2004

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WVU REGIONAL RESEARCH INSTITUTE RESEARCH PAPER SERIES

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RESEARCH PAPER 2004-1

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Classification JEL: C53, Q31, Q32

Key Words: Intensity of Use, Dematerialization, Transmaterialization, Materials Demands, Materials Life-Cycles

Abstract: Long-term materials demand patterns are important to examine because of the possibility of material obsolescence as well as the long lead times required to create new mineral productive capacity. Since structural changes in materials demand are inevitably linked to the performance and adjustments of national economies, materials life cycles have often been examined in the context of intensity of use (IOU). Explanations of these structural changes have focused on dematerialization; this concept implies a structural change in an economy embodying a reduced demand for materials and, therefore, a decline in overall industrial growth. An alternative view is that of transmaterialization, which implies a recurring industrial transformation in the way that economic societies use materials, a process that has occurred regularly or cyclically throughout history. These patterns vary notably across regions. The purpose of this paper is to explore more recent developments in the analysis of these concepts and to provide new directions for future applications.

DEMATERIALIZATION AND TRANSMATERIALIZATION: WHAT HAVE WE LEARNED?

Walter C. Labys*

Introduction

Long-term materials demand patterns are important to examine because of the possibility of resource depletion as well as the long lead times required to create new mineral productive capacity. Since structural changes in materials demand are inevitably linked to the performance and adjustments of national economies, these changes have been historically measured relative to national income, employing a measure known as intensity of use (IOU). The demand declines observed in the IOU have been characterized as *dematerialization* or a decoupling of the materials sector from the industrial and other sectors of the economy. However a preferable view is that the demand decline observed can be more aptly explained by *transmaterialization.* Transmaterialization implies a recurring industrial transformation in the way that economic societies use materials, a process that has occurred regularly or cyclically throughout history. Instead of a once and for all decline in the intensity of use of certain materials, transmaterialization suggests that materials demand instead experiences phases in which old, lower quality materials linked to mature industries undergo replacement by higher quality or technologically more advanced materials.

The present purpose is to explore more recent developments in the analysis of these concepts and to provide new directions for future applications. This paper consists of the following parts: Background, The Dematerialization Concept, The Transmaterialization Concept, an Empirical Example, Further Issues of Measurement, New and Needed Developments, and Conclusions.

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Background

The concept of dematerialization as developed in the 1980's can be said to be applicable only to a select group of technologically inferior materials, and not to an overall decline in the use of materials in general. Throughout history, the introduction, growth and decline of materials has been recorded as newer, more technically advanced materials have come into use. Several ages have even been named after the dominant materials consumed during their span; for example, witness the "Stone Age", the "Bronze Age", or the "Iron Age". When we examine individual materials, boilers in the early 1800s were made of cast iron or sheet iron; by the 1860s steel boilers were being used in response to the need for weight reductions in order to increase efficiency and to reduce costs. Materials used in the construction industry have gone through similar changes over time. Natural stone was probably the first mineral commodity used by modern man, while dimension stone has been used for several millennia as a construction material. Since the late 1800s, the use of dimension stone in building has been partially replaced by concrete, glass, and bricks, because of the superiority of the latter materials in that they were stronger, less heavy and less costly. In roofing, clay and slate tiles have been replaced by sheet metal, wood shingles, asbestos-cement shingles and synthetic materials. In response to the need for more fuel efficient automobiles, aluminum and synthetic materials have significantly replaced steel in the manufacture of lighter weight cars. While aluminum earlier experienced very high demand growth, the newer aluminum alloys are now being challenged by a new breed of materials, including advanced alloys, ceramics and composites (Eggert,1986).

The Dematerialization Concept

A number of studies in the 1980s stressed the concept of dematerialization, that is the prospect that the United Kingdom, the United States and other national economies were experiencing a permanent decline in the use of materials in industrial production. In general, these studies have had three major limitations. First, they have taken a very short-run perspective often including data only since 1970. Second, they typically cover only metals and industrial minerals. And third, few of them have included the "life cycle theory" of product development in explaining the perceived changes in materials consumption. They thus ignored the possibility that with changing needs, economies will replace old materials with newer, technologically more advanced materials in a cyclical fashion.

Much of this research began with Malenbaum's study (1978) on the *World Demand for Raw Materials in 1985 and 2000*. That work also was one of the first to analyze materials demand employing the IOU method and surmised that an inverted "U” shaped curve could be empirically observed from the IOU data, reflecting an initial rapid increase in the use of minerals as per capita GDP increases, and then a slow decline. Malenbaum, however, focused only on a small group of minerals while making many subjective judgments as to changes in IOU. In addition, he erroneously assumed that declining IOU occurred because of a shift in demand from manufacturing to the less materials-intensive service sector. It has been shown in other studies that employment has declined in the manufacturing sector, most likely because of increases in productivity, but that the demand for manufactured goods has not significantly declined relative to the service industries. Also the limitation of a small group of materials examined is that they were largely older minerals, neglecting composites, plastics and advanced ceramics.

A variation on Malenbaum's IOU methodology was utilized by Fischman (1980) in his *World Mineral Trends and U.S. Supply Problems*, which found downturns in IOU for several of the seven metals analyzed (aluminum, chromium, cobalt, copper, manganese, lead, and zinc) over the period from 1950 to 1977. Humphreys and Briggs (1983) examined the consumption trends for twelve metallic and nineteen nonmetallic minerals in the United Kingdom from 1945 to 1980. They found that the consumption of most minerals in the U.K. displayed a tendency to stagnate prior to the early 1970s, and that the consumption of nonmetallics had shown a faster growth as compared to the metallics, indicating that their share of the total value of minerals consumed in the U.K. had increased significantly.

About the same time, Tilton (1985) in his study of “Atrophy in Metal Demand” examined seven metals whose growth in consumption had mostly declined since 1974. Although Tilton implied that a structural transformation has been occurring in the U.S. materials industries since the mid-1970s, the metals examined (aluminum, copper, steel, lead, tin, zinc, and nickel) excepting aluminum had been in use for more than 100 years and the total consumption of each of them had peaked decades ago. In addition, most of these metals had been or are being replaced by technologically more advanced and lighter high-performance metals. Other attempts to explain dematerialization can be found in a special metals demand conference proceedings by Vogely (1986), and international investigations were made by Lahoni and Tilton (1993) and by Roberts (1996). More recent studies include Humphreys (1994), Moore, et.al. (1996), and Rogich (1996).

The main challenge to the IOU concept was made by Auty (1985) in his "Materials Intensity of GDP". Auty reviewed the above studies of Malenbaum and Fishman as well as of Leontief, et.al. (1983) and Radcliffe et.al. (1981) to determine the reliability of their measures of declining materials IOU and to improve their interpretation. He disputed the inevitability of structural change in minerals for several reasons. Substitution between materials tends to be erratic over time; the range of materials we use is widening rapidly as new technologies are employed, a fact that dematerialization does not take into account; and changes in the mix of manufacturing activity are proceeding faster than changes in the overall composition of GDP. He thus suggested that an alternative route to determining the direction of structural change and tracing underlying trends in minerals intensity could be provided by research on long-wave cycles.

This was confirmed in works of Larson, Ross and Williams (1985) who provided evidence of some earlier or pre-World War II downturns in materials IOU and of Clark and Flemings (1986) who demonstrated that technological processes cause fluctuations in the way in which materials are used. The implications of these insights are that levels of IOU change regularly for different materials and that cyclical swings in this index might be a better indicator of mineral industry adjustments than that of a declining trend. This view was also supported by Sterman (1985) who concluded from his systems dynamics research and analyses of IOU patterns that structural changes in the economy can be better described as following a cyclical rather than a declining trend pattern. Finally Ayres and Ayres (1996) show how dematerialization can be better explained in terms of materials substitution and recycling strategies.

The Transmaterialization Concept

This idea that materials undergo life cycles and substitution was furthered in the development of the new concept of transmaterialization, i.e. see Labys (1986), Labys and Waddel (1989), Waddel and Labys (1988), and Hurdelbrink (1991). Cyclical changes are in contrast to structural changes that imply growing obsolescence but not awareness of product life cycles. Transmaterialization describes the characteristic behavior of material markets over time by focusing on a series of natural replacement cycles in industrial development. As needs of economic society change, industries continually replace old materials by newer, technologically more advanced materials (Bernardini and Galli, 1993). This is part of the scientific process and, therefore, should not only be observable, but also be predictable from the point of view of profitability of individual mineral firms. Many developed countries have thus undergone an industrial transformation in which materials basic to twentieth-century society are being replaced by materials with ramifications to the twenty-first century.

The origins of transmaterialization can be found in several aspects of the growth literature. Schumpeter (1927) developed a theory supporting the view that growth comes in spurts and appears as cyclical upswings. According to Schumpeter, progress is due to economically induced new innovations, their gradual adoption, and successful entrepreneurship. A more familiar notion of growth and one which underlies the Schumpeterian idea of progress specifies growth as following an S-shaped curve. Prescott (1922), Kuznets (1930) and Burns (1934) evaluated this growth theory for a sample of individual commodities and industries. (A tendency has arisen to refer to the shape as a Kuznets environmental curve; however, this misnomer reflects a failure to realize that Kuznets (1930) much earlier had already conceived of the possibility of declining materials consumption with increasing national product). Later Dean (1950) expanded this theory in the form of the "product life cycle" theory. The application of these theories to a number of different variables and different industries was later confirmed by Nakicenovic (1990) and a more up-to-date assessment appears in Frankl (2002). Evidence of long waves in Italian IOU patterns can be found in Fortis (1994).

The application of the life cycle model to transmaterialization requires five stages. The first model stage is the initial introduction of a new material. The performance of the material is not yet proven and sales are therefore sluggish. The consumption rates (measured as quantity/GDP) are typically low, along with vast potential markets. Representative of this stage are advanced ceramics, such as the silicon carbide and silicon nitride based ceramics. These newer ceramics have been developed in order to fulfill a particular need for higher resistance to abrasion and to wear, high strength at high temperatures, superior mechanical properties, greater chemical resistivity, and good electrical insulation characteristics.

The second or growth stage (sometimes referred to as the youthful stage) follows the discovery of a commodity or a major application. During this stage, consumption of the commodity increases rapidly as its properties are appreciated and promoted through research and dissemination of information. Consumption generally increases at a rate much faster than the economy as a whole, and this is reflected in a rise in the IOU index. Examples of youthful materials include gallium and platinum group metals. During the third or mature stage, the growth in IOU begins to decline. The material has been accepted into industrial processes and the rapid growth of the youthful stage begins to level. Aluminum represents a material presently in the mature stage.

According to Humphreys (1982), during the fourth or saturation stage, the IOU peaks and begins to decline, although the consumption as measured in physical quantities, may still be increasing. Molybdenum, manganese and cobalt are currently in their saturation stage. The fifth or declining stage witnesses a significant decline in IOU of a material. During this stage, even total consumption declines, mainly because of newer materials replacement. Examples of materials in this last stage include tin, asbestos and cadmium.

Expanding upon the work of Humphreys and the life cycle theorists, Waddell and Labys (1988) showed that the recognition and the empirical determination of these cycles can make a strong case for transmaterialization. The hypothesis that growth and development occur in waves or cycles as defined in the product life cycle theory can be applied to materials markets. We would thus expect to see regular product life cycles for a number of minerals over extended periods of time. The timing and phases of these cycles obviously will vary with the nature of the products or minerals selected.

An Empirical Example

Labys and Waddell (1989) have provided empirical confirmation of the existence of these cycles and thus of transmaterialization for some thirty commodities in the United States. To provide a more aggregate demonstration of this phenomenon, these commodities have been aggregated into five groups, each of which represents a different cyclical period in which the IOU has peaked and declined or has increased. The grouping of the commodities and the periods they represent have been summarized in Table 1. (1) The first group consists of those materials which experienced a peak in their IOU prior to World War II. Iron ore and copper are two of the materials included. (2) The second group consists of those materials having their IOU peak just after World War II. Examples of materials in this category include nickel and molybdenum. (3) The third group consists of materials for which the IOU peaked during the period from 1956 to 1970, namely manganese, chromium, and vanadium. (4) The fourth group consists of materials for which IOU peaked after 1970 and includes phosphate rock, aluminum and cobalt. (5) The fifth and final group consists of materials for which the lOU has yet to peak. This group consists of newer, lighter, more technologically intensive materials, such as the platinum group metals, titanium, plastics, and advanced ceramics (Mangin et.al., 1995).

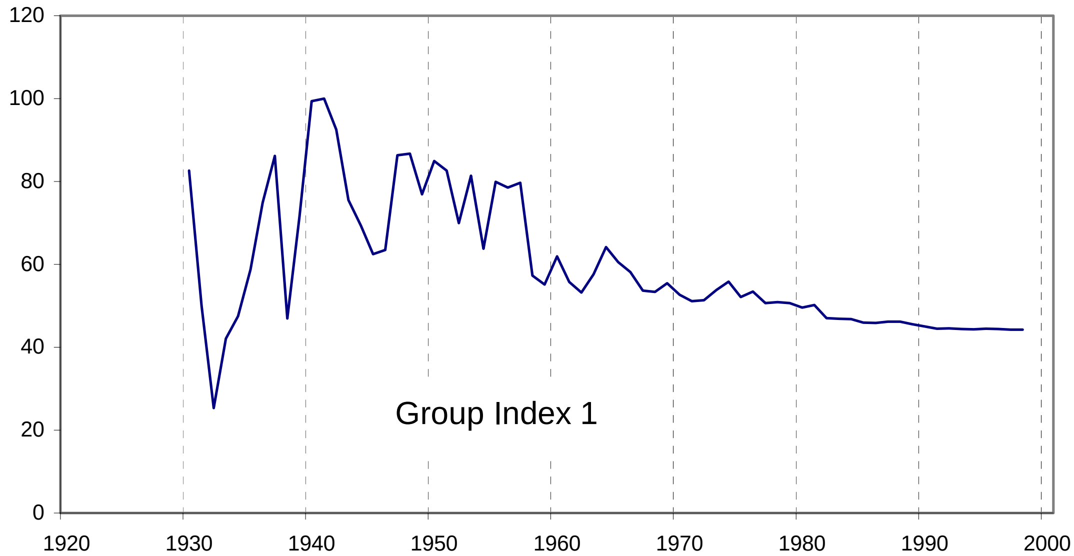
The graphs of the five IOU indexes covering the years 1900 to the present appear in Figure 1. Sources for the commodity consumption data include the *Mineral Commodity Summaries* (originally the US Bureau of Mines but now the US Geological Survey) and for GDP the *Survey of Current Business* (US Bureau of Economic Analysis). Beginning with the Group Index 1, those materials appeared to have experienced rapid growth until the 1920s, followed by a phase of moderate growth lasting until the 1940s, when the IOU peaked. The phase of rapid growth of the materials found in Index 2 began in the late 1930s and lasted until after the end of World War II. Figure 1 suggests that growth then continued at a moderate rate and peaked soon thereafter, decline beginning around 1955. The upswing of the materials Group Index 3, which includes the years 1934 to the mid-1950s, increases until 1957, with a definite decline beginning in the early 1960s. The consumption of the materials contained in Index 4 continues to increase, but at a decreasing rate, so that the IOU is declining. The growth in IOU began in the late 1940s, peaked in the early 1980s, and is now in a declining phase. The Group Index 5 features those materials currently in their rapid growth stage. This phase of their lifecycle began in the 1970s and still has not yet peaked. These and other published displays of materials life cycles suggest that over the longer run, the transmaterialization concept provides a more realistic view of how changes in materials consumption are likely to occur.

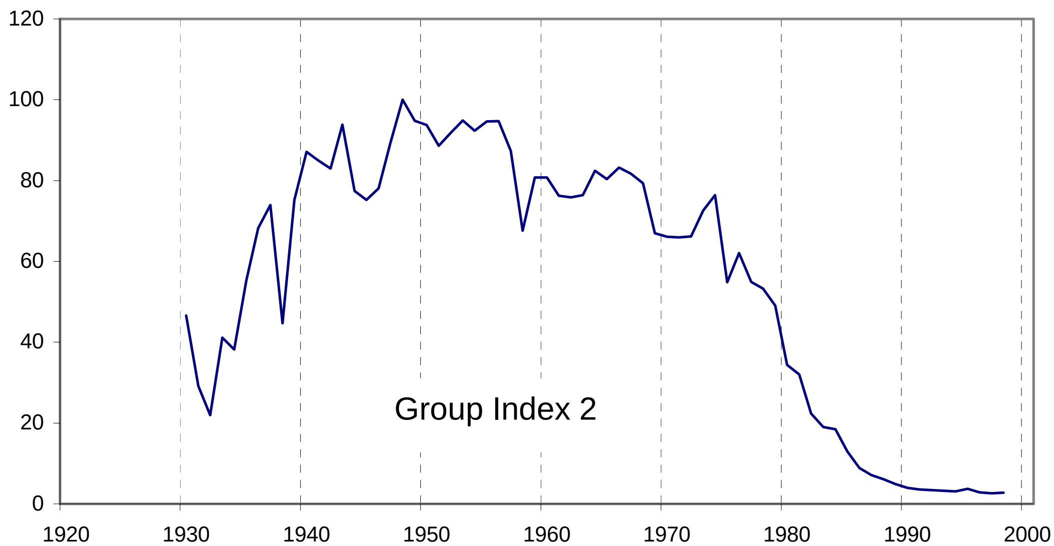
Table 1. **US MATERIALS GROUPINGS, END-USES AND PERIODS OF PEAK INTENSITY OF USE**

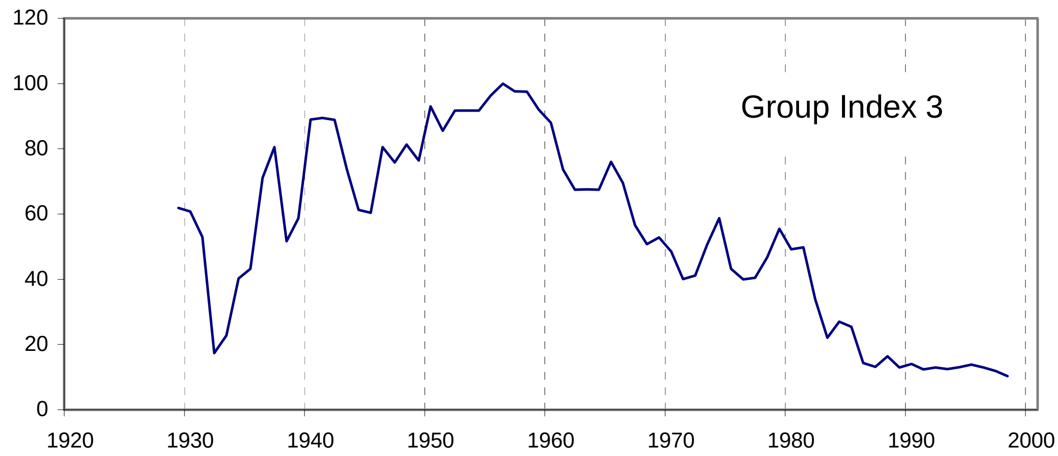
Materials Groups	Materials Included	Major end-use Sector	Time Span[a]	Peak of Intensity Of Use
1	Arsenic	Glass Manufacturing	1885-45	1935
		Industrial Chemicals	(1941)	
	Copper	Electrical Equipment		1943
	Iron Ore	Construction Industry		1941
		Transportation Industry		
	Lead	Electric Industry		1941
		Chemical Industry		
	Tin	Containers		1930
	Zinc	Iron and Steel Industry		1941
		Construction		
2	Asbestos	Friction Products	1925-70	1949
		Insulation	(1949)	
	Bismuth	Pharmaceuticals		1948
		Industrial Chemicals		
3	Molybdenum	Steel Industry	1935-73	1955
	Vanadium	Iron and Steel Industry	(1956)	1942/66/80
		Construction		
	Chromium	Stainless Steel		1957
	Lithium	Nickel and Iron Alloys		1955
		Manufacture of Aluminum		
4	Aluminum	Electrical Applications	1945-86	1972
		Packing Industry	(1973)	
		Construction Industry		
	Cobalt	Super Alloys		1952/75
	Barite	Oil and Gas Industry		1956/80
	Phosphate Rock	Agriculture (fertilizers)		1979
	Rutile	Pigment		1974
5	Gallium	Electronics	1955-present	1979+
	Geranium	Electronics	(climbing)	1985+
	Hafnium	Nuclear Reactors		1982+
	Platinum Metals	Automotive Industries		1983+
		Chemical Industries		
	Titanium Metals	Aerospace Industry		1969/80+
	Rare Earth Elements And yttrium	Catalysts		1985+
		Electronics		
	Polyethylene	Packaging		1985+
	Ceramics	Optical Fibers		
		Machine Parts		
		Magnet Components		
	Composites	Aerospace and Automotive		

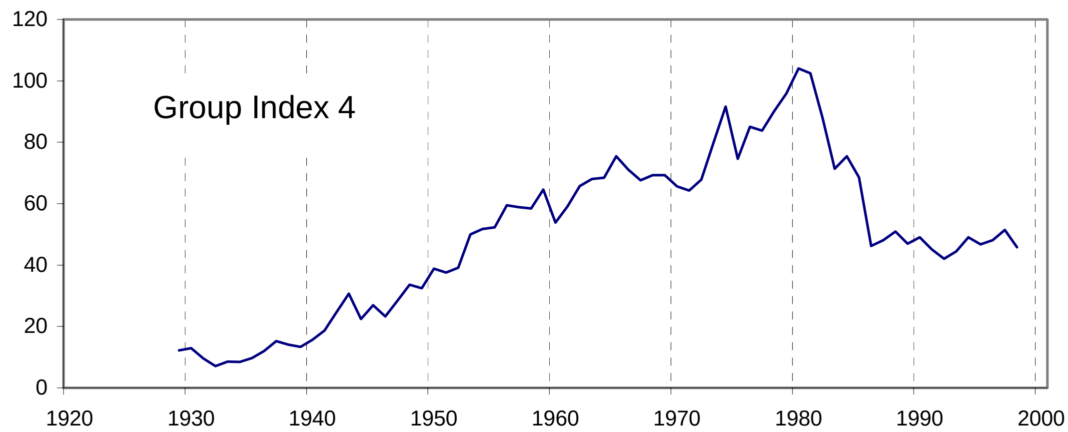
a. Peak use indicated in parenthesis.
b. Source: Labys, W.C. and L.M. Waddell, "Commodity Life Cycles in U.S. Materials Demand." *Resources Policy* 15(1989):238-251.

Figure 1. **MATERIALS GROUP INDEXES OF INTENSITY OF USE**






Group Index 3
120
100
80
60
40
20
0
1920
1930
1940
1950
1960
1970
1980
1990
2000


Group Index 4
120
100
80
60
40
20
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1920
1930
1940
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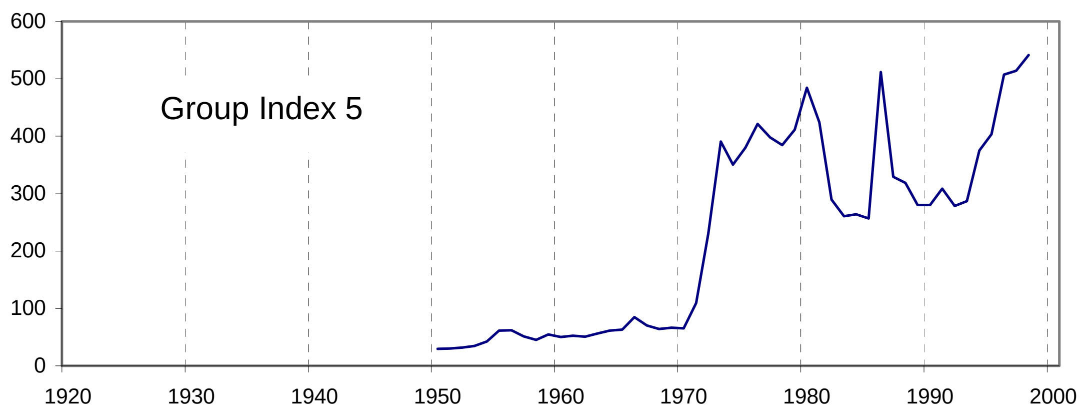
1970
1980
1990
2000


Group Index 5
600
500
400
300
200
100
0
1920
1930
1940
1950
1960
1970
1980
1990
2000

Further Issues of Measurement

Most evaluations of the dematerialization concept are based on the visual inspection of the empirically derived curves and thus lack the rigor that is obtained from statistical methods that generate levels of confidence. As a consequence, time series regression analysis was employed as the first step to remedy this problem (Roberts, 1990). Because time series data typically contain trends, Labson and Crompton (1993) and Labson (1995) went one step further to employ cointegrating regression analysis. This enabled them to determine whether metals consumption and economic activity are affected by a common stochastic trend and exhibit a stable long run relationship, whereby the divergence of consumption of metals from income is simply the result of short run disequilibrium. Their results appeared to support the latter. Using a wider data set, Janicke et. al. (1989) turned to cross-section regression analysis based on data now using a sample of countries. Janicke et. al. (1997) were able to extend this analysis to a larger group of materials. Because their cross-section was measured only in 1970 and 1985, de Bruyn and Opschoor (1997) questioned their results by employing a panel data set that covered the years 1966 to 1990.

Other methods of measurement concentrate more on the long wave aspect of these curves. The influence of technological change often has been analyzed based on forms of a diffusion model resembling an S-shaped curve, such as a logistic function. Logistic substitution models describe the rate at which a product embodying a particular technology captures market share. Sadler (2003) based on the Duisenberg (1985) model employed regression analysis to estimate the IOU curve for raw steel consumption in six global regions. Roberts (1996) has applied this method using regression analysis to explain the dynamics of substitution of aluminum for steel in US markets.

Input-output analysis provides a broader evaluation of the factors behind intensity of use. Changes in consumption patterns, import mix, substitution, and improvements in materials use efficiency all come to bear. In an earlier study Leontief et. al. (1983) employed this approach to measure and to forecast long run changes in the use of materials. Linked to an I-O table expressed in monetary values, they estimated the IOU as the physical quantity of material used per dollar output of the consuming sector. More recently Duchin and Lange (1994) have adapted this approach in a global assessment of material and energy use and waste management. Here their measure is the value of material delivered per dollar of output of a particular industry. Forecasts are made of these coefficients for a variety of metals.

Since the process of materials substitution is a dynamic one, evolutionary models also have been used to analyze materials consumption and intensity of use. Here the evaluation of intensity of use often represents only a convenient by-product of a much larger set of variables and computations. For example, one can analyze interactions between materials use and factors such as technical change, recycling, dematerialization, energy demands, and pollution. An early such dynamic modeling application was made by Meadows, et. al. (1972) in their assessment of “The Limits to Growth” and later by Sterman (1985). More recently Ruth and Harrington (1997a,b) have forecast materials and energy use in the pulp and paper industry; Cleveland and Ruth (1998) utilize a similar model to forecast changes in the copper industry; and van Vuuren et. al. (2002) explain long-term world metal use.

New and Needed Developments

A detailed analysis of new developments in this area appears in Cutler and Ruth (1999). Recent attempts to analyze IOU have scrutinized the quality of the underlying data and their meaning. It is obvious that quantity or weight represent only one dimension of how we measure materials consumption. Other dimensions include prices or value, quality or physical properties such as density and strength, and processing technology or efficiency in use. While these dimensions vary widely from material to material, they actually can be altered or combined when new synthetic materials are designed, e.g. see US-OTA (1998). The empirical measure of IOU not only uses the consumption of a material in weight but also the output of industries that consume that material or the total output of the economy, typically measured in GNP. It can also be measured as the ratio of materials use to value added, which is equivalent to GDP or gross domestic product. A variety of factors that can be seen to cause changes in IOU stem from the material composition of product and the product composition of output. Influences underlying these components include technical efficiency improvements, materials substitution, changes in the structure of final demand, saturation of bulk markets, and government use regulations, including the environment. These complications might dictate that the best interpretation of IOU can only be found in bulk materials consumption.

Studies estimating IOU for a variety of materials have increased considerably in the 1990's. The researcher is likely to find some evidence of IOU changes for any given material in a number of different studies. Some examples include Bernardini and Galli (1993), Humphreys (1994), Labys (2002), Moore et. al. (1996), Rogich (1993a), Tilton (1990), etc. However, as mentioned above, there is a need to advance these studies to embody more sophisticated quantitative empirical methods. A first step in this direction has been the use of regression methods to estimate the S-shaped or logistic curves. Examples mentioned above include time series estimation (Roberts, 1990,1992; Rogich, 1993b; Sadler, 2003), cross-sectional (Janicke, 1997), panel (de Bruyn and Opschoor, 1997), and cointegration (Labson and Crompton, 1993; Labson, 1995). More advanced methods tend to be structural in nature, encompassing a much wider set of influences and variables. Duchin and Lange (1994) have employed input-output analysis in this respect, while Ruth and Davidsdottir (1997) have constructed a dynamic simulation model. It would seem important that future studies should concentrate more on deciphering the complex forces behind IOU. The latter would include demand shifts, technical changes, substitution effects, structural changes, and new international trader patterns including the materials composition of traded goods.

The need to aggregate individual materials into meaningful wholes has also been addressed. These analyses attempt to say something about the overall efficiency of materials use. Rogich (1996b), for example, provides such an aggregate view based on five separate materials consumption groups: metals, minerals, agriculture, forestry, and nonrenewable organics. Other logical aggregations might include ferrous or nonferrous metals, precious metals, light metals, industrial minerals, construction materials, plastics, petrochemical materials or synthetic materials. An overall measure termed material input per unit service (MIPS) has been developed by Schmidt-Bleek (1994) and Bringezu (1997) among others. Their approach includes several categories of direct materials inputs such as those suggested, along with materials flows of a more hidden nature. It is interesting to observe that the study of materials life cycles in this context has advanced to include energy, environment and more general ecological considerations. Extensive investigations in these areas can be found in the several books of Ayres and Ayres (1996 1998 1999, 2002).

The prospect of aggregating materials in use, nonetheless, is a difficult one to face. Index number problems abound of which the most difficult is weighting the quantities of specific materials to be included. Relative quantity weights have been most frequently employed. This may not be perfect but weights such as sales or value-added often are not sufficiently disaggregated to deal with individual products or materials. Volume also has been used, since consumers often select materials on a cost per unit volume basis. Cleveland and Ruth (1999) would modify index-weighting schemes to include quality factors. One suggestion is to use price as a surrogate for quality and to use the prices of materials to weight their mass units. Considine (1991) has employed the known Divisia index, which uses the prices of materials that could be substituted. This permits the estimation of price, output and technical change elasticities. Finally Ayres et. al. (1996) go as far as to weight by the useful work obtainable from materials. No conclusions have been drawn as to which method should be adopted. Relative price weights have always made sense in substitution, but physical units such as weight delineate actual material utilizations.

Aggregation brings us to the overall question as to whether dematerialization, rematerialization or service shifts really are occurring in the overall economy. Certainly, older, less useful materials such as lead and mercury are giving way to more exotic materials such as titanium, beryllium or platinum. Cleveland and Ruth (1999) in their survey of dematerialization studies conclude that little evidence exists to support the dematerialization hypothesis; however, they believe that the use of materials in an economy is becoming "lighter." De Bruyn and Opschoor (1997), in fact, suggest possible upturns in aggregate materials consumption with their suggestion to replace S- shaped with N-shaped curves. As we move from visual observations of the S-shaped curves based on simple data plots to more rigorous regression analysis such as cointegration, little scientific evidence exists to confirm dematerialization, at least for the major metals. While the visual inspections come with no statistical confidence levels, even the regression models that find the existence of an inverted U-function may be mis-specified or suffer from omitted variable bias. That is, they neglect explanatory variables, such as composition of production and consumption, international trade, and the density of economic activity (Kaufmann, et. al., 1998). It goes without saying that attempts to verify dematerialization are confounded by increases or decreases in the net imports of materials embodied in goods. This is particularly true given the globalization of national trade patterns. And to assess the shift to a service economy, what is needed is a full accounting of the direct and indirect use of materials in the supply of services.

The forecasting of IOU for different materials is more difficult than explaining it. Basic approaches to forecasting can be either univariate or multivariate. The univariate approach can embody either technological or economic forecasts. In the case of predicting dematerialization, one might employ nonlinear trends or logistic time series models. Transmaterialization forecasts might require state-space or cyclical models. Attention might also be paid as to whether the forecasts are intended to be more long term or short term. The former might depend on a long wave or trend approach, while the latter might examine deviations from trends. One has to decide whether any such deviations are temporary or reflect “rematerialization” or “rebound” effects.

Because of the many complexities influencing the behavior of IOU, forecasts might better be based on a bivariate or multivariate approach. Recall from above that the influencing or causal variables can include *economic factors* such as GDP, own prices and relative material prices, *technological factors* such as new production methods and efficiency upgrades, and *institutional factors* such as government regulations. Above some of these have been aggregated into a component reflecting changes in the mix of materials and a component featuring a change in the mix of goods produced. One example of a bivariate model is that of Sadler (2003) that combines exogenous industrial production with state-space variables to forecast steel consumption.

Multivariate models have the advantage of being able to integrate a number of specific influences. Possible models mentioned earlier are materials decomposition models that combine technological and economic submodels, divisia models that embody relative prices and capital adjustments, materials balance models that analyze throughput, dynamic models that capture technological and structural adjustments, or input-output models that include a wider range of influences in the domestic economy as well as international trade and exchange rates. Excepting the latter, most of the multivariate models are econometric and forecasting depends on the extrapolation of or external forecasts of the exogenous or influencing variables. Forecasts might thus be conditional, depending on systematic variations in the exogenous variables. Such a forecasting approach lends itself easily to the inclusion of risk analysis.

Conclusions

The concept of IOU depends on a simplistic index that measures how industrial economies have consumed materials over time. When the IOU variable is estimated over short periods of time for materials whose use is becoming obsolete, values of IOU will be found to be declining. However, IOU is a simple index and results obtained from measuring it appear to have little to do with explaining the decoupling of the US and other economies from the use of primary materials. The observed pattern of obsolescence occurs because different primary materials are no longer consumed in large quantities, basically because of technical and environmental reasons. Cycles of materials substitution such as those explained by transmaterialization are thus what we observe.

The explanation of such cycles is of extreme importance to industries that produce, process or trade bulk commodities. It is thus important to realize at what stage of its product life cycle important materials such as raw steel or engineered steel products might be. In fact we want to observe changes in the product life cycle of these materials and to forecast any changes in the cycles or their turning points. It is in this context that IOU plays an important role in forecasting future changes in materials production, consumption and trade.

Finally, one should be aware that limitations exist in the use of IOU to forecast those variables. Rapid growth of GNP, for example, can bias the value of IOU downwards. Given the narrowness of employing a univariate model for forecasting, a multivariate model might be preferable. Indeed if one is interested in forecasting materials production, consumption and exports, a multivariate model employing appropriate causal factors that explain those variables directly might be preferable to deriving values from IOU.

Note: This work provides an extensive updating of W.C. Labys, "Transmaterialization", in R.V. and L. W. Ayres, *Handbook of Industrial Ecology*, Cheltenham: Edward Elgar, 2001. Thanks are due to Armand Sadler and other participants of the International Industry Outlook Meeting (BAK and OEF) in Luxembourg (November 26-27, 2003) for their helpful comments.

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