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Christopher L. Magee
Professor of the Practice
Engineering Systems Division and
Mechanical engineering
Massachusetts Institute of Technology
Co-Director
SUTD/MIT International Design Center
Cambridge, MA USA
Email: cmagee@mit.edu

Tessaleno C. Devezas
Associate Professor
Faculty of Engineering
University of Beira Interior
Portugal
Email: tessalen@ubi.pt

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An Extension of Dematerialization Theory: Incorporation of Technical Performance Increases and the Rebound Effect

Christopher L. Magee[1] and Tessaleno C. Devezas[2]

Abstract:

Dematerialization is the reduction in the quantity of materials needed to produce something useful over time. Dematerialization fundamentally derives from ongoing increases in technical performance but it can be counteracted by demand rebound - increases in usage because of increased value (or decreased cost) that also results from increasing technical performance. A major question then is to what extent technological performance improvement can offset and is offsetting continuously increasing economic consumption. This paper contributes to answering this question by offering some simple quantitative extensions to the theory of dematerialization. An inequality criterion for dematerialization is developed that includes technical performance changes over time and demand rebound effects: the inequality highlights the importance of demand elasticity and the annual technical performance improvement rate. The paper then empirically examines the materials consumption trends as well as cost trends for a large set of materials and a few modern artifacts over the past decades. In all 57 cases examined, the particular combinations of demand elasticity and technical capability rate improvement for each case are consistent with continuation of materialization. Overall, the theory extension and empirical examination indicate that dematerialization and sustainability are significant challenges not easily met by undirected technological change.

Keywords: dematerialization theory; technical performance progress; rebound effect; demand elasticity.

1. Introduction:

Attempting to answer the basic underlying question and concern of sustainability – whether humans are taking more from the earth than the earth can safely yield- is the main objective underlying the concept of dematerialization. Malenbaum (1978) was one of the first researchers in this area and his key results are still among the most important. He utilized the concept of intensity of use defined as the ratio of the amount of materials (or energy) measured in bulk mass divided by GDP. When plotting intensity of use over time, he found "bell curves" peaking at different times in different countries (and for different materials) but at roughly a given GDP per capita for given materials. Also importantly, the peak intensity for a given material reached by subsequently developing countries decreases over time (relative to

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[1] Engineering Systems Division, Massachusetts Institute of Technology and SUTD/MIT International Design Center, USA

[2] Faculty of Engineering, University of Beira Interior, Portugal

earlier developing countries). These two regularities are the essence of the conceptual basis for the "theory of dematerialization" according to Bernardini and Galli (1993). These authors go further and note that the decreasing maximum intensity over time with usage per GDP decreasing in all economies beyond a given GDP per capita indicates that: "*Taken together the two postulates* (empirical regularities noted by Malenbaum) *imply a declining trend in the rates of growth in materials and energy consumption at the world level and, depending on the rate of economic growth of the developing countries and in the world as a whole in the coming decades, they may even imply a decline in absolute terms in materials consumption over the next 50 years*."

However, later in the paper they conclude that the results at that time (1993) were insufficient to make such a conclusion and recommended further examination of data.

Since Malenbaum's research, there has been extensive work focused on dematerialization, generally defined as the quantity of stuff and of energy needed to produce something useful and applying the measure of intensity of use (consumption/production of energy and/or goods per GDP). Some of this research, Ausubel and Sladovick (1990) and Ausubel and Waggoner (2008), is encouraging emphasizing continuing decreases in consumption as a fraction of GDP. However, other researchers [Ayres (1995), Allwood et al (2011), Gutowski et al (2013)] are not as encouraging about continuation of economic growth with global dematerialization. These authors call for much more attention to reducing the amount of material needed to fulfill a given function (referred to as "materials efficiency"). Although empirical efforts will still be the major way to explore many of the issues involved with this large question, those efforts might be aided by some simple theoretical exploration. In this paper, we extend the theory of dematerialization by explicit consideration of the ongoing improvement in technical capability on dematerialization.

Overall, there are three aspects to consider when approaching an understanding of dematerialization:

1 – environmental impact as measured by the sustainability in the usage of natural resources and the reduction of industrial waste generation, as well as the process of decarbonization;

2 – economic aspects including the declining rate of the intensity of use and increasing efficiency in energy/materials usage, looking for a possible decoupling of economic growth from its materials base.

3 –increasing technological capability as the strongest agent enabling the production of 'more with less' and moving the socioeconomic realm towards a sustainable future.

Regarding the third item, a fundamental question that must be addressed extends the one initially asked by Bernardini and Galli: does improving technical performance offer substantial potential for continuing global economic growth accompanied by an *absolute* decrease in usage of materials from the earth? This question in fact links economic growth, technical capability and the environmental impact.

In this work, we frame the variables involved looking for critical questions that can be approached empirically. Before doing so, we consider a possible constraint and a possible enabler. The constraint is Jevon's paradox stating that "improving technical efficiency results in enhanced demand and thus does not reduce the amount consumed": we might add thus not reducing the environmental impact. A potential enabler of achieving a positive answer to the question is Engel's Law- followed for a long time- stating that "commodities" decrease in importance (as % of GDP) as wealth increases. Two other introductory points are worth noting. First, the Bell shaped curves seen by Malenbaum are fully consistent with Engel's Law being followed on the *right hand or descending side* of the bell curve. Secondly, the decrease in usage of a resource over time at the peak is consistent with increases in technical performance over time.

2. Dematerialization theory extension

In this paper we extend the theory of dematerialization by explicit consideration of three important factors that can enhance and/or mitigate the dematerialization process: i – the ongoing improvement in technical performance; ii – the rebound effect (Jevon's paradox), and iii - Engel's law, which states that the consumption of artifacts as a proportion of GDP decreases when the artifact becomes a "commodity" (and income demand elasticity becomes less than 1). In order to analyze dematerialization quantitatively the following measures must be considered:
1 – the rate of change of per capita materials consumption – dm_c/dt
2 – the rate of population growth – dp/dt
3 – the rate of GDP growth per capita – dg_c/dt
4 – the yearly *relative* increase of technological capability, defined as k and as k_i for a specific technology, i.
5 – the demand income elasticity ε_{di} for goods and services, defined as relative increase in consumption of i divided by the relative increase in national income
6 – the demand price elasticity, ε_{dp} is the relative increase in consumption divided by the relative decrease in price of the good or service
7 – the rate of change of cost of a good or service with time ,dc_i/dt ,and rate of change of the performance of the good or service with time, dq_i/dt

The key to analysis of dematerialization is the measure dm_i/dt which is the time rate of change of usage (in mass or volume) of a specific material class *i*. The condition for absolute dematerialization in regard to *i* is that the usage of the material (m_i) must decrease with time. Since materials use is simply population (p) x m_{ci}, one obtains decreasing m_i over time if the relative rate of population growth is exceeded by the relative (decreasing) rate of per capita usage of a given material, or

$$\frac{1}{p} \times \frac{dp}{dt} + \frac{1}{m_{ci}} \times \frac{dm_{ci}}{dt} < 0 \tag{1}$$

Defining dM_{ci} as dm_{ci}/m_{ci}) and, dP, dG_c similarly as relative changes in population and GDP per capita , the criterion for dematerialization is then:

$$\left|\frac{dM_{ci}}{dt}\right| > \left|\frac{dP}{dt}\right|$$

Considering that the world population is still increasing, even if at a lower increasing rate, the *strong dematerialization criterion* means that the absolute value of change in per capita use must exceed the absolute value of population growth.

Since population growth can be estimated adequately, it is appropriate to focus next upon modeling $\left|\frac{dM_{ci}}{dt}\right|$. The next steps in our extension are to incorporate technical performance improvement and demand elasticity into this time derivative of relative per capita materials usage. We refer to our extension as "simple" because we treat technical progress fairly simply and also eventually equate income and price elasticity. The assumptions are thus relatively crude but - in our view- nonetheless useful. Our treatment of technical performance change is to first treat all such changes as occurring in metrics that either increase the performance or decrease the price of a technical artifact in an exponential fashion. This generalization of Moore's Law is

$$\frac{Q_i}{C_i} = \exp(k_i . t) \tag{2}$$

where Q_i is the relative performance associated with use of i, C_i is relative cost, and k_i the relative annual increase in technical performance affecting use of material i.

Thus, the relative performance (relative cost) of a given good or service *i* increases (decreases) exponentially with time. There is extensive empirical evidence for such generalizations of Moore's Law being widely followed [Moore (2006), Martino (1971), Nordhaus (1997), Koh and Magee (2006), Koh and Magee, (2008) Koomey et al (2011), Nagy et al (2013)]. However, assuming k_i identical for performance and cost is only empirically supported in some cases. Nonetheless, for simplicity of exposition, they are considered equal in this extension of dematerialization theory as the assumption is quantitatively immaterial to the conclusions.

Allwood et al (2011) and Gutowski et al (2013) introduce the important concept of "materials efficiency" which measures the amount of material to *achieve a given level of function* (they use the term service) in a downstream artifact or service. They differentiate "materials efficiency" from resource efficiency which includes the energy and other costs needed to *produce* the material (extraction, refining, etc.). We model the time dependence of both of these efficiencies using Equation (2)–resource efficiency is reflected by the cost of the artifact -and efficiency of use by performance changes over time.

Performance (Q) is assessed by metrics that describe the effectiveness of a technology for a user/purchaser. The metrics of interest here have the form output/constraint and the constraint is usually directly related to the amount of material used. For examples that follow equation 2, one can see from the metrics following the equal sign that the *materials* used: 1) to store a given amount of information [metric = mbits/cm^3 –see Koh and Magee, (2006)], 2) to perform a given amount of computation (MIPS/cm^3) –see Koh and Magee (2006) or 3) to store a given amount of energy (watt-hours/kg)- see Koh and Magee (2008), all decrease as the metric improves (or as technical performance increases). In fact, with such metrics, equation 2 shows the usage of materials to fulfill a given function decreasing as the technology improves exponentially by a constant ratio k_i per year.

In other words, technical capability change results in a given function being delivered with less material as

$$dM_{ci}/dt = -k_i \tag{3}$$

Equation 3 gives an estimate of the “materials efficiency” change with time without considering rebound. However, in the same time period, the rebound effect (purchasers opt for more function and not just lower cost) offsets material usage decrease by k_i x ε_{dc} which represents material that must be added back as technology improves. In addition, the amount of material used increases due to economic growth (through increased consumption of function) which is ε_{di} x dG_c/dt. Thus, overall we have:

$$\frac{dM_{ci}}{dt} = -k_i + \varepsilon_{dc}k_i + \varepsilon_{di}\frac{dG_c}{dt} \tag{4}$$

Equation 4 gives the change in materials consumption taking into account the combined effect of the yearly increase of technological capability (k_i), the rebound effect (ε_{dc} x k_i), and the effect of economic growth $\varepsilon_{di} \times \frac{dG_c}{dt}$. In fact, given constant output ($dG/dt = 0$) the annual % change in materials usage simply equals minus the relative change in annual technical capability (k_i) plus the rebound effect.

A second area of technical capability change that influences materials usage is improvements in extraction and processing of raw materials. Although resource depletion and demand growth masks this effect by countering some or all of it, one can ignore these effects and use Equation 2 (assuming function, Q, as constant) as

$$C_i = \exp(-k_i)$$

This cost/price reduction with time also results in increased demand; it results in a second rebound effect of magnitude ε_{dc} x k_i. (the decreased cost of the material makes the artifact more attractive so more is purchased). Thus, Equation (4) becomes

$$\frac{dM_{ci}}{dt} = -k_i + 2\varepsilon_{dc}k_i + \varepsilon_{di}\frac{dG_c}{dt} \tag{5}$$

Since cost reductions are counteracted by depletion, Equation 5 probably overstates the rebound effect while Equation 4 probably understates it. In the following section, we will just consider equation 4 but in later discussion, we will remind the reader that our dematerialization criterion is not a conservative one.

Making our second simplifying assumption that the demand elasticity for price and income are equal and substituting equation (4) into inequality (1) we get for absolute dematerialization that:

$$\frac{dP}{dt} - k_i + \varepsilon_{di} \text{ x } k_i + \varepsilon_{di}\times\frac{dG_c}{dt} < 0$$

or

$$\frac{dP}{dt} - k_i + \varepsilon_{di}\left(k_i + \frac{dG_c}{dt}\right) < 0 \tag{6}$$

3. Graphical representation

In inequality (6) dP/dt and dG_c/dt are variables that can be obtained from available time series data on the growth of population and from the growth of GDP. k_i is a complex measure that is different for different families of technologies and will be given for cases later in this paper but has been found to be in the range of 3-65% per year (Magee et al, 2014). Finally, ε_{di} is also complex but can be estimated and will also be considered in the cases covered later in this paper. Before undertaking empirical examination, it is useful to show graphically how the fundamental parameters (k_i and ε_{di}) delineate what is possible relative to dematerialization.

Figure 1 below depicts the time dependence (last 50 years) of the two "less-complex" terms of inequality (6), namely $dP/dt + \varepsilon_d$ x dG_c/dt, assuming $\varepsilon_d = 0.5$, which represents an approximate value for metals that are evidencing declining rates of demand. Figure 1 demonstrates that the sum of the non-rebound growth terms exhibits a declining linear trend that favors dematerialization emerging over time.

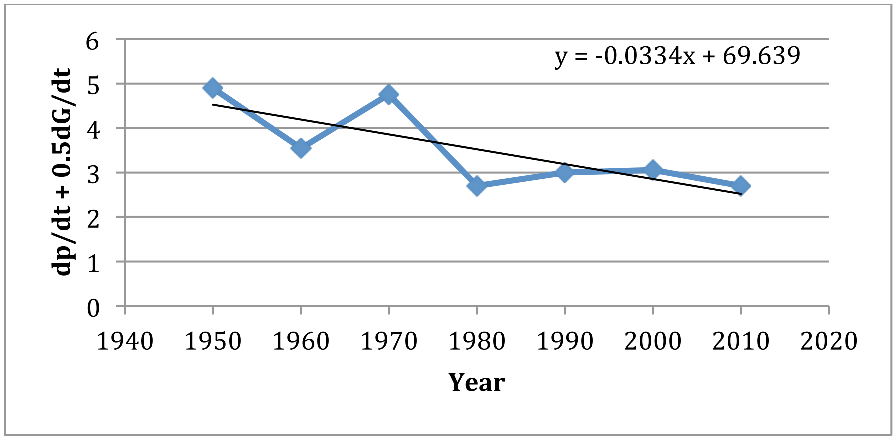

Figure 1: Trends over time in population growth + .5x GDP growth

We now turn to examining the effect of key variables on dematerialization by showing the boundary defined by Inequality 6 as a function of the variables. The next three graphs show the areas of materialization and dematerialization for some possible values of ε_{di} and k_i, and for approximate actual current values of dP/dt and dG_c/dt (0.01 and 0.03 respectively). Figure 2 shows that dematerialization occurs (under the somewhat reasonable assumption of $k_i = 0.05$ and $\varepsilon_{di} = 0.5$) in the lower left triangle bounded by a maximum GDP growth of 5% per year and a max population growth of 2.5%. This is somewhat encouraging for being able to achieve economic growth while dematerializing.

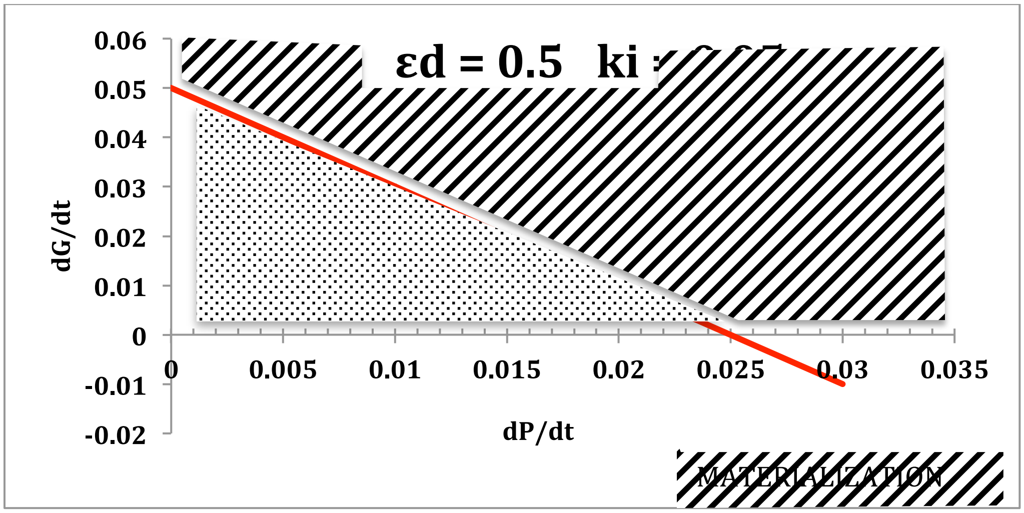

Figure 2: materialization and dematerialization for fixed demand elasticity and population growth for various values of GDP growth and population growth

Figure 3 is even more encouraging as it shows a large dematerialization region at high (but not unreasonable) k_i values when $\varepsilon_{di} = 0.5$ and population growth is 1.5% per year. In this instance, *much higher economic growth with dematerialization* is possible (10% or more) at $k_i = 0.15$ and beyond showing apparently substantial potential for higher rates of technical improvement. However, the encouragement offered by Figures 2 and 3 is strongly countered by the fact that ε_{di} is perhaps even more important than k_i. This is shown by Figure 4 where all possible values of k_i and ε_{di} are shown assuming actual values for population and economic growth. For all values of ε_{di} greater than or equal to 1, *no dematerialization* is possible for any value of k_i which demonstrates that Engel's Law must operate for dematerialization and it only holds when ε_{di} is less than 1.

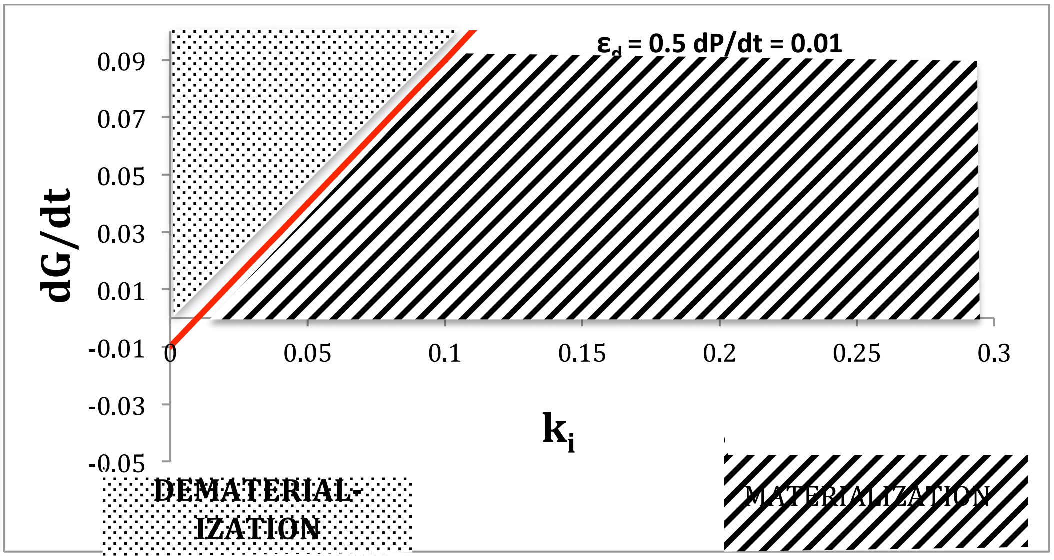

Figure 3: Materialization and dematerialization for various levels of economic growth and technical capability improvement rate at population growth of 1% per year and demand elasticity = 0.5

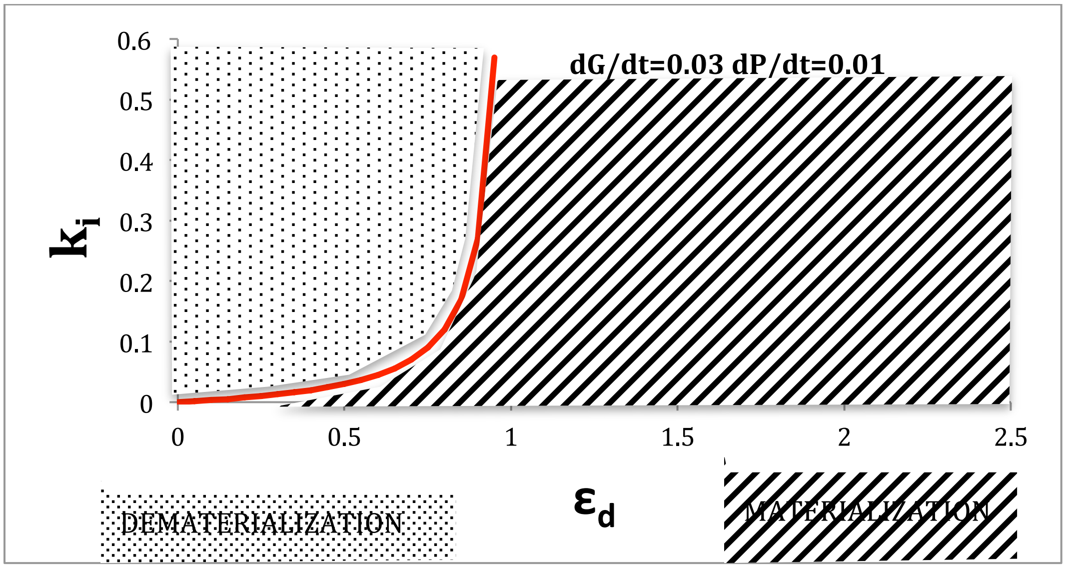

Figure 4 Materialization and dematerialization at values of k and epsilon

Our extension of dematerialization theory to include technical performance and the rebound effect shows the extreme importance of k_i and ε_d in assessing the feasibility of dematerialization with economic growth. The intuitive result of demand elasticity offsetting performance improvement has been known since Jevons and our model simply estimates the quantitative effect. Despite previous intuition, the simple graphical representation (Figures 3 and 4) nonetheless adds to understanding of how the key processes of technological improvement and the rebound effect exert large influence on the potential for sustainable dematerialization. In doing so, the model also specifies the assumptions to arrive at the results. We do not argue that answers to the key questions are thereby known. One challenge is to prescribe values for k_i and ε_d. The next section of the paper develops a new approach for estimating ε_d: this method and a key recent data-rich paper [Nagy et al (2013)] allows estimates for k_i and ε_{di} to be made for a large number of cases. The key empirical contribution of this paper is to examine the most relevant 57 of these 62 cases in light of the dematerialization criteria given in inequality 6 (which defines the dematerialization region in Figure 4). This involves mapping all of the 57 cases onto plots such as Figure 4 in order to determine if they are either in the materialization region or the dematerialization region.

4. k_i and ε_{di} estimation method

Nagy et al (2013) have examined 62 cases of changes in prices and production/demand as a function of time. For all cases, Nagy et al found exponential relationships between price and time as well as production/demand with time. The authors report the exponent in these relationships in their Supplemental Information. The key relationships are:

$$\begin{aligned} C &= c_0 \exp(-kt) \\ D &= d_0 \exp(gt) \end{aligned} \tag{8}$$

Since price/cost (C) is one functional measure for technological improvement, fits to the first equation directly yield an estimate of k_i[3]. More importantly, the exponent for the demand exponential (g) can be used to estimate ε_d for each of the 62 cases as well as will now be shown. We can write g as the total derivative of demand with respect to time and examine its decomposition into dependence on G (still GDP per capita) and C (price) since G and C are both separately dependent upon time. We have:

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[3] Called m by Nagy et al in their paper; we also note that Nagy et al report g and m in their SI based upon a log 10 basis and these are converted in our Tables 1 and 2 to natural logs consistent with Equation 8 (and their equation 9 as well).

$$g = \frac{dD}{dt} = \frac{\partial D}{\partial G} \cdot \frac{\partial G}{\partial t} + \frac{\partial D}{\partial C} \cdot \frac{\partial C}{\partial t} \tag{9}$$

The right hand side of this equation has two terms both of which are products of two partial derivatives. The first term is the income elasticity of demand, ε_{di} times the growth rate of G and the second term[4] is the price elasticity of demand ε_{dp} multiplied by k. If we again take the demand elasticities as equal (and constant over time), we have

$$g_i = \varepsilon_{di}(\frac{dG}{dt} + k) \tag{10}$$

This can be rearranged to find ε_{di} from known quantities (using g_i and k_i from Nagy et al and dG/dt from the World Bank) as

$$\varepsilon_{di} = \frac{g_i}{(k_i + \frac{dG}{dt})} \tag{11}$$

5. Results

5.1 Key variables and mapping onto formalism

The estimates of ε_{di} (and the range of years for the data and the values of k_i and g_i from Nagy et al) are given in Table 1 and 2 for the 57 cases (of the 62 in Nagy et al) most relevant to dematerialization. Table 1 is for the chemicals category in Nagy et al and Table 2 includes the hardware and energy industry cases.

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[4] Two negative signs in the second term are not shown as their product is positive.

Table 1 For Chemical technologies: Values of g_i and k_i from Nagy et al (2013), values of ε_{di} calculated from Eq. 11 and the dematerialization value from inequality 6.

Technology Chemicals	**Time period**	g	k	ε_{di}	**Inequality 6**
AcrylicFiber	1960-1972	0,176744	0,104651	1,142857	0,092093
Acrylonitrile	1959-1972	0,17907	0,076744	1,412844	0,122326
Aluminum	1956-1972	0,081395	0,009302	1,372549	0,092093
Ammonia	1960-1972	0,109302	0,090698	0,77686	0,038605
Aniline	1961-1972	0,062791	0,05814	0,580645	0,024651
Benzene	1953-1968	0,083721	0,062791	0,742268	0,04093
BisphenolA	1959-1972	0,151163	0,062791	1,340206	0,108372
Caprolactam	1962-1972	0,213953	0,116279	1,286713	0,117674
CarbonDisulfide	1963-1972	0,044186	0,02093	0,622951	0,043256
Cyclohexane	1956-1972	0,139535	0,053488	1,348315	0,106047
Ethanolamine	1955-1972	0,113953	0,062791	1,010309	0,071163
EthylAlcohol	1958-1972	0,072093	0,013953	1,127273	0,07814
Ethylene	1954-1968	0,193023	0,037209	2,213333	0,175814
Ethylene2	1960-1972	0,134884	0,065116	1,171717	0,089767
EthyleneGlycol	1960-1972	0,095349	0,067442	0,811881	0,047907
Formaldehyde	1962-1972	0,095349	0,060465	0,863158	0,054884
HydrofluoricAcid	1962-1972	0,081395	0,002326	1,555556	0,09907
LDPolyethylene	1953-1968	0,255814	0,102326	1,679389	0,173488
Magnesium	1954-1972	0,051163	0,006977	0,897959	0,064186
MaleicAnhydride	1959-1972	0,127907	0,055814	1,208791	0,092093
Methanol	1957-1972	0,088372	0,05814	0,817204	0,050233
NeopreneRubber	1960-1972	0,076744	0,02093	1,081967	0,075814
Paraxylene	1958-1968	0,232558	0,1	1,550388	0,152558
Pentaerythritol	1952-1972	0,090698	0,04186	0,987342	0,068837
Phenol	1959-1972	0,097674	0,081395	0,743363	0,036279
PhtalicAnhydride	1955-1972	0,081395	0,072093	0,666667	0,029302
PolyesterFiber	1960-1972	0,27907	0,137209	1,490683	0,16186
PolyethyleneHD	1958-1972	0,216279	0,097674	1,464567	0,138605
PolyethyleneLD	1958-1972	0,17907	0,088372	1,294118	0,110698
Polystyrene	1944-1968	0,2	0,05814	1,849462	0,16186
Polyvinilchloride	1947-1968	0,169767	0,076744	1,33945	0,113023
PrimaryAluminum	1930-1968	0,102326	0,025581	1,353846	0,096744
PrimaryMagnesium	1930-1968	0,174419	0,025581	2,307692	0,168837
Sodium	1957-1972	0,032558	0,016279	0,491228	0,036279
SodiumChlorate	1958-1972	0,1	0,039535	1,116883	0,080465
Styrene	1958-1972	0,118605	0,069767	0,990291	0,068837
TitaniumSponge	1951-1968	0,27907	0,116279	1,678322	0,182791

Urea	1961-1972	0,151163	0,074419	1,214953	0,096744
VinylAcetate	1960-1972	0,127907	0,076744	1,009174	0,071163
VinylChloride	1962-1972	0,14186	0,090698	1,008264	0,071163

Table 2: For Hardware and Energy technologies: Values of g_i and k_i from Nagy et al (2013), values of ε_{di} calculated from Eq. 11 and the dematerialization value from inequality 6.

Technology Hardware Ind.	**Time period**	g	k	ε_{di}	**Inequality 6**
DRAM	1972-2007	0,604651	0,44186	1,281419	0,182791
HardDiskDrive	1989-2007	0,651163	0,651163	0,955958	0,02
LaserDiode	1983-1994	0,744186	0,325581	2,092871	0,438605
Transistor	1969-2005	0,488372	0,488372	0,942127	0,02
Technology Energy Ind.	**Time period**	g	k	ε_{di}	**Inequality 6**
CCGTElectricity	1987-1996	0,174419	0,02093	3,424658	0,173488
CrudeOil	1947-1968	0,05814	0,009302	0,980392	0,068837
ElectricPower	1940-1968	0,106977	0,037209	1,226667	0,089767
Ethanol	1981-2004	0,139535	0,053488	1,671309	0,106047
GeothermalElectr	1980-2005	0,097674	0,051163	1,203438	0,066512
MotorGasoline	1947-1968	0,065116	0,013953	1,018182	0,071163
OffshoreGasPipel.	1985-1995	0,255814	0,113953	1,77706	0,16186
OnshoreGasPipel.	1980-1992	0,15814	0,016279	3,417085	0,16186
Photovoltaics1	1976-2003	0,225581	0,065116	2,371638	0,180465
Photovoltaics2	1977-2009	0,213953	0,104651	1,588946	0,129302
WindElectricity	1984-2005	0,44186	0,093023	3,591682	0,368837
WindTurbine1	1982-2000	0,27907	0,04186	3,883495	0,257209
WindTurbine2	1988-2000	0,534884	0,039535	7,692308	0,515349

Figure 5 shows the 57 cases in Tables 1 and 2 mapped onto the format of Figure 4. The k_i and ε_{di} values for each of the individual lines in the Tables become a point in either Figure 5a (chemicals), Figure 5b (hardware) or Figure 5c(energy). Since dP/dt and dG/dt are not precisely constant over time, the dematerialization boundary for figures 5a and 5c are drawn for approximate dG/dt and dP/dt for the 1940s through 1960s whereas figures 5b is consistent with Figure 4 and is applicable for the 1980s onward. Earlier dated cases are placed on Figure 5a (the chemical cases from Table 1) and figure 5c (energy cases from Table 2) where the dematerialization border is at higher values of k_i. The more recent hardware cases from Table 2 are mapped onto Figure 5b. Examining Figures 5a, 5b and 5c, it appears that none of the 57 cases are in the dematerializing region. Table 1 shows the actual value for inequality 6 for each individual chemicals case. Table 2 shows the actual values for the hardware and energy industry cases. None of the values are less than zero so *none* are reducing in material usage and thus none are dematerializing.

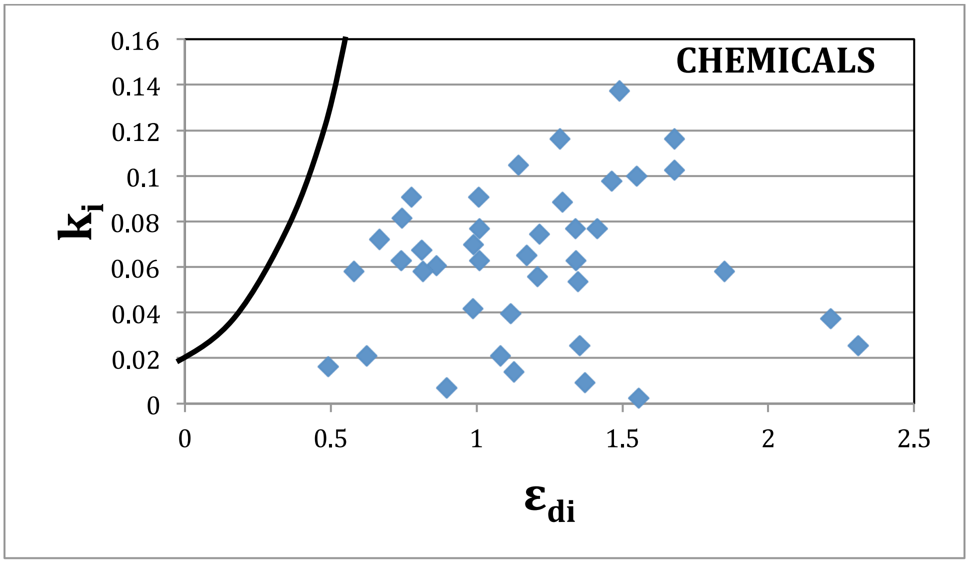

Figure 5a: All chemical technology cases from Table 1 plotted in the format of figure 4 but for values of population growth and GDP growth consistent with the time frame of the chemical technologies data.

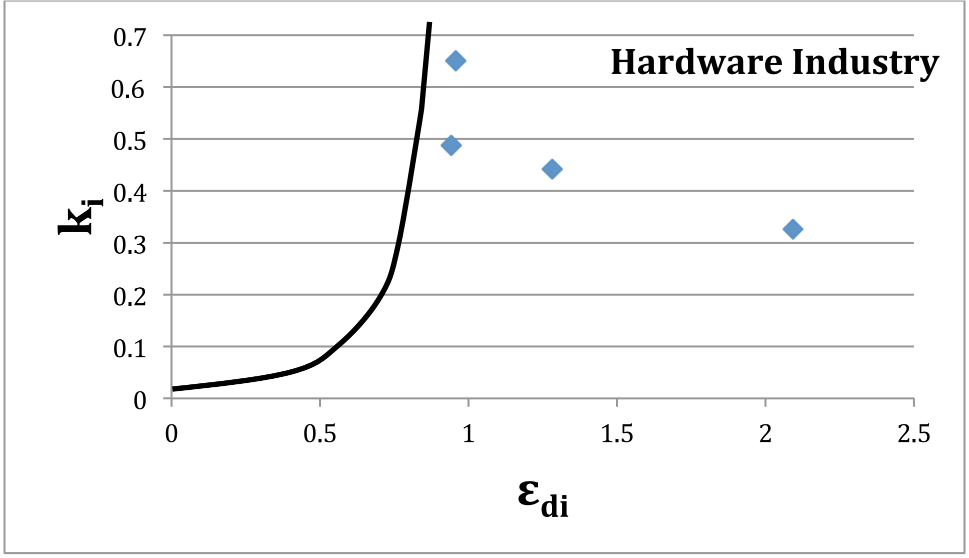

Figure 5b: The hardware technology cases from Table 2 plotted in the format of Figure 4

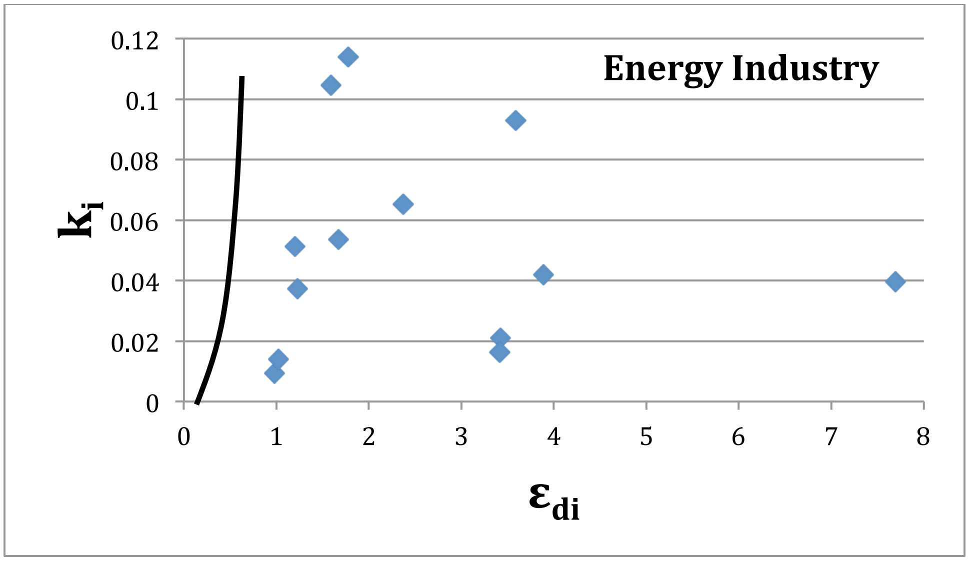

Figure 5c: The energy technology cases from Table 2 plotted in the format of Figure 4 with values for population growth and economic growth consistent with the time frame for the energy technology data.

Absolute dematerialization requires high enough k_i and low ε_{di}. However, the cases with higher k_i values (for example, hard disk drives) have relatively high ε_{di} and are in the materialization region. Moreover those with the lowest ε_di (Aniline, CarbDisulf, Sodium) have very low k_i and are also in the materialization region. For those looking for easy paths to dematerialization through technical change, this is a very disappointing and convincing set of undesirable results for the optimists.

5. 2 Additional Results

Although Table 1 and Figure 5 are strong evidence, we note limitations from our use of the data from Nagy et al (2013). The first source of limitation arises from Nagy et al only considering cost. Higher rates of improvement (higher k) have often been found for functional performance than for decreases in cost because of depletion and other effects mentioned above. Secondly, the focus in Nagy et al on resources and not products translates to some lack of breadth despite 57cases. In addition, the early dates associated with the bulk of the Nagy et al cases is not good evidence of what may be occurring today.

The authors have recently completed a study (Devezas and Magee, 2014) of 69 materials cases from 1960 to 2010 and that data are also interesting in that 6 out of these 69 cases show an absolute decline in materials usage over the 50 year period suggesting that some materials are now entering automatic dematerialization. However, examining the six cases instead suggests that the major conclusion based upon the application of our simple theory to the Nagy et al data is largely upheld. The 6 cases are asbestos, beryllium, mercury, tellurium, thallium, and wool. Four of these are clearly not examples of technological improvement automatically leading to dematerialization but instead the dematerialization for asbestos, beryllium, mercury and thallium has occurred because of legal restrictions on their use due to toxicity issues. The other two cases are probably examples of substitution which is a major outstanding issue relative to dematerialization [Kander(2005), Ruth (1998)] and it will be discussed further below.

6. Discussion

The possible data shortcomings mentioned in the first paragraph of sub-section 5.2 are counteracted by other effects. First, using Equation 5 instead of equation 4 would greatly expand the materialization region and this would almost surely override any effects of data shortfalls. The results shown in Figure 5 consider both technological change and the rebound effect and clearly show a challenge in relying on "automatic dematerialization" for the future. The results also indicate that "materials efficiency" through new designs and technology is not sufficient to obtain dematerialization. The significant increase in "materials efficiency" (reductions of needed material to achieve a given level of function) in the DRAM example will be hard to surpass but this example (and the other few rapid improving material efficiency cases) still result in materialization due to relatively high ε_{di}. When demand elasticity is near (or worse greater than) 1, dematerialization will not occur with any level of improvement in efficiency of materials usage. In regard to our desire to understand the combined effects of technical capability improvement and rebound, the results are apparently quite determinative. Although continuation of work to find better k_i and ε_{di} values is certainly worth pursuing, developing neither a more complex model nor more data is likely to reverse the major empirical finding of our work. Further theory and empirical work might better focus on the remaining critical issues in dematerialization.

A major issue not addressed by our theory is the issue of *substitution*. Both the constraint (Jevon's paradox) and the potential enablers (Engel's Law and technical capability increases with time) do not consider substitution of materials, artifacts or functions and all are possible. In the Engel's law case, a decrease as a percent of GDP for an old technology is of no help, if newer technologies substituting for it (or supplementing it) cause the total consumption to continue increasing. This would appear to be the case for wool (and probably tellurium) in its dematerialization. Synthetic fiber is one of the strongest growing material classes in the 69 we studied (Devezas and Magee, 2014) and the decrease in wool usage is more than counterbalanced by this growth. In the case of Jevon's effect, technological development does not only increase the performance of existing technologies but also results in the emergence of totally new technologies. If the new technologies use a very different resource base, technological development might be able to achieve success environmentally and economically [Ruth (1998)]. However, it is also possible that the totally new technologies will be just as problematic as the outgoing technology [Kander (2005)]. We here qualitatively discuss a major case of sufficient breadth to introduce the full scope of the substitution issue relative to dematerialization.

The continuing rise of Si based semiconductors is perhaps the major technological fact of the past five or more decades. Silicon-based technology is a "general purpose technology" [Bresnahan and Trajtenberg (1995)] underlying much of the improvement in information storage, information transmission and computation since the 1960s and some have argued [Brynjolfsson and McAfee (2014)] that it is the most important general purpose technology ever. From 1968 to 2005, the number of transistors sold for use has increased by 10^{9}; by 2005 there were more transistors used then printed text characters (Moore, 2006)! However, the industry revenue per transistor has fallen almost as dramatically (Moore, 2006) as has the amount of material needed to make a transistor. Nonetheless, the usage of silicon has grown significantly since 1970. Devezas and Magee (2014) find it has grown by 345% over this period but also find the growth is less than GDP growth (472% in the same period) and that much of the growth of Si usage is associated with non-electronic applications. This growth would be 10^5 (or more) times as high if a 2005 transistor used as much Si as one manufactured in 1968 showing the importance of the profound change in "materials efficiency" for this technological domain[5].

For a general purpose technology such as transistors, examination of substitution requires more than considering usage. Si-based technologies have enabled entire new industries such as wireless communication, the Internet, social networks, software systems and others. Each of these involves artifacts and systems that consume materials so the continuous rapid development of this technology has far broader implications on dematerialization than the use of Si. Moreover, a key question is to what extent these new technologies enabled by silicon have substituted for more energy and/or material intensive industries.

Two example questions are offered to clarify the complexity of the substitution issue. The first is to consider the potential for a changing basic function: substitution of electronic communication enabled "virtual" visits to replace travel. Although the communication technologies are not yet able to meet this desire (and it is not clear that it will ever be an adequate full substitute for "real" travel), if reversal in the rapid growth of long distance travel were to occur, it is likely (but would take careful study of the infrastructure and artifacts created and eliminated) that significant real dematerialization could occur. A second example is the growth of Si usage associated with Solar Photovoltaics: Devezas and Magee (2014) find that this usage has now eclipsed electronic uses of Silicon. Since this application is essentially on a path to replace fossil fuel generation of electricity[6], [Devezas et al (2008)],the comparison would have to involve all the infrastructure and devices for both of these alternatives in order to determine the actual dematerialization. The significant reduction in CO_2 is –in this case- perhaps more important than the net

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[5] This counterfactual is somewhat misleading because the growth of usage would be much lower if the improvements had not occurred ("reverse rebound").

[6] We note that the promise for solar PV relative to fossil fuels is that the technical capability increase (k) is about 0.1 per year for solar PV [Benson and Magee (2012)] and less than 0.03 for fossil fuel energy systems [McNerney et al (2011)].

materialization associated with the alternatives. Nonetheless, the consideration of the full impact of solar cells vs. fossil fuels on materialization would be quite complex on its own involving not only solar modules and fossil fuel generating plants but also needed electrical transmission and storage infrastructures, fossil fuel extraction systems, extraction systems for solar module materials, and many others to understand the materialization aspect of this one substitution being enabled at least partly by improvement in silicon-based technology.

7. Concluding Remarks

We believe that the theory/framework introduced in this paper clarifies the interaction of technological improvement with demand rebound in a simple but fairly useful manner. The framework and its application to 57 different cases clearly indicate that technological improvement has not resulted in "automatic" dematerialization. Moreover, the combination of high improvement rates with high demand elasticity seems to indicate that the future is not highly likely to reverse this finding. An optimistic possibility yet remains: drastic substitution (on a functional and system basis) of more benign technologies where such technologies result from continuing technological change. The discussion of the silicon-enabled general purpose technology here is qualitative and only a minimal outline. Nonetheless, this hopefully is sufficient to indicate the importance of theory and empirical efforts on substitution studies. With our current very limited knowledge about substitution, we have no way to objectively assess the potential for an overall benign effect of the major technology of the past 50 years. Reliable assessment is complex as semi-conductor technology has enabled so many other technologies that even an approximate global substitution study appears quite challenging.

8. References

Allwood, J. A., Ashby, M. F., Gutowski, T. G. and Worrell, E., 2011. Material Efficiency: A White Paper. Resources, Conservation and Recycling, 55, 362-381

Ausubel, J.H. and Sladovich, H.E., 1990. Dematerialization. Technological Forecasting & Social Change 37, 333 – 348.

Ausubel, J.H. and Waggoner, P.E., 2008. Dematerialization: variety, caution, and persistence. Proceedings of the National Academy of Sciences (PNAS) 105, 12774-12779

Ayres, R. U., 1995. Economic Growth: Politically Necessary but not Environmentally Friendly. Ecological Economics, 15, 97-99

Benson, C.L. and Magee, C.L., 2012. A framework for analyzing inventions that drive improvement in a specific technological field. Engineering Management Research 1, 2-15. doi:10.5539/emr.v1n1p2

Bernardini, O. and Galli, 1993. Dematerialization: long-term trends in the intensity of use of materials and energy. Futures (May), 432 – 448.

Bresnahan, T.F., and Trajtenberg, M., 1995. General Purpose Technologies: Engines of Growth?. Journal of Econometrics, 65, 83-108.

Brynjolfsson, E., and McAfee, A., 2014, The Second Machine Age: Work Progress, and Prosperity in a time of Brilliant Technologies. W. W. Norton, New York.

Devezas, T.C., LePoire, D., Matias, J.C.O., and Silva, A.M.P., 2008. Energy scenarios: Toward a new energy paradigm. Futures 40, 1-16.

Devezas, T. C. and Magee, C. L., 2014, The consumption of Materials from 1960-2010, unpublished.

Gutowski, T. G., Sahni, S., Allwood, J. M., Ashby, M. F., and Worrell, E., 2013. The Energy required to produce materials: constraints on energy-intensity improvements, parameters of demand. Phil. Trans. Roy. Soc., http://dx.doi.org/10.1098/rsta.2012.0003

Kander, A., 2005, Baumol's Disease and Dematerialization of the Economy. Ecological Economics, 55, 119-130.

Magee, C. L., Basnet, S. Funk, J. L., and Benson, C. L. 2014. Quantitative empirical trends in technical performance. Unpublished manuscript.

Malenbaum, W., 1978. World Demand for Raw Materials in 1985 and 2000, McGraw Hill, New York.

McNerney, J., Farmer, J. D., and Trancik, J. E., 2011, Historical Costs of coal-fired Electricity and its Implications for the Future. Energy Policy, 39, 3042-3054.

Nagy B, Farmer, J. D., Bui Q. M., and Trancik J. E. ,2013, Statistical basis for predicting technological progress. PLoS ONE;8:1-7.

Ruth, M., 1998. Dematerialization in five US metal sectors: implications for energy use and CO2 emissions. Resources Policy 24, 1- 18.