and enable development, they can also represent objects of fulfilment and gratification or sometimes substitute for the real objects of desire. They may represent immortality[1] through their durability, or status, or convenience, or security. They can delight and amuse. And the inclination to possess still more things has been written about, often with a warning, throughout history. The Greek myth about King Midas is a warning about avarice, and one of the Ten Commandments warns against coveting thy neighbours' possessions. Yet the struggle with human acquisitiveness continues with business models finding it to their advantage to offer still more, and consumers finding it difficult to resist. Marketing focuses on how people justify these acquisitions, and packages their products to make clear how deserving you are to commit this one additional act of consumption [6]. The interplay between wealth and increased consumption has been written about extensively [7,8] diagnosed and analysed [9,10] with the pathological consequences documents [11] yet little changes in these patterns of human acquisitiveness. In fact, Adam Smith's famous 'invisible hand' justifies these potential excesses as a virtue [12]. These basic impulses greatly complicate any attempt to modify our consumption and to turn society away from increased consumption.

The result of these complex interactions has been a steady growth in materials used by human society. A recent report ~~from~~ [13] shows materials growing exponentially at 2.3% a year from 1980 to 2010. This growth rate is less than the growth in GDP, but higher than the growth in population. The estimated total of 72 Gt per year is large enough to rival global geological phenomena [14,15]. With current population at about 7.3 billion people, this means the average material intensity for a person on this planet is about 10 t per cap. As will be discussed, further industrialization, under a business as usual scenario, could double this number.

Of central concern are the carbon emissions associated with this high level of materials use. For example, engineering materials (steel, cement, paper, plastic, aluminium) dominate greenhouse gas emissions from industry [16,17], fossil fuel burning dominates greenhouse gas emissions from the use of buildings, electricity and transport systems, and our demands for biomass dominates greenhouse emissions connected to agriculture and deforestation.

In this paper, we first examine the historical drivers behind industrialization and increased material use before going on to track the global use of materials today through national accounts,

[1]See for example the poem 'The Museum' by W. Szymborska [5].

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comparing material use with various metrics intended to measure human well-being. Finally, we cast an eye towards the future use of materials.

2. Industrialization

Early industrialization, starting in the late 1700s with the Industrial Revolution in the UK and then followed by Western Europe and North America, allowed these countries to break off economically from the rest of the world and greatly improve their standard of living. Significant increases in materials production, manufacturing and consumption accompanied their industrialization. For example, from 1709 to1850 pig iron production grew in the UK by a factor of 60, or an annual rate of 3% a year. While raw cotton consumption grew in the UK from the 1780s to the 1860s by a factor of 59, or 5.2% a year, and during the same time period, in the United States by a factor of 88, for an annual rate of 5.8% a year [18]. So clear was the link between using materials and economic growth that in the early days of economic accounting the economic progress of the nation was often measured in terms of tons of pig iron produced [19].

The historical case for the connection between industrialization and development (as measured by economic growth) can be made quite convincingly using the data collected by Bairoch [20] on international industrialization levels from 1750 to 1980 and comparing them with estimates of GDP by Maddison [21] as was done by Williamson [22].

Bairoch defines industry as 'the totality of those activities whose object is to produce or to transform material goods, excluding all those activities properly described as agricultural (including everything up to the harvest) and excluding mining, construction and various utilities such as electricity, gas, water and sanitation'. So by definition, industry means making physical products, and making and using materials. Bairoch relies heavily on the use of standard international industrial classifications to identify specific components of industry. The term, 'industrialization', therefore is generally described as an increase in the share of economic activities based in industry [22]. The resulting plot then of industrialization levels and GDP over the time period 1820 to 1950 gives us figure 1. This figure shows two log scales; on the y-axis GDP *per capita*, and on the x-axis levels of *per capita* industrialization in the given economy, 50 to 70 years earlier. The correlation as described by Williamson is 'steep and strongly significant'. The interpretation of the plot is that faster economic growth comes with industrialization. The underlying explanation for the high correlation between growth and industrialization given in most theories of economic growth is that industry, most notably in urban areas, offers far greater opportunities for productivity improvements and cost reductions than the other sub-sectors of the economy, i.e. agriculture and services [22].

A second observation from figure 1 is that while those who have industrialized have seen their standard of living rise, those who have not industrialized have fallen very far behind. Notably, there are no examples of low industrialization and high GDP *per capita*. This makes the trip between the developing and developed nations enormous. As an extreme example, to go from a World Bank poverty level of $1.90 per day (approx. $700 a year) to $10 000 per year (approximately the world median) would require a GDP *per capita* growth rate of about 6.6% a year over two generations (*ca* 60 years), so with a population growth rate between 1 and 2% this would require approximately 8% growth in GDP per year for 60 years. This is a daunting challenge. (Note this calculation assumes that the developed world is growing at 2% per year, GDP *per capita*.)

Nevertheless, in recent decades, several nations have grown their GDP at an average rate of about 6% a year for two generations [23]. These nations (Japan, South Korea and Taiwan) have accomplished this feat again by industrialization. The method of how this was implemented however differs from earlier examples. The economic historian Robert C. Allen has called this 'Big Push Industrialization'. He states that, 'the only way large countries have been able to grow so fast is by constructing all of the elements of an advanced economy—steel mills, power plants, vehicle factories, cities and so on—simultaneously.' The success of these countries required a 'planning authority to coordinate the activities and ensure they were carried out' [23]. The Soviet Union initiated such a plan starting in 1928 and was partly successful, but the most success

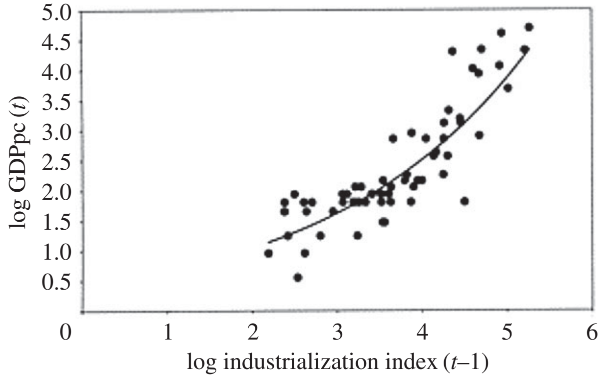

Figure 1. *Per capita* GDP versus previous industrialization levels (industrial economic activity relative to GDP 50 to 70 years earlier). See [22, p. 50].

has been in Asian countries, as mentioned above, and now in China. It is not clear to what extent other countries will try this plan, or indeed are capable of carrying off this plan, but currently it is the only known way to accelerate a large nation from developing to developed status. The connection between these Big Push Industrialization examples and materials use can be illustrated by the steel and cement statistics. During Japan's growth from 1950 to 1980, their steel production grew by a factor of about 22×, or 10.8% per year. Currently, they are number two in world steel production. More recently, China's steel production has grown from 1970 to 2010 by a factor of about 30 or 9% per year. Currently, China is number one and makes about half of all the steel produced in the world—about 626 Mt in 2010 [24]. South Korea ranks about sixth in steel production, and is 12th in cement production worldwide. While China is first in cement production, and Japan is sixth [25].

It is also worth noting the consequences of not industrializing. Countries who participate in global manufacturing primarily by supplying primary materials usually find themselves at a developmental disadvantage. There are several well-known problems associated with this status that include a likely perpetuation of inequality in income, exposure to volatility in global prices, and an increased valuation of the currency, because the primary materials are usually paid for in terms of the home currency, that put manufacturing exports at a disadvantage [22]. Furthermore, industrialization in one part of the world often results in deindustrialization and other parts of the world. If the industrial nations offer less expensive products, industries of the developing nations who import often find they cannot compete, with the result that their own industries will close down. This has been extensively researched starting from the times of the mercantile era and the industrial revolution [22,26–28] and has been observed recently as China rises, and industries find it hard to compete in South Asia, Africa and Latin America [29–31]. Hence, there are very powerful incentives to industrialize. If you do it successfully you can grow significantly, and if you do not do it, you can stagnate or even decline. This does not bode well for efforts to reduce materials production and consumption.

The second part of the story about humanity's increased use of materials occurs in those countries who successfully industrialize and become wealthy. Of course, industrialization may follow many paths, but for those countries that have been successful, a clear pattern can be observed. As industrialization succeeds, the demand for capable workers will increase, eventually leading to higher wages and potentially significantly increased benefits and power in the society for these workers. Many societies have transitioned to more democratic institutions with this change [32]. At the same time, this increased wealth leads to increased consumption as well as an increased demand for services. As a fraction of society's activities (both GDP and employment), services grow and manufacturing actually declines. For example, since the 1970s manufacturing employment in Germany, Sweden, Japan, US, and the Netherlands as a per cent of total employment has gone from a range of 25–35% to about 10 to 20% [33]. As these industrialized nations increase their wealth, they become consumer economies. In this process consumer spending comes to dominate the economy. Firms compete to attract this spending by providing appealing products, easy credit, lowering transaction costs and pervasive advertising. Consumers generally fall in line with this regime, even working longer hours to buy more products [7,12]. An ensuing dynamic develops that always leads to more consumption and economic growth. This is the Consumer Society. Some have speculated that this increased consumption does not necessarily have to be accompanied by increased material use. Various examples of significant 'dematerialization' of certain products or activities have been cited as evidence. We will come back to this later in the article, but at this point it is fair to say that analysis at larger boundaries, rarely, if ever, shows an absolute dematerialization effect. In general, the current data strongly suggest that materials use in developed countries continues to grow [34,35].

3. Materials accounts

In this section, we will examine different methods to account for materials used by a country. And toward the end of this section, we will show the relationship between materials use and two different measures of human well-being. For economic well-being, we will use GDP based on purchasing power parity (GDPppp), and for the social well-being we will use a composite measure called human development index (HDI). Toward the end of the paper, we will discuss other measures of human well-being.

HDI is an aggregate measure intended to give a numerical value to the quality of life in a country. HDI has three components: life expectancy at birth, GNP *per capita* and adult literacy or educational level. The index ranges from 0 to 1 with highly developed regions such as the US, Western EU and Australia greater than 0.90; Russia and South America stand at about 0.8; and Africa and India are currently below 0.7, the very poorest are much lower.

There are two basic ways to assign responsibility for the materials used by countries. In the first, a country takes responsibility for all of the materials it produces; in the second, a country takes responsibility for all of the materials it consumes. If there is no trade with the outside world, then the two measures give the same result. However today, as the effects of increased globalization have played out, the two measures can give very different results. The production measure, which unfortunately has acquired the name domestic material consumption (DMC), and sometimes 'apparent consumption' is calculated as follows:

$$\text{DMC} = \text{domestically produced materials} + \text{imported materials} - \text{exported materials}. \qquad (3.1)$$

The DMC, measured in mass units, can be applied to any individual material, group of materials or a total of all materials. When not specified, DMC used in this paper will apply to aggregate materials use.

The DMC is the older of the two measures and somewhat easier to calculate, and as a consequence has been widely used. However, the DMC fails to take account of trade between nations. The second measure accounts for the materials used to make the products that a country consumes (connecting to where they were made) and is called the material footprint (MF). This is a complex metric to calculate because one must take into account not only how much steel is produced in the world, to use one material as an example, but also where it goes; to which products, and ultimately to which countries. This calculation usually involves using economic Input–Output tables (I/O tables) that connect materials with products through financial transactions between a multisector economic model of the economy. For the US, the input–output table is a matrix of approximately 500×500 sectors and is updated only once every 5 years. In order to include trade, the I/O tables for different nations (which may differ significantly from the sectors used in the US tables) must interact, resulting in what is called a multiregional input–output model (MRIO model).

The MF, like DMC, is measured in mass units but—as it attributes responsibility for material production to the consumer—appears to be a better metric with which to examine correlations between human well-being and the use of materials (opposed to the economic benefits of production). Despite these advantages, it must be acknowledged that the complexity of calculating the MF is likely to introduce some uncertainty: material tonnages do not necessarily relate directly to money flows and a degree of double counting due to trade is possible.[2]

In this paper, mankind's 72 Gt annual use of materials is split into the four categories used by the OECD's accounting system [13]: the smallest is metals at about 6.7% by weight, the next largest is fossil energy carriers at about 19%, then biomass at about 29%, and the largest is construction and industrial minerals with a total of 46%. Metals provide important construction materials and the inputs for many of the durable goods that society wants as it transitions from developing to developed, while at the same time using significant amounts of fossil fuels in their processing. The fossil energy carriers provide most of our energy resources and dominate climate change and air pollution impacts. Biomass provides for our food, some energy needs and construction materials, and can play a significant role in climate change through land-use change and methane emissions. Construction and industrial minerals are dominated by stone and aggregate, which are non-reactive and relatively benign in the atmosphere. However, industrial minerals also include cement, the production of which alone accounts for around 5% of total anthropogenic CO_2 emissions for the planet [37].

In the following sections, the DMC and MF metrics of different countries are compared in order to examine to what extent human well-being depends upon the use of materials. If mankind's well-being becomes less dependent on materials as societies develop, this may appear as a decoupling between these variables. In an extreme case, our material usage may saturate, that is we stop increasing our material use of some category of material, or our well-being may 'saturate' in the sense that additional materials usage does not improve our well-being. We have found instances of both of these, which we present below.

4. Observed materials saturation with domestic material consumption accounting

A recent paper on the global use of lighting suggests a useful identity equation for detecting saturation. The equation developed by Tsao *et al*. [38] decomposes the demand Q for a good or a service into four variables: (i) population, P, (ii) affluence, A, often measured as GDP *per capita*, (iii) market choice, M, measured as the *per capita* money spent on Q divided by A, and (iv) price, p, meaning money spent on Q, divided by Q. The equation is given below in two forms: absolute value and *per capita*.

$$Q = P \cdot A \cdot M \cdot \frac{1}{p}, \tag{4.1}$$

or

$$q = \frac{Q}{P} = M\frac{A}{p}. \tag{4.2}$$

These equations suggest a simple decomposition that could be performed that could be used to detect saturation. That is, in general, one would expect M to vary with time. Should it diminish or tend toward zero even in the face of increasing income and declining prices this would indicate a type of saturation.[3] We have used equation (4.2) to study the use of steel, aluminium, copper and zinc in the US, China and India using the DMC metric over the time span 1950–2005 as shown in figure 2 below. Note that in general, a larger value of A/p would suggest market conditions that favour more demand. Furthermore, as a general rule, A/p increases with time, as A usually increases and p often declines, so a crude interpretation of the plot would be that it indicates how *per capita* demand might change with time. (This interpretation is subject to occasional deviations

[2]The estimation of physical flows from economic transactions presents some challenges. As an example, there is the particular issue of different sectors paying different prices for the same commodity. See for example [36].

[3]Note that saturation was not found in the lighting paper. Rather, lighting demand appears to remain steady with a constant value for M [38].

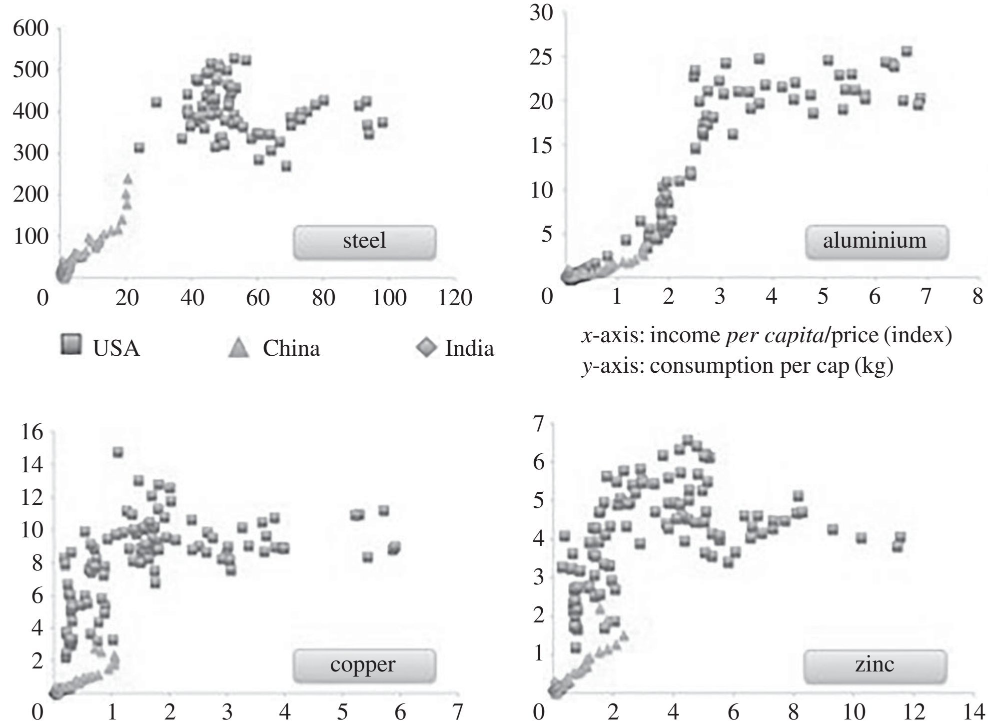

Figure 2. *Per capita* DMC demand (*Q*/*P*) versus affluence over price (*A*/*p*) for four metals from 1950 to 2005 for the US, China and India [39]. (Online version in colour.)

as we will indicate shortly.) The parameter M indicates how the sector being studied spends their available income. A declining M indicates less income relative to the total available is being spent on the product that is being considered. Saturation *per capita* is indicated when q is constant or declining, even in the face of increasing A/p, hence when M is constant or declining.

Figure 2 shows *per capita* materials use (kg yr^{-1}) plotted versus A/p (indexed to 1950) with the three countries overlaid. Each plot shows the same general trend; a significant rise in q followed by saturation for the United States, with China and India still growing. The fluctuations in the US data during saturation are due largely to the time delay between price and quantity fluctuations. This is explained further for steel in figure 3 that shows the time-series decomposition of equation (4.2) for steel in the US and China. Note we have also seen the same trends (saturation in the US) for cement [39].

Looking at the United States in figure 3, saturation is indicated by the fall in q while a/p has increased significantly. The scatter in figure 2 for steel can be seen as related to the sharp change in a/p due mostly to price fluctuations in the 2000s shown in figure 3. All values in figure 3 are indexed to 1950. A look at the time-series decomposition for China shows the rapid rise in M in the time period 1950 to 1960 in spite of a relatively flat A/p. What causes such a rise? We speculate that this is due to 'Big Push' industrialization led by government intervention in China. Note also the significant difference in the x-axis scales for the two plots in figure 3 indicating the fairly stable steel demand in the US while demand has soared in China.

We are not the first to suggest that DMC material usage may have decoupled from GDP in some developed regions of the world. But our analysis suggests not only a decoupling, but also a saturation for the four metals analysed. The recent report in [13] shows that while both global GDP and global aggregate material usage have risen significantly from 1980 to 2010, material usage does not rise as quickly, about 2.3% yr^{-1} versus 3.4% yr^{-1}, also suggesting a partial decoupling. Steinberger *et al.* [40], who has studied the DMC for 175 countries for the year 2000, found an income elasticity for the aggregate DMC of 0.52, but with striking differences between

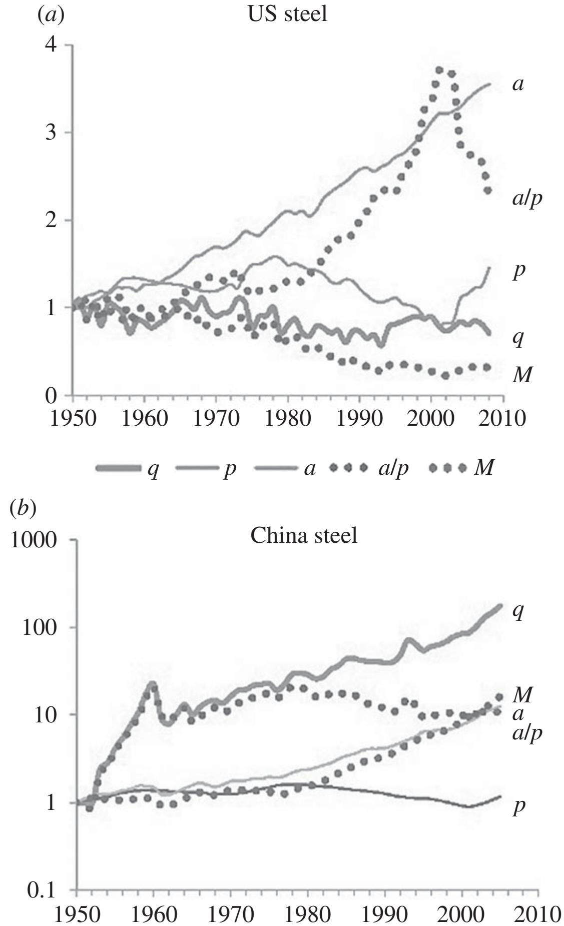

Figure 3. Time series decomposition of equation (4.2) for steel in the (*a*) US and (*b*) China from 1950 to 2010 [39]. (Online version in colour.)

material groups, with income elasticities of 0.2 for biomass, 0.68 for construction minerals, and 1.07 and 1.19 for ores/industrial minerals and fossil fuels, respectively. Müller *et al*. [41] has also presented estimates for the in-use steel stocks of nations and found temporal trends that suggest saturation in the US, UK and France, but not in Japan and Australia.

5. Consumption based accounting

Using a MRIO model including 168 countries, Wiedmann *et al*. [35] calculated the DMC and the MF for each country for the year 2008 as well as providing some historical results from 1990 to 2008. The results are compelling. The historical data show a general rise in MF for the developed nations (US, Japan, UK and EU-27), while the DMC for these regions was generally steady or decreasing. These trends are clearly seen in table 1. At the same time, a set of developing countries, and developed countries with major mining sectors (China, India, Brazil, Chile and Australia) showed the MF and DMC both generally increasing with time. Additional details using cross country multivariate regression analysis revealed that the MF/cap elasticity with respect to GDP *per capita* was 0.6, while the DMC *per capita* elasticity with respect to GDP *per capita* was only 0.15. And when sub-sectors of material use are broken out, the MF elasticities for fossil fuels and metals were both greater than 0.9. Wiedmann's results suggest that well developed countries modify their domestic production, but continue to consume more materials, only now more from

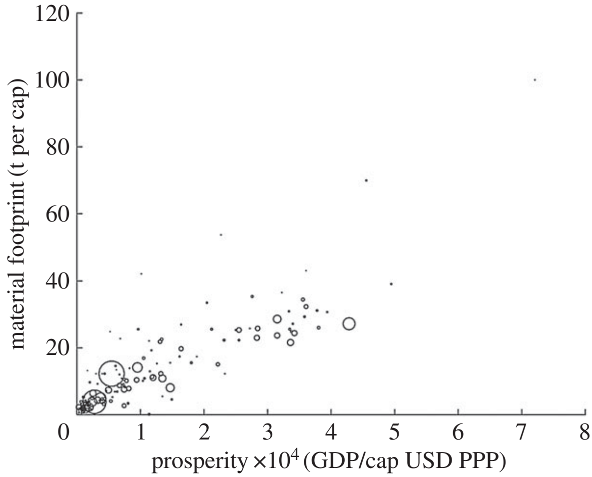

Figure 4. MF/cap versus GDP/cap (USD) for 2008, the area of each data-point is proportional to the population of the corresponding country.

Table 1. MF and DMC for developed countries 1990 and 2008 ([35]).

material use (t per cap)	MF 1990	MF 2008	DMC 1990	DCM 2008
US	20	27	20	19
Japan	23	28.5	14.5	10.5
UK	16	23.5	10.5	8
EU-27	17.4	24	13.5	13.5
OECD	18	24	16	16

the embodied materials in imported products. These high level, aggregate material measures do not support claims of dematerialization; in fact, when imported material consumption is included in the material footprint, the data indicate that materials use tends to go up.

In figure 4, we show the relationship between MF/cap and GDP/cap for 168 countries in 2008. The size of the data points is weighted by the population size of each country. The plot shows an apparent saturation in material usage, but at a relatively high value, in the vicinity of 25 tons *per capita*, or about two and a half times the current world average. This information, coupled with other studies on the limits of materials production improvements [16,25,42], suggests the significant environmental consequences that a business as usual economic development strategy could yield as more countries increased their *per capita* MF. And of course, the time-series data shown in table 1 suggests that the MF for the developed countries could continue to rise.

In figure 5, HDI is plotted against MF. And two of the components of HDI, life expectancy and education level are shown in the inserts. The third component of HDI, income, can be inferred from figure 4.

Figure 5 has several prominent features and provides a framework to discuss the current economic development narrative. The first noticeable feature is that the graph is nonlinear in the two variables suggesting a certain decoupling between MF and HDI at higher levels of MF > 10 t per cap. That is, in the early stages of development small changes in MF can correspond to large increases in well-being as measured by the HDI. At the same time, additional increases in materials consumption up to about 30 t per cap go along with an additional rise in HDI from ~~about 0.7 above 0.9~~. Above this point, there are a few outlier nations (hard to see in figure 5, but visible in electronic supplementary material, figure S1) with MF up to 100 t per cap but with

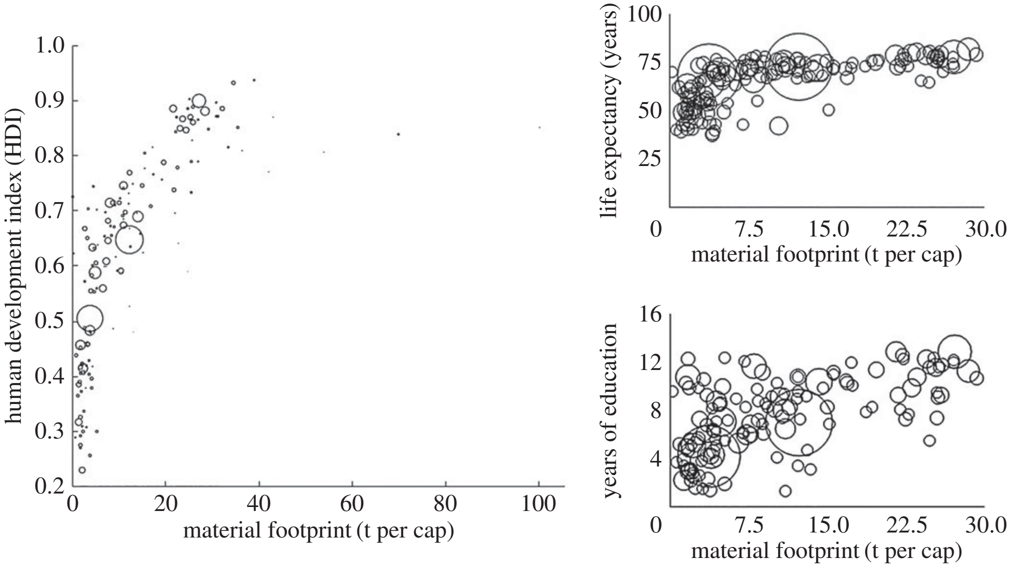

Figure 5. HDI versus MF for 2008, including two components of HDI; life expectancy and years of education. HDI and MF data from [35].

slightly lower HDI. Looking more closely at the two inserts in figure 5, we see a very rapid rise in life expectancy even for MF values well below the world average of 10 t per cap. At the same time, educational levels have much more scatter with an apparent slow rise. Both of these components are much more likely to be related to other explanatory variables, for example sanitation, clean water and healthcare services for life expectancy; and income and cultural norms for educational level. The idea that educational improvement actually lags development rather than the other way around has been suggested by others [30,43]. More data on the relationships between MF and life expectancy, years of education and the GINI coefficient can be found in the electronic supplementary material.

As far as we know, the only way large nations can move up along the path suggested in figure 5 is by industrialization. If successful, these countries will eventually export manufactured goods to others including those more developed countries in the second stage. The wealthier countries in the second stage will, in turn, be transitioning from manufacturing to service based economies, and will be increasingly buying goods from other nations including those in stage one. Hence these two stages are highly coupled. Consumption in the developed world goes to provide manufacturing jobs and opportunities in the industrializing, developing countries. In fact, exporting is an important part of industrialization. A recent analysis called exports the single most important driver of economic booms [30].

6. The role of material efficiency

We have seen that up to the present day human well-being and materials use have been inextricably linked. On average, the annual material footprint of each human being is currently 10 metric tons, but no country with an HDI equal to or greater than 0.9 (such as the United States) has a material footprint less than 20 t per cap. Is it possible to lift the bulk of humanity to a state of wellbeing equivalent to that enjoyed in the developed world without requiring a doubling of our material production? A potential solution is to pursue materially efficient strategies (providing material services using less raw material) by, for example, making lightweight products, using products for longer and reusing components at product end-of-life. The technical (physical) opportunities and barriers to employing such strategies for metals have been explored through research centred at the University of Cambridge [44–48]. There are, however, likely to be other constraints to implementation at scale. Here we touch briefly on four areas for consideration: (a) human behaviour, (b) economic incentives, (c) rebound effects, and (d) policy interventions.

(a) Human behaviour

The human attachment to material goods goes far beyond utilitarian purposes. Material goods can be symbolic and represent a range of intentions and attributes. Any programme of reduced materials usage will need to consider these emotional and symbolic attachments and perhaps offer less material intense substitutes. In this issue, Fletcher offers an alternative fashion clothing 'usership' model as an example of how this could be done in the fashion industry [49]. From the producers point of view, however, the possibility to use these emotional ties to financial gain must be irresistible as anyone who has seen an advertisement knows. As a result, we see the constant invention of still more things we must have. Harari's [50] puts this very succinctly: 'One of history's few iron laws is that luxuries tend to become necessities and to spawn new obligations'. Some have suggested that to get out of this trap we may need societal therapy [51].

(b) Economic incentives

In many cases, an increase in the labour used to provide a service could decrease the quantity of new material used. For example, more people could be employed in order to deconstruct—rather than demolish—buildings, and to repair domestic appliances, rather than see them recycled or land-filled. However, for decades the price of materials has declined relative to labour [52], providing an economic incentive to actually do the reverse: use more materials and be less materially efficient. This strategy plays out repeatedly in automation, where materials and energy, power and make the automation equipment that substitutes for labour.

(c) Rebound effects

The apparent decoupling observable in figure 2 may give some hope that mankind does not possess an insatiable thirst for material services. However, there is evidence that using less material to make a component or product (being more materially efficient) might not result in an equivalent absolute reduction in material production. For example, lighter car structures have often not led to lighter cars but have permitted more electronics and comfort equipment to be included in the vehicle without decreasing fuel efficiency. Mackenzie *et al*. [53] show this manifestation of a materials rebound effect in cars. Across an economy, Cooper & Gutowski [54] present several instances of rebound associated with the reuse of products: early replacement of products that have become 'liquid assets' spurring new production. It appears that increased material efficiency may not translate to an equivalent decrease in material mobilization without regulatory pressures constraining the absolute quantity of material production.

Perhaps, an even more sobering example of materials growth has been in the semi-conductor industry, which for decades has followed a phenomenal improvement trajectory called Moore's Law. Observations show that the number of transistors per device has doubled every 18 to 24 months for the last 40 years. Yet in spite of this breath-taking material efficiency, the amount of silicon produced (area *per capita*) has grown by 5% a year from 1970 to 2010 [25]. For still more examples of products with so-called 'dematerialization' potential that has not materialized see [34]. The pattern of efficiency improvements being offset by growth has been found for a variety of products and materials [55,56].

(d) Policy interventions

If government decides to intervene then regulators could pursue prescriptive (command and control) based strategies or incentive based strategies such as Pigouvan taxes[4] or marketable

[4] A tax intended to correct for negative externalities, set equal to the social cost.

permits/cap and trade. Christiansen & Smith [57] present a detailed review of the advantages and disadvantages of these two approaches. Economists have traditionally been in favour of incentive-based policies that 'tax the root problem' (in this case greenhouse gas emissions) as such an approach does not require the regulator to have detailed knowledge of the business structures and physical processes of the industry and also leaves maximum room for free market innovations and efficient solutions. Similarly, in an article specifically discussing material efficiency, Söderholm & Tilton [58] argue that policy interventions should target environmental damages as closely as possible. Politically, in comparison with command and control based strategies (e.g. setting a limit to consumer material purchases), such strategies may be more palatable to the public. However, Pigouvan taxes and the like may not be workable in practice. First, it may be very difficult to monitor actual emissions from material production. Second, setting an effective, but not overly detrimental, carbon tax may also be problematic; Skelton & Allwood [59] find that the incentives for material efficiency in the steel industry due to a carbon tax alone are likely to be offset due to the disincentives caused by labour taxes. Reorienting regulations towards 'taxing the material' may reduce, though not eliminate, these difficulties. Finally, there are moral arguments against using an incentive-based market approach: Harvard philosopher Michael Sandel has argued that 'turning pollution into a commodity to be bought and sold removes the moral stigma that is properly associated with it ... [and] may undermine the sense of shared responsibility that increased global cooperation requires' [60]. We may wish to recognize the moral distinction between a fee for polluting and a fine. Benthamites, on the other hand, may not be troubled with Sandel's concerns.

Effective government intervention may be devised; however, the majority of governmental regulations cease at the border of the nation state. Section 5 of this paper highlighted the importance of considering global trade when calculating the material footprint of nations. It seems likely that the deployment of material efficiency at scale will perturb established international trade, over 60% of which (by dollar value) is in materials and manufactured goods. There are several reasons why there will likely be resistance to a potential decrease in global trade. Firstly, as highlighted in §5, wealthy countries are increasingly buying goods from other nations including those in the development stage. Hence, consumption in the developed world goes to provide jobs and opportunities in the developing countries. Any strategy, such as material efficiency, that might suggest reductions in consumption needs to provide an alternative source of income for those who will lose their jobs (perhaps disproportionately in the developing countries) as a consequence. Secondly, world trade liberalization has, as seen by some, been a source of peace with the ability, according to the philosopher Montesquieu, to 'cure [mankind's] destructive prejudices' [61]. It is perhaps pertinent that a key pillar of post-war European peace was the construction of a single market in coal and steel.

Engineers have shown that material efficiency is a potential solution to the dilemma of wishing to elevate prosperity while living sustainably (e.g. [16]). As material efficiency moves up the academic, business and policy agenda it is important that we address potential barriers (most outside of the engineering discipline) early enough to both ensure its correct adoption and that it is not easily dismissed. We hope this sub-section helps to stimulate discussion, and ultimately strategies to overcome the above potential barriers.

7. Discussion and conclusion

In this preliminary study, we argue, using the available historic data, that economic development and materials use are intimately intertwined. We also point out the many psychological and sociological interconnections between people and materials. At the same time, previous work has made clear the huge role materials play in our global carbon emissions [16]. Several important themes emerge from this study. Clearly, less material intense forms of economic development are needed. On the one hand, alternatives to material intense industrialization for the developing nations are needed. And on the other hand, alternatives to material intense consumer economies are needed. Both of these challenges are complex and demand a much more trans-disciplinary discussion. There are a number of options that could be explored to address these issues from new technologies to new organizations; for example, new ways to deliver services, perhaps employing virtual, autonomous or digital technologies [62], or new forms of industrial development leveraging knowledge and policy control [63], or alternative community development strategies especially for cities that allow for growth and consensus on values [64]. But based upon a historical perspective, there seems to be little reason to believe that any of these new approaches could be effective without new incentives to reduce materials use and carbon. Below, we add a few more concerns and comments.

(a) New automation

A recent report on employment claims that nearly 50% of all jobs in the US, many of them manufacturing jobs, are at risk of being displaced by automation [65,66]. That is, new developments in robotics, artificial intelligence, cloud computing and digital manufacturing are already changing manufacturing significantly and could seriously disrupt both the developed and developing world. Given that a key ingredient of successful industrialization has been that it offers economic opportunities for many, it appears that these new developments in automation could seriously disrupt this dynamics. On the one hand, even if the emerging economies could master (and finance) these new technologies and industrialize, the benefits may not be as wide spread as in the past. Or, the developed nations, using these new technologies, could recapture the lead in manufacturing, thereby seriously affecting the ability of developing nations to advance. Note that, this is similar to the pattern of development during the Industrial Revolution, when high wage countries (the UK in particular) by employing new technologies, successfully competed with the industries in low-wage countries (China and India). These possibilities, only serve to emphasize the importance of developing alternative paths to development for poor countries. The basic question is, where will the new jobs come from, and will they be available to many in the developing economies? The social implications of stagnating economic growth are significant [67].

(b) More work on the relationship between materials and human well-being

In spite of the clear historical trends relating materials use with economic development, it is necessary that we consider alternative metrics and relationships between human well-being and materials. Both the measure of GDP and the activity of material consumption can be challenged as contributors to human well-being. Further studies using alternative measures of human well-being such as Happiness [68,69], or the Capability Approach [70,71], or Satisfaction with Life Scale [72] and their possible connection to human materials use could provide new insights into how this new relationship might be developed.

(c) Moving forward

The use of materials is a key aspect of economic growth and the industrialization of nations. We have found evidence that the use of materials may saturate at around double today's level. However, in the face of climate change the main question is, to what extent would a programme of enhanced material efficiency alter this dynamic? And would the change be for the better or not overall? A starting point could be to identify what types of material efficiency in which industries are easiest to implement, have the least deleterious effects/most positive effects on employment, trade and general well-being while still resulting in significant cuts to greenhouse gas emissions. Does such a sweet spot exist whereby initial efforts could focus?

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