In-use product stocks link manufactured capital to natural capital

Wei-Qiang Chen[1] **and T. E. Graedel**[1]

Center for Industrial Ecology, School of Forestry and Environmental Studies, Yale University, New Haven, CT 06511

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In-use stock of a product is the amount of the product in active use. In-use product stocks provide various functions or services on which we rely in our daily work and lives, and the concept of in-use product stock for industrial ecologists is similar to the concept of net manufactured capital stock for economists. This study estimates historical physical in-use stocks of 91 products and 9 product groups and uses monetary data on net capital stocks of 56 products to either approximate or compare with in-use stocks of the corresponding products in the United States. Findings include the following: (*i*) The development of new products and the buildup of their in-use stocks result in the increase in variety of in-use product stocks and of manufactured capital; (*ii*) substitution among products providing similar or identical functions reflects the improvement in quality of in-use product stocks and of manufactured capital; and (*iii*) the historical evolution of stocks of the 156 products or product groups in absolute, per capita, or per-household terms shows that stocks of most products have reached or are approaching an upper limit. Because the buildup, renewal, renovation, maintenance, and operation of in-use product stocks drive the anthropogenic cycles of materials that are used to produce products and that originate from natural capital, the determination of in-use product stocks together with modeling of anthropogenic material cycles provides an analytic perspective on the material linkage between manufactured capital and natural capital.

in-use stocks | manufactured capital | industrial ecology | sustainability

Wealth, as a stock concept, refers to the total value of economic resources at a given time and consists of both financial and nonfinancial wealth (1, 2). A nation's nonfinancial wealth is also characterized as manufactured (or produced) capital. It is traditionally measured by the "net capital stock" [which is termed "net stock" by the US Bureau of Economic Analysis (BEA)] of fixed assets owned by private business, nonprofit institutions, and government, plus the net stock of durable goods owned by consumers (3, 4). In the context of developing indictors for measuring sustainability, there have been efforts (5–8) in recent years to provide a more comprehensive measurement of wealth by taking into account stocks of additional forms of capital (e.g., natural and human capital). These efforts remind us that there are linkages between manufactured and natural capital [which is a stock that includes land, water, forests, minerals, solar energy, fossil fuels, living organisms, and the services provided by the interactions of all of these elements in ecological systems (5–9)]. From an industrial ecology perspective, one of these linkages is that the formation and operation of manufactured capital requires the transfer of physical materials from natural capital to manufactured capital, such as from iron ores to iron metal and then to components of automobiles. Currently existing approaches use monetary (rather than physical) metrics when measuring manufactured capital, and there is a lack of analytical methodology to explore the linkage between manufactured capital and natural capital in terms of physical materials transfer.

Thus, after providing a definition of "in-use stock," a concept that was developed in the field of industrial ecology, the present study seeks to demonstrate how long-term estimation of in-use stocks of manufactured products can complement existing monetary approaches to measuring manufactured capital and helps to explore the linkage between manufactured and natural capital in terms of physical materials transfer. In-use stock can be defined either for a tangible manufactured product (hereafter "product" unless otherwise noted) as the amount of the product in active use or for a material (such as iron or copper) as the amount of the material contained in in-use stocks of all products that use that material. In-use stocks of products are essential for sustaining our modern lifestyle because they provide various functions or services on which we rely in our daily work and lives (Fig. 1). Because products that have been identified as fixed assets or consumer durable goods by the BEA are basically the products for which industrial ecologists estimate in-use stocks (3, 10), the concept of net manufactured capital stock for economists is similar to the concept of in-use product stock for industrial ecologists. However, there are at least three differences between these two concepts: (*i*) Net stocks are measured in monetary units, whereas in-use stocks are mostly measured in physical units (e.g., number of computers, kilograms of iron); (*ii*) only stocks of products are quantified when estimating net stocks, whereas both stocks of products and materials contained in products can be quantified when estimating in-use stocks; and (*iii*) the stocks of some intangible products such as software are included in the determination of net stocks but are excluded in the determination of in-use stocks (10).

The determination of net stocks has been carried out by governmental organizations in the United States since the 1950s (3, 11). Extensive determinations of in-use stocks have only appeared in the last two decades (12–16), and, unfortunately, almost all in-use stock studies focus on materials rather than products. We argue that the determination of in-use stocks and relevant flows of products has its own special importance. (*i*) The

Significance

The determination of long-term in-use stocks of manufactured products can complement existing monetary approaches to measuring manufactured capital and helps to explore the linkage between manufactured capital and natural capital in terms of materials transfer. The development of new products, substitution among products, and the historical evolution of in-use product stocks in the United States reveal the increase in variety, improvement in quality, and growth in quantity of US manufactured capital. Because products are produced from materials, and products developed more recently tend to use a greater diversity of materials, this study also reveals that US modern manufactured capital relies on the use of more diverse materials and on the increasing use of materials that originate from natural capital.

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[1] To whom correspondence may be addressed. Email: weiqiang.chen@yale.edu or thomas.graedel@yale.edu.

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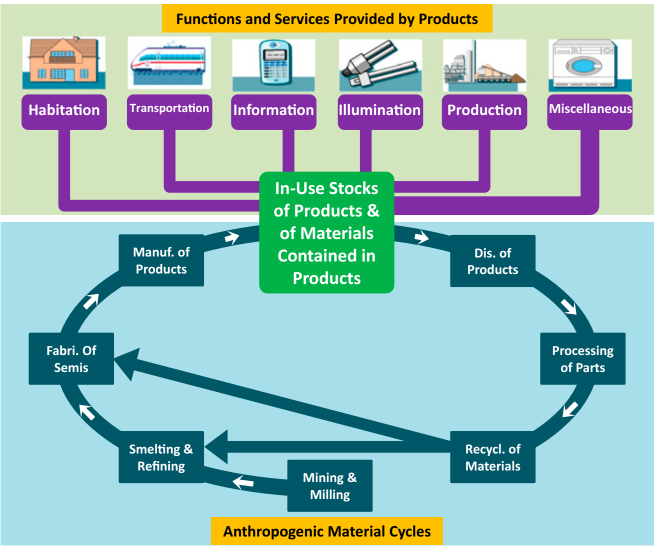

Fig. 1. In-use product stocks drive anthropogenic material cycles and provide functions or services demanded by modern human society. Fabri, fabrication; Manuf, manufacturing; Dis, discard, disposal, and dismantling; Recyl, recycling.

functions or services demanded by human society are directly provided by products rather than materials contained in products. (*ii*) In-use stocks of products, especially from the per capita (PC) or per household (PHH) perspective, can serve as measures of functions or services demanded by human society. (*iii*) It is the demand for functions or services that drives the demand for the existence and operation of in-use stocks of products; this second demand drives the subsequent demand for building up, renewing, renovating, and maintaining in-use stocks of products (17); and this final demand drives the anthropogenic cycles of both products and materials contained in products (Fig. 1). In this sense, in-use stocks of products play the role of driving anthropogenic material cycles (16) and linking these cycles with manufactured capital, as well as functions and services demanded by modern society (15). (*iv*) When integrated with price information, in-use stocks of products can be used to estimate or to be compared with net stocks of products. And (*v*) when integrated with information on material compositions of products, in-use stocks and relevant flows of products can be used to estimate in-use stocks and flows of materials.

In this study, we characterize and quantify long-term in-use stocks of products (*Materials and Methods* and *SI Appendix*, Tables S1–S3). A product was so defined because its stocks and flows data could not be further decomposed. For example, all mobile phones were grouped into a product because we could only estimate in-use stock for them as a whole, although it could be more helpful if they were divided into more specific products such as smart and nonsmart cell phones. In some cases, products providing similar or identical service(s) were aggregated into a "product group" for convenience in showing results or comparing in-use stocks with net stocks. For example, five kinds of televisions (TVs) were aggregated into the TV group. The available data enabled us to estimate in-use stocks for 91 products (*SI Appendix*, Table S1) in the United States. Some of them were aggregated into nine product groups (*SI Appendix*, Table S2). We also collected data on net stocks of 56 products (*SI Appendix*, Table S3) (3, 10) from the BEA and used them either for approximating the corresponding in-use stocks when data for the latter were unavailable or for a comparison with corresponding in-use stocks data for 13 products or product groups (*SI Appendix*, Table S4) of which the latter are available. Our initial analysis refers to absolute stocks (i.e., overall total US stocks). To explore stock issues further, both in-use stocks and net stocks in absolute terms at the US national level were divided by the US population (by the number of adults in the case of "road vehicles") and/or household numbers to get PC and/or PHH in-use and net stocks, respectively. Patterns and reasons for patterns of the historical evolution of product stocks in different terms were then explored.

Results

For our entire dataset, the historical evolution of in-use stock and/or net stock for each product or product group, in absolute, PC, and/or PHH terms, is illustrated in *SI Appendix*, Figs. S3–S40. Those that we regard as most important and/or most typical are shown in Fig. 2. The evolution of stocks in different terms may differ from each other in features (e.g., increase, decrease, or stable) and increase/decrease rates (*SI Appendix*, *Section 4*) because the US population and household numbers have been increasing and the household size has been shrinking (*SI Appendix*, Figs. S1 and S2). Stocks of each product, in whatever terms, increase for a given period after the product is introduced into the market. For some products, such as passenger cars, personal computers, and coal electricity generation capacity (Fig. 2 *B*, *F*, and *K*), an accelerating period succeeds the beginning period during which the stocks were increasing relatively less quickly (a similar analysis cannot be carried out for all products, however, because data for a small number of product stocks do not extend backward to the year in which the products were introduced into the market).

In-use and/or net stocks of most products, especially in PC or PHH terms, do not always currently or continually increase. Rather, after the early growth period(s) their evolution over time follows one of four different patterns:

i) PC and/or PHH stocks (and therefore also absolute stocks) for a small number of products are continuing to increase (we term this "pattern I"). This pattern generally occurs in three situations: (*i*) for products recently developed and introduced into markets to provide new services or functions (e.g., personal computers and mobile phones; Fig. 2*F*); (*ii*) for products developed to replace products providing similar services or functions (details discussed later); and (*iii*) for products providing services or functions for which demand is still increasing (e.g., medical instruments and books; Fig. 2*I*).

ii) Absolute stocks (and therefore PC and/or PHH stocks) for some products have disappeared, decreased, or are currently decreasing (we term this "pattern II"). This pattern generally occurs in four situations: (*i*) for products providing services or functions no longer needed by modern society (e.g., tape drives; Fig. 2*H*); (*ii*) for products replaced by later products that provide similar services or functions (details discussed later); (*iii*) for some products or product groups, such as home appliances as a whole (*SI Appendix*, Fig. S50), PHH in-use stocks have been increasing after 1980, but PHH net stocks are decreasing due to the decrease in average prices; and (*iv*) for almost all machinery, net stocks decreased from approximately 1980 to approximately 1995, probably because the United States transferred part of its industrial production capacities to other regions in this period (Fig. 2*D*).

iii) Saturation of stocks occurs for a majority of products or product groups, either in absolute, PC, or PHH terms (we term this "pattern III"). This pattern includes: (*i*) products whose stocks have been relatively stable for years or even decades [e.g., PHH floorspace of residential buildings (Fig. 2*C*), PC ownership of TVs (Fig. 2*G*), and absolute in-use stock of aluminum cans (Fig. 2*J*)]; (*ii*) products whose stocks basically remain stable but with fluctuations within a narrow range [e.g., PHH in-use stocks of ranges (Fig. 2*E*), PC stock of desktop computers (Fig. 2*F*)]; (*iii*) products whose stocks remained stable for varying periods some years or decades

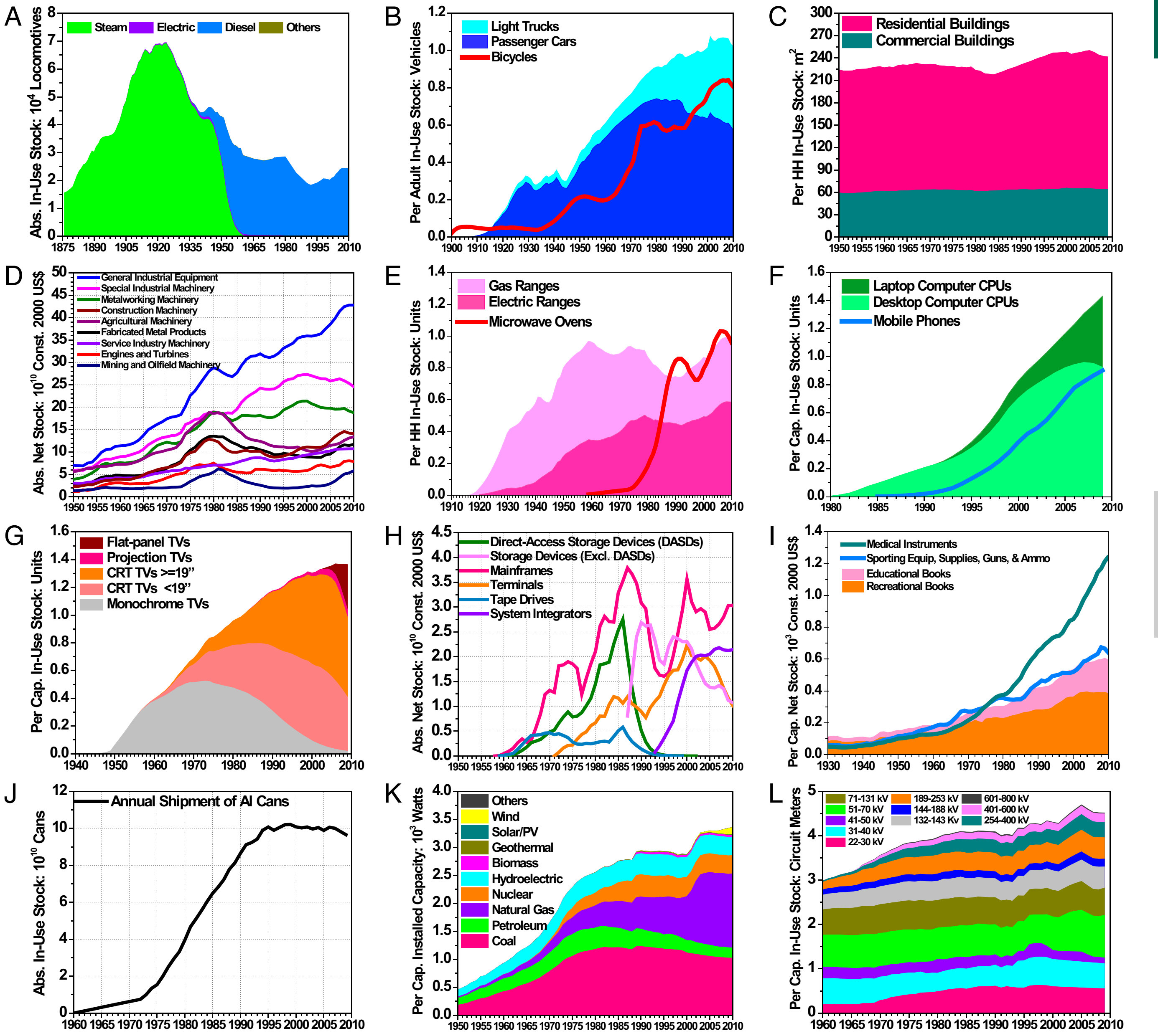

Fig. 2. Examples of absolute (abs.), PC (per cap.), per adult, or PHH (per HH) in-use or net capital stocks (in constant 2000 US$) of products in the United States: locomotives (*A*); road vehicles (*B*); buildings (*C*); machinery (*D*); ranges and ovens (*E*); computer CPUs and mobile phones (*F*); TVs (*G*); storage devices (*H*); books (*I*); aluminum cans (*J*); electricity generation capacities (*K*); and electricity transmission lines (*L*). More figures and data sources are available in *SI Appendix*.

ago, but increased after that and then again became stable at a higher stock level [e.g., per adult in-use stock of passenger cars and bicycles (Fig. 2*B*), PC electricity generation capacity from natural gas (Fig. 2*K*)]; and (*iv*) for almost all machinery, net stocks after 1995 remain basically stable, probably because the United States retained a relatively stable industrial production capacity (Fig. 2*D*).

iv) Stocks of a very few products experience fluctuations with a large range (we term this “pattern IV”), such as net stock of mainframes (Fig. 2*H*) and in-use stock of motorcycles (*SI Appendix*, Fig. S4).

We find that substitution occurs for nine product groups in which different products provide the same or similar services or functions (*SI Appendix*, Table S2). For seven of these product groups [except locomotives (Fig. 2*A*) and personal computer central processing units (CPUs) (Fig. 2*F*)], total in-use stocks, either in PC or PHH terms, have been stable for years or decades. However, in-use stocks of products within each product group show varying features: in-use stocks of older products are decreasing (situation *ii* of pattern II) or in a few cases remaining stable, whereas those of newer products are increasing (situation *ii* of pattern I). For example, total per adult in-use stocks of passenger cars and light trucks are relatively stable after 2000, but light trucks are substituting for passenger cars (Fig. 2*B*). Similar phenomena can be observed for other product groups (Fig. 2 *E*, *G*, *K*, and *L*, and *SI Appendix*, Figs. S28C and S31*B*).

A summary of the number of products or product groups following different patterns of historical stock evolution is shown in Table 1. More than 50% of these data series follow pattern III, and patterns I and II each account for ∼20%. Because almost all products or product groups following pattern I can be fitted by an S-curve (see below), and we expect that saturation may also take place for them in the near future; therefore, stocks of most studied products or product groups have reached or are approaching an upper limit.

Comparisons between in-use stocks and net stocks for the 13 products or product groups (*SI Appendix*, Table S4) for which we have data are conducted in two ways. In the first approach, both in-use and net stocks of each product or product group are displayed together (*SI Appendix*, Figs. S41–S52, *Left*). This comparison demonstrates that the two types of stocks share very similar historical evolution for most products or product groups except for residential buildings, home appliances, and personal computers. In the second approach, the net stock to in-use stock ratios were calculated (*SI Appendix*, Figs. S41–S52, *Right*), and their historical evolution was found to resemble that of market prices for the above three product groups (*SI Appendix*, Table S9). For home appliances and personal computers, the dissimilarities between net stock and in-use stock evolution result from continuous price decreases due to technology development. The consistencies observed from comparisons in these two methods verify the reliability and robustness of our estimation of in-use stocks.

By drawing the historical evolution of in-use stocks of products on the same time scale (Fig. 3), we observe the several waves of stocks that occur in different time periods. These waves mean that different products and the functions or services they provide are developed or introduced into markets at different times, such as passenger cars at the beginning of the 1900s, refrigerators in the 1920s, TVs in the 1940s, microwave ovens in the 1960s, desktop computers in the 1980s, and laptop computers in the 1990s. The development of transportation infrastructures is shown in Fig. 3*A*. The canal length peaked in ∼1860 and then declined over the next two to three decades as railways and roads provided more efficient alternatives. Railway length peaked in ∼1920 and declined over the next several decades, simultaneous to the development of highway and air transportation. The length of oil pipelines peaked in ∼1970 and then decreased as well. The number of airports, the length of paved roads, and the length of gas pipelines grew simultaneously and are approaching their respective peak levels. Waves of the development of transportation facilities as shown in Fig. 3*B* accurately reproduced and thus verified those of transportation infrastructures.

Home appliance development is shown in Fig. 3*C*. A diversity of patterns is seen, but in nearly every case there is an approach to saturation, with the peak level for some products (ranges, microwave ovens, and refrigerators) at one unit PHH. The implication is that households gradually added these appliances as they became available, but unlike the canals to road and rail transition, appliance substitution has not been a significant factor in stock development in most cases (the exception being electric ranges and dryers substituting for their gas equivalents). Electronic devices entered service only in the middle of the 20th century but already show definite wave patterns in their stocks (Fig. 3*D*). The two obvious examples are monochrome TVs to cathode-ray tube (CRT) TVs to flat-panel TVs, and desktop computers to portable computers. Note that it took a much shorter time for computers, flat-panel TVs, and mobile phones to reach the saturation level compared with monochrome TVs, CRT TVs, and home appliances such as ranges and refrigerators.

Table 1. Number of studied products or product groups with different stock historical evolution patterns in the United States

	Patterns of stocks evolution				
Data series	I	II	III	IV	Sum
In-use stocks of products*	18	20	49	4	91
In-use stocks of product groups†	1	1	7	0	9
Net stocks of products‡	13	12	27	4	56
All data series together§	32	33	83	8	156

*Refer to *SI Appendix*, Tables S1 and S6.

†Refer to *SI Appendix*, Tables S2 and S7.

‡Refer to *SI Appendix*, Tables S3 and S8.

§Sum of the above three rows.

Discussion

In the field of technology analysis, a life-cycle model usually classifies the development of a technology into three (or sometimes four) phases: childhood (or introduction), adolescence (or growth), and maturity (or saturation), sometimes followed by senescence and ultimate death (18). For convenience in quantitative analysis, a technology's life cycle is indicated by any of various indicators such as output volumes, market share, product characteristics, or performance (18). The logistic model, which is fully specified by three parameters and has an S-shape, is often used to quantitatively model typical temporal patterns of technology development over time (18, 19). It shows slow growth in childhood, followed by accelerating and then decelerating growth in adolescence, and saturation in maturity. A widely accepted explanation for the logistic model is that every anthropogenic system has a carrying capacity that is limited; therefore, the growth rate of a technology inside the system begins exponentially but decreases to zero as the development of the technology approaches the system's carrying capacity (19, 20).

The fitting analysis we have performed shows that the three-parameter logistic model (*SI Appendix*, *Section 7*) effectively simulates the temporal evolution of in-use stocks for 80 products and 9 product groups and of net stocks for 50 products (excluding the "senescence and death" phase for products following pattern II), either in absolute, PC, or PHH terms, as appropriate (*SI Appendix*, Tables S6–S8). For seven of the nine product groups listed in *SI Appendix*, Table S7, the saturation of in-use stocks of all products and the substitution among products inside each group coexists. Therefore, the logistic model is more suitable for simulating the total stock of all products within a group than for the stock of individual products. The logistic model fails to simulate historical evolution for in-use stocks of only 11 products and net stock of only 6 products, and these are mainly in two cases: (*i*) for products of which the time length of the stock data is too short to cover the whole adolescence or to reach back to the childhood of the technology life cycle, such as the net stock of railroad equipment (*SI Appendix*, Fig. 5*D*); and (*ii*) for products of which the stock historical evolution follows pattern IV, such as motorcycles. The good applicability of the logistic model in simulating stock data means that the temporal evolution of stocks of most products or product groups identified in this study can be explained by the three-phase technology life-cycle model and that stocks of most products or product groups have become or will become saturated in the United States.

Unlike some former studies that use flow indicators such as output volumes (18) or quasi-stock indicators such as cumulative production (21), one of the characteristics of this study is that only stock indicators are used for the logistic curve fitting. We note that in the field of population biology/ecology from which the logistic model was originally developed (22), all data were actually based on stock indictors (e.g., population of humans, animals, or bacteria) rather than flow indicators (e.g., growth or birth of population). Using stock indicators for the present study provides several advantages. (*i*) It helps to explain where the carrying capacity exists and how it can be quantitatively estimated. For example, our results show that the saturation level of both ranges and microwave ovens is about one unit PHH, whereas the saturation level of the total of passenger cars and light trucks is about one vehicle per adult (18 y and older).

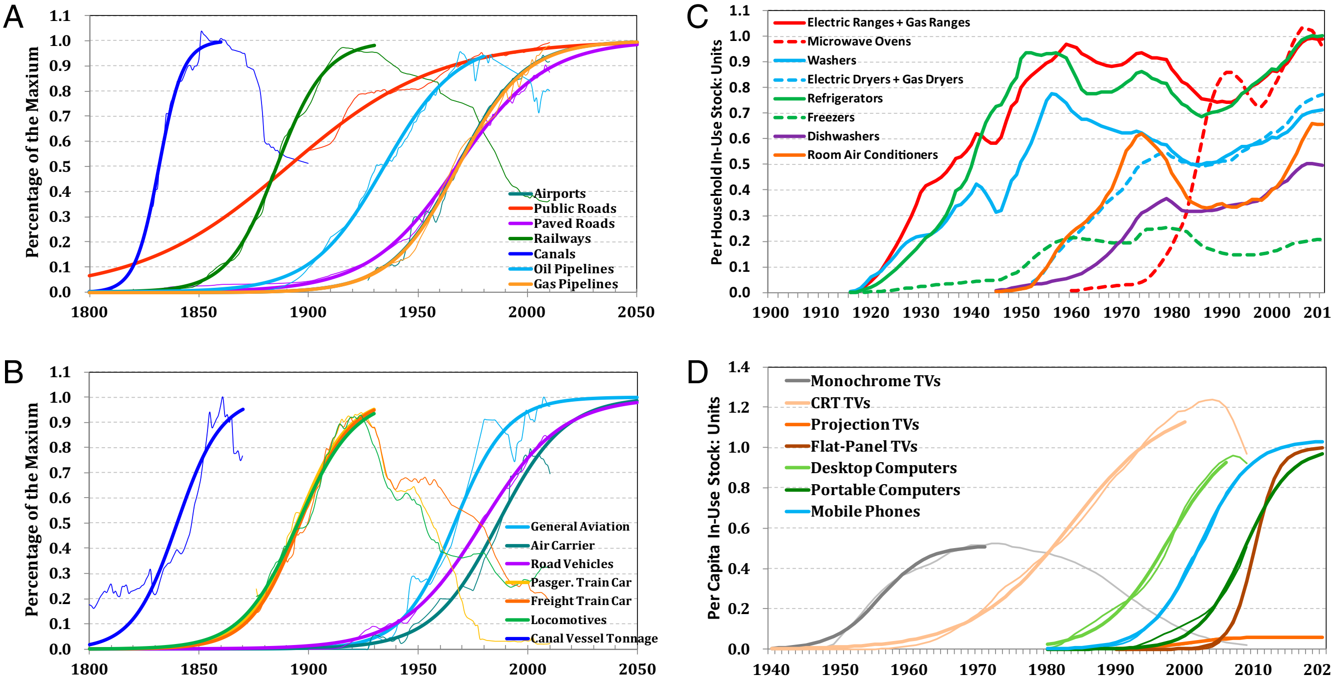

Fig. 3. Waves of the historical evolution of in-use stocks for transportation infrastructures (*A*), transportation facilities (*B*), home appliances (*C*), and electronic products (*D*) in the United States. The thin lines in *A*, *B*, and *D*, as well as all lines in *C* show the empirical data; the bold, smooth lines in *A*, *B*, and *D* show results of the S-curve fitting.

(*ii*) There is potential for using data compiled by this study and the three-parameter logistic model to approximate product stocks in geographical regions for which historical development patterns or current GDP levels are similar to those of the United States or to develop future scenarios of the evolution of product stocks in the developing world by using the level of product stocks in the developed world as a benchmark (17, 23).

Fig. 3 calls to mind the Kondratieff waves, the 1920s observation that the world's industrial nations have undergone ∼50-y cycles of economic growth and decline over the past two centuries (24), with each wave correlated with a rapidly evolving technological innovation (25). The legitimacy and significance of the Kondratieff waves have been the subjects of vigorous academic debate for decades (26, 27), but an important finding of the well-known "growth of US transport infrastructures" diagram (28, 29) is that economic long waves are reflections of in-use stocks of some products. Fig. 3*A* is essentially a 30-y extension of that work, showing that by 2010, railway track distance, paved road length, and number of airports have reached or are approaching the peak. Fig. 3*C* extends the concept to household appliances, a level of specificity not before attempted in long-wave analysis. Fig. 3*D* does the same for electronic products, which could be regarded as emblematic of a fifth Kondratieff wave of telecommunications and information technology, extending over half a century from a starting point around 1980 or 1990 (26, 27, 30). (Note, however, that our analysis is for the United States only, whereas the classical Kondratieff analysis is for many industrial nations combined.)

The approach and data demonstrated in this study permit us to estimate the historical evolution of three indicators: (*i*) the number of products or product groups in use in a particular epoch; (*ii*) the improvement and substitution of products by newer and better products; and (*iii*) the in-use stock of each product or product group of interest. For example, if we choose an example list of products in three sectors (Table 2) and determine their product stocks, the following information can be uncovered: (*i*) The variety of US in-use product stocks and thus of manufactured capital in these sectors increased from 1900 (only 2 products) to 1950 (9 products) and then to 2000 (14 products) due to the invention of new products; (*ii*) the quality of many types of manufactured capital has been improved due to substitution among products that provide similar or identical functions, such as the different types of TVs; and (*iii*) the quantity of many types of manufactured capital, as indicated by product stocks, increased for a period but then largely became saturated. This information demonstrates that our approach enhances perspectives of manufactured capital that are not fully captured in existing monetary metrics for measuring wealth, and thus complement those approaches.

If integrated with information on the material compositions of products, in-use product stocks can be used to estimate in-use material stocks. This approach, together with methods for

Table 2. A non-exhaustive example list of products in three sectors showing the variety increase and quality improvement of in-use product stocks and thus of manufactured capital in the United States

Year	Transportation facilities	Home appliances	Electronic products
1900s	Bicycles Train cars	—	—
1950s	Bicycles Train cars Passenger cars Light trucks Air carriers	Ranges Refrigerators Washers	Monochrome TVs
2000s	Bicycles Train car Passenger cars Light trucks Air carriers	Ranges Microwave ovens Refrigerators Washers	Cathode-ray tube TVs Flat-panel TVs Desktop computers Laptop computers Mobile phones

modeling anthropogenic material cycles (13, 31), helps to explore how materials are transferred from natural capital to manufactured capital and demonstrates how US manufactured capital relies on the use of materials that originate from natural capital (32). By exploring metals typically used by the products listed in Table 2, our data (details in *SI Appendix*, Table S10) demonstrate the following phenomena. (*i*) Increasing types and numbers of materials have been used in new products developed in different periods, such as the Al, Mg, Ti, and Be used in aircraft after the 1920s and the >36 metals used in computers after the 1980s (33). (*ii*) The improvement or substitution of products can also result in the use of more types of materials or the use of different materials in the same product—e.g., the demand for safer and more comfortable airplanes resulted in the transition from wood-and-fabric airplanes to all-metal airplanes before World War II (34), and passenger cars started to use platinum group metals in catalytic converters in the 1970s (18). (*iii*) The growth of in-use product stocks results in the growth of in-use metal stocks, and therefore also for metal flows, although for metals such as iron and aluminum, the saturation of product stocks may result in the saturation of metal stocks (13, 16).These phenomena reveal that manufactured capital in the United States has increasingly relied on the use of more and more types of materials and on the growing magnitude of use of most of them.

The final point to make concerning in-use product stocks is that their analysis is more than just an interesting complementary approach to the measurement of manufactured capital. The formation and operation of manufactured capital almost always requires the transfer of mineral and material resource components of natural capital, a linkage that has not been quantitatively assessed heretofore. The realization that in-use products are repositories of materials, however, provides that link. If the materials palette of a product is known, its connection to natural capital becomes quantifiable. If all in-use products are similarly evaluated, the transfer of capital from natural to manufactured capital becomes comprehensive, supplementing an economic assessment with one that evaluates the full panoply of the associated natural resources. We thus view the dynamic quantification of in-use product stocks as opening a previously unidentified window into the estimation of capital.

Materials and Methods

Products and product groups involved in this study were classified into 10 sectors (*SI Appendix*, Tables S1-S3): (*i*) transportation infrastructures; (*ii*) transportation facilities; (*iii*) buildings and structures; (*iv*) machinery and equipment; (*v*) consumer durables [different from those in the BEA's definition on consumer durables because we excluded transportation facilities and some other products (3, 10)]; (*vi*) electronic products; (*vii*) containers; (*viii*) oil and gas pipelines; (*ix*) electricity generation technologies; and (*x*) electricity transmission and distribution. These products provide most of the functions or services that are demanded by modern society. However, all possible products could not be listed or analyzed, nor is each product or sector analyzed comprehensively. For example, we have data on aluminum containers but not for iron or plastic containers, and we analyze all mobile phones as a whole but do not have data for smart cell phones. These gaps provide the potential for further studies in this field should suitable data become available.

Physical in-use stocks of products were quantified for as long a time period as possible by two methods: (*i*) using available stock data; and (*ii*) the top-down method (*SI Appendix*, *Section 1* and Table S1). The unit for measuring in-use stock is appropriate for each product, but is not necessarily consistent among products. For example, the unit for in-use railway stocks is meters, whereas the unit for in-use building stocks is square meters. BEA's monetary data on net stocks of products (current-cost valuation) for the period 1925–2011 or 1947–2011 were collected to either approximate or be compared with in-use stocks of the corresponding products or product groups (3, 10). These data were originally measured in current US$ and they were transformed into constant 2000 US$ to exclude the impacts of inflation (*SI Appendix*, Table S3).

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