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A Simple Substitution Model of Technological Change*

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Introduction

For people who attempt to forecast the future, there is a continuing need for simple models that describe the course of unfolding events. Each such model should be based upon easily understood assumptions that are not available for unconscious or invisible tampering by the forecaster in his efforts to make the future what he wants it to be. The model should be easy to apply to a wide variety of circumstances, and should be easy to interpret. It is our purpose to describe such a model and, by way of example, to apply it to a few illustrative forecasts.

If one admits that man has few broad basic needs to be satisfied—food, clothing, shelter, transportation, communication, education, and the like—then it follows that technological evolution consists mainly of substituting a new form of satisfaction for the old one. Thus, as technology advances, we may successively substitute coal for wood, hydrocarbons for coal, and nuclear fuel for fossil fuel in the production of energy. In war we may substitute guns for bows and arrows, or tanks for horses. Even in a much more narrow and confined framework, substitutions are constantly encountered. For example, we substitute water-based paints for oil-based paints, detergents for soap, and plastic floors for wood floors in houses.

The view of advancing technology as a set of substitution processes may seem evolutionary or revolutionary, depending upon the time scale of the substitution. Regardless of the pace of the change, however, the end result to the user is almost always to allow him to perform an existing function or satisfy an ongoing need differently from before. The function or need rarely undergoes radical change. Whenever exceptions to this view are found, the notion of competitive substitution as a model for technological change does not apply.

The Model

The model is based on three assumptions: (1) Many technological advances can be considered as competitive substitutions of one method of satisfying a need for another. (2) If a substitution has progressed as far as a few percent, it will proceed to completion. (3) The fractional rate of fractional substitution of new for old is proportional to the remaining amount of the old left to be substituted.[1]

When a new method is first introduced, it is less well developed than the older method

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[1] A special form of Pearl's law; cf. Raymond Pearl, *The Biology of Population Growth* (New York: Alfred A. Knopf, 1925).

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with which it is competing. It therefore is likely to have greater potential for improvement and for reduction in cost. Our second assumption is based upon the idea that any substitution that has gained a few percent of the available market has shown economic viability, even without the improvement and cost reduction that will come with increased volume, and hence that the substitution will proceed to 100 percent.

Experience shows that substitutions tend to proceed exponentially (i.e., with a constant percentage annual growth increment) in the early years, and to follow an S-shaped curve. The simplest such curve is characterized by two constants: the early growth rate and the time at which the substitution is half complete. The corresponding fraction substituted is given by the relationship

$$f=(1/2)\ [1+\tanh \alpha(t-t_0)] \tag{1}$$

where α is half the annual fractional growth in the early years and where t_0 is the time at which $f=1/2$. This equation can be derived from our third assumption, which in mathematical form is

$$(1/f)\ df/dt=2\ \alpha(1-f). \tag{2}$$

Before proceeding with some examples of the application of the model, a few useful characteristics of the S-shaped expression $f=(1/2)\ [1+\tanh \alpha(t-t_0)]$ will be developed. First, recall that $f=1/2$ when $t=t_0$. Thus t_0 signifies the point in time when the substitution is half complete. It will be convenient, in addition, to characterize a substitution by

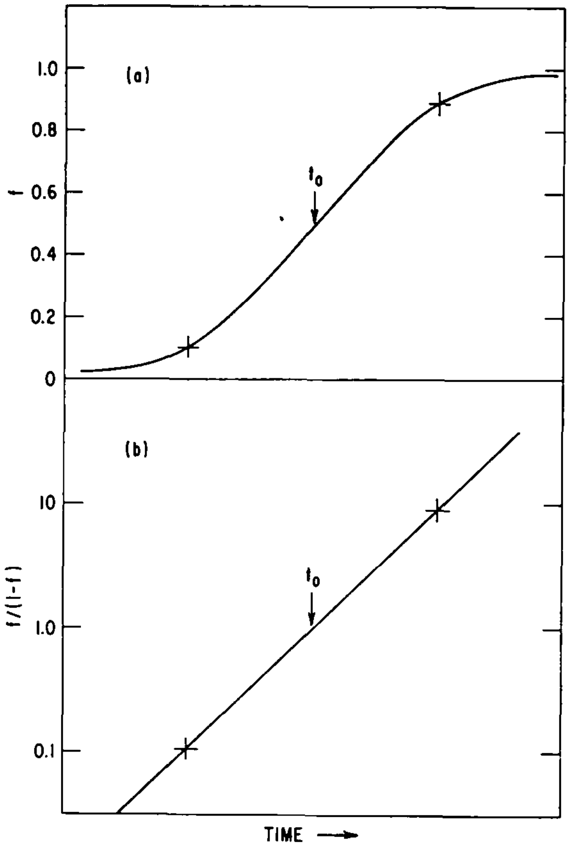


Fig. 1. General form of the substitution model function.

its "takeover time" defined as the time required to go from $f=0.1$ to $f=0.9$. This time is inversely proportional to α,

$$t=t_{0.9}-t_{0.1}=2.2/\alpha. \tag{3}$$

A more convenient form of the above substitution expression (1) is

$$f/(1-f)=\exp 2\,\alpha\,(t-t_0). \tag{4}$$

This expression allows one to plot the substitution data in the form of $f/(1-f)$ as a function of time on semilog paper and fit a straight line through the resulting points, as illustrated in Fig. 1. The slope of the line is 2α, the time t_0 is found at $f/(1-f)=1$, and the takeover time is easily measured as the time between $f/(1-f)=0.11$ and $f/(1-f)=9$. The resulting curve can then be replotted on linear graph paper for display.

It will be readily recognized that the model contains at least one obvious flaw: all substitutions in reality start at a specific point in time, whereas the model predicts that all substitutions began in the infinite past. In practical circumstances, this is of little consequence, however, since the model, by our first assumption, is not to be applied to substitutions prior to their achieving a magnitude of a few percent, at which time a definite growth pattern is established and the very early history has little effect upon the trend extrapolation.

Applications

Synthetic vs. Natural Fibers

Table I shows the history of the U.S. consumption of natural and man-made or

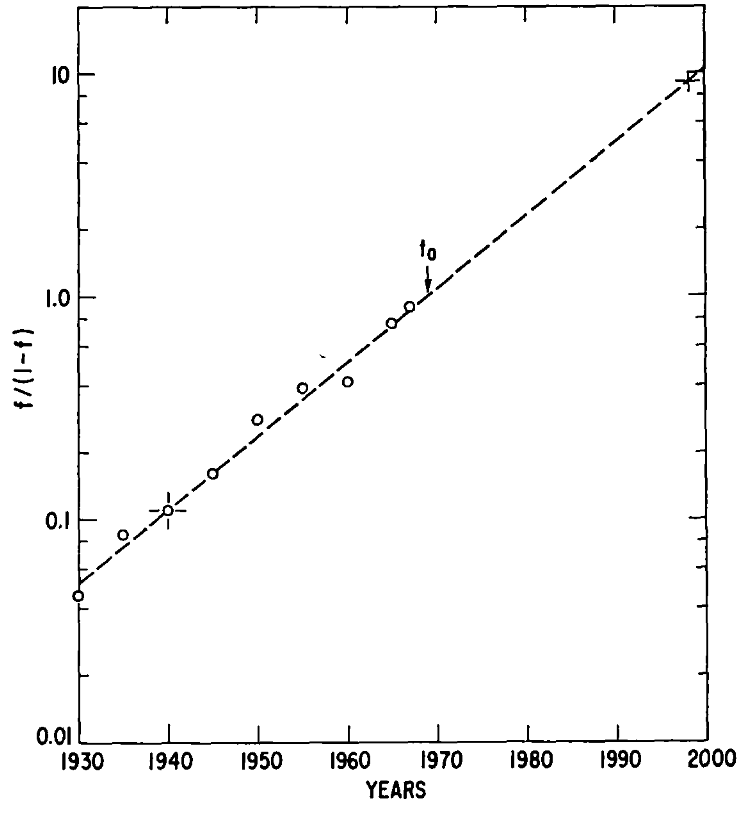


Fig. 2. Synthetic for natural fiber substitution vs. years—substitution model fit to data.

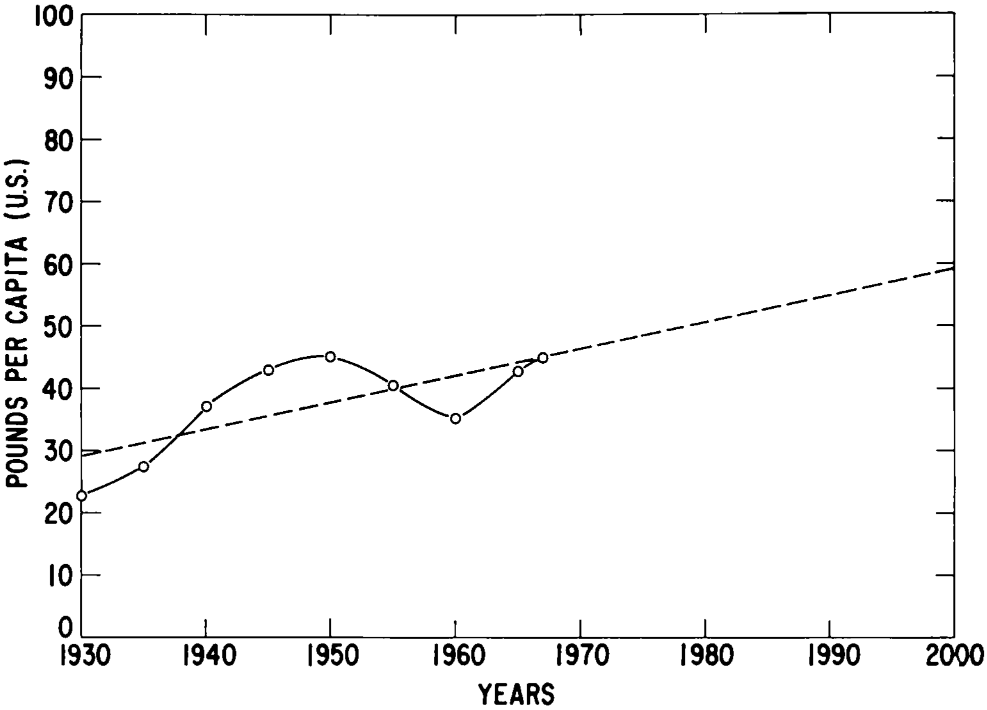


Fig. 3. Total per capita U.S. fiber consumption vs. years—data and straight-line projection.

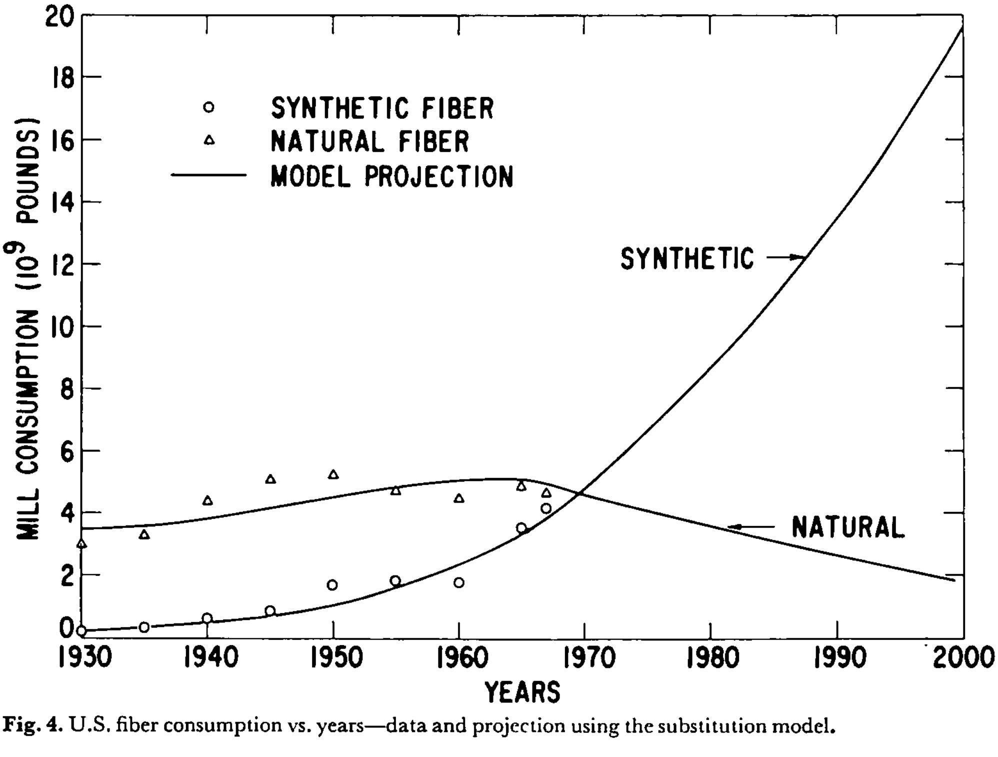


Fig. 4. U.S. fiber consumption vs. years—data and projection using the substitution model.

Table I

Mill Consumption of Natural and Synthetic Fibers

	Synthetics		Cotton		Other Natural			
Year	$\times 10^9$ lbs.	lbs. per capita	$\times 10^9$ lbs.	lbs. per capita	$\times 10^9$ lbs.	lbs. per capita	Total per capita	Fraction Synthetic
1930	0.12	1.0	2.62	21.3	0.36	2.88	22.66	0.044
1935	0.27	2.2	2.76	21.7	0.50	3.97	27.87	0.079
1940	0.50	3.7	3.96	30.0	0.47	3.55	37.25	0.10
1945	0.85	6.1	4.52	32.3	0.65	4.66	43.06	0.14
1950	1.82	10.1	4.68	30.0	0.66	4.34	45.34	0.22
1955	1.90	11.5	4.38	26.5	0.433	2.62	40.62	0.28
1960	1.89	10.4	4.19	23.2	0.423	2.37	35.97	0.29
1965	3.62	18.6	4.47	23.0	0.40	2.07	43.67	0.43
1967	4.24	21.3	4.42	22.2	0.32	1.65	45.15	0.47

synthetic fibers since 1930. Wool, silk, and flax have been lumped together under "all others." The fraction f of synthetic to total fiber is listed in this table. The function $f/(1-f)$ vs. time has been plotted in Fig. 2. This indicates a half substitution date of 1969 and a takeover time of fifty-eight years, from an $f=0.1$ in 1940 to $f=0.9$ in 1998. If one wishes so use this projection to forecast the total use of synthetics or natural fibers, two additional pieces of information are required: projections of population growth and of per capita fiber consumption in the United States. Per capita consumption is listed in Table I and shown in Fig. 3, including a linear trend projection into the future. Combining these curves with the Bureau of the Census population projection [1], assuming 1962–1966 fertility levels, a forecast of synthetic and all natural fibers for the United States through the year 2000 is obtained and shown in Fig. 4. This forecast suggests a substantial increase in consumption of synthetics and a decline in the consumption of natural fiber. The degree of concern this should cause the natural fiber producers depends upon one's confidence in the forecast.

Plastic vs. Leather

A similar example is the substitution of plastic for leather. Everyday experience suggests that plastic materials have been substituting for leather in the United States. The per capita consumption of leather has undergone a steady decline since about 1930, but we were not able to find data on the consumption of plastic leather-substitutes. However, assuming a constant per capita consumption of the combined materials over the past few decades, it is possible to deduce the fraction of plastic for any given year. Figure 5 shows the substitution curve generated in this way. If the curve in Fig. 5 is projected ahead, assuming a constant per capita consumption of combined leather and plastic substitutes, and using the same population projection as in the former fiber example, one obtains the curve of Fig. 6. This shows the forecast total of tanned animal hides to be sold in the United States as a function of time. Again, if one believes the model, a rapid and continuing reduction in the sale of leather products will take place. As illustrated in these two examples, the proposed substitution analysis model can be used not only to forecast expanding opportunities, but to point to areas where additional attention may be needed to adjust to potential adverse changes.

Some of the principal advantages of this substitution analysis can now be seen. First, the analysis is simple to perform and not open to much subjective judgment by the

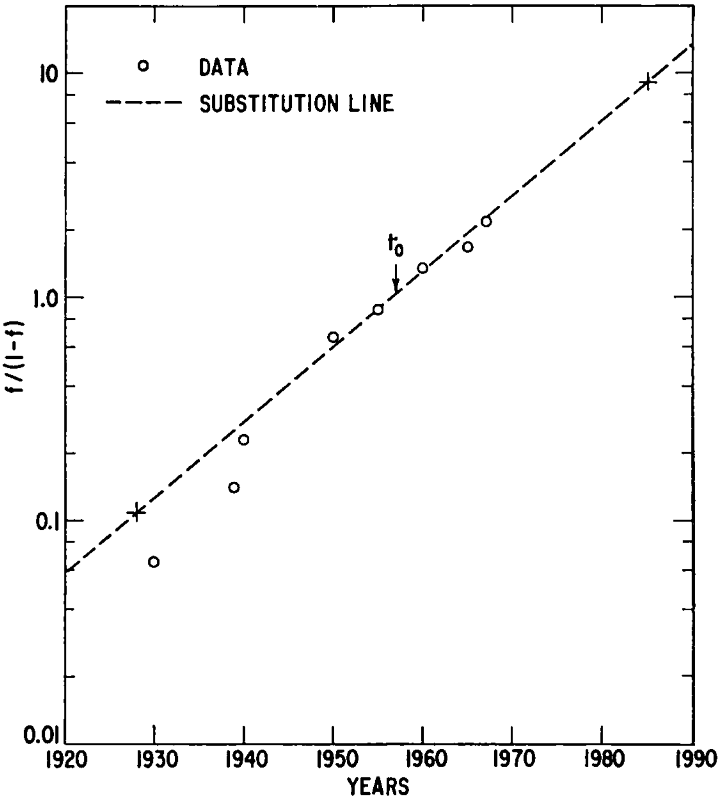


Fig. 5. Synthetic for natural leather substitution vs. years—substitution model fit to data.

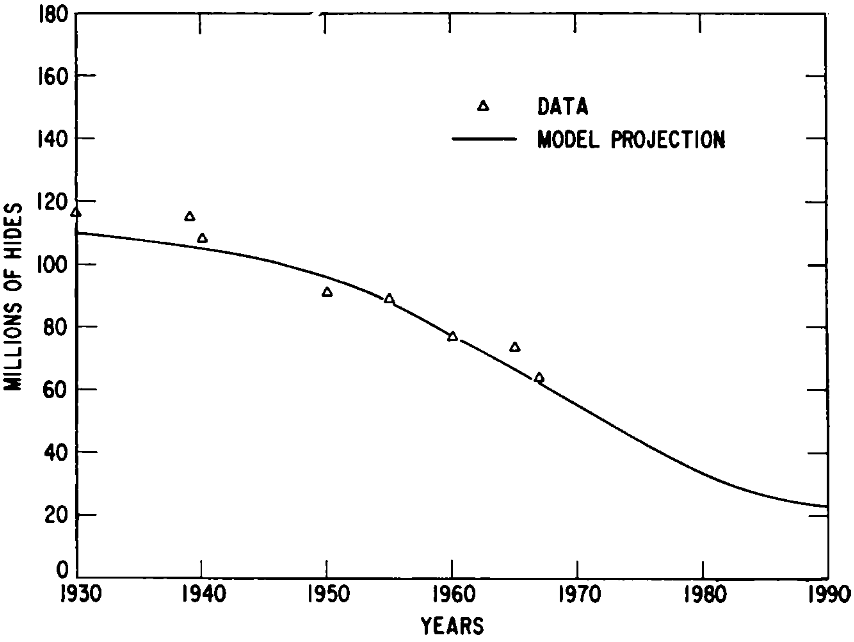


Fig. 6. U.S. consumption of tanned animal hides vs. years—data and substitution model projection.

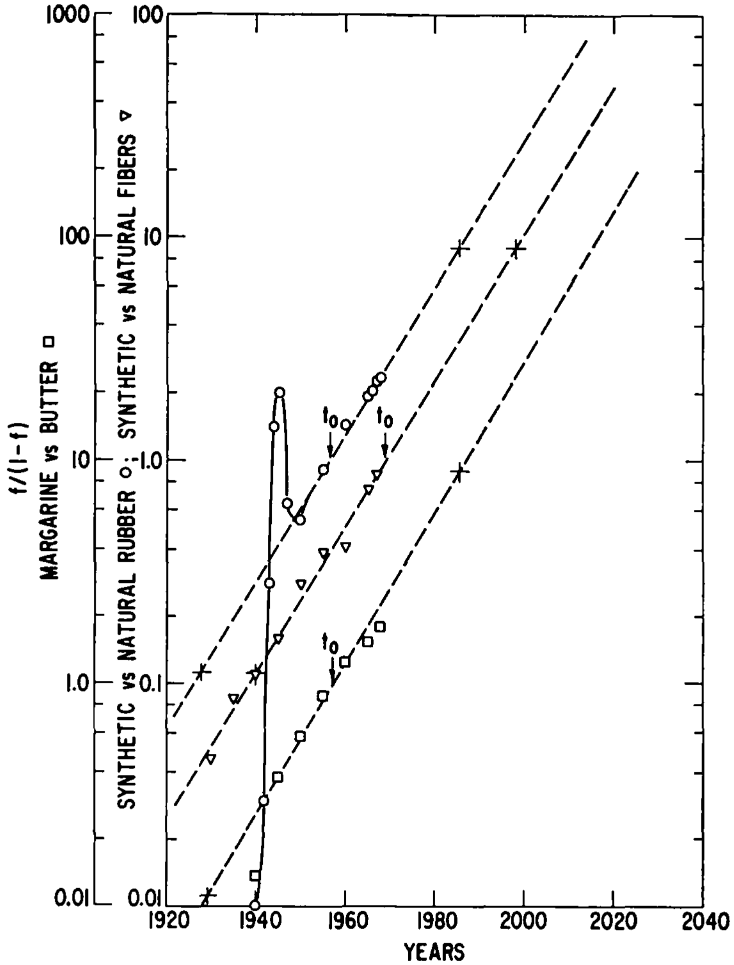
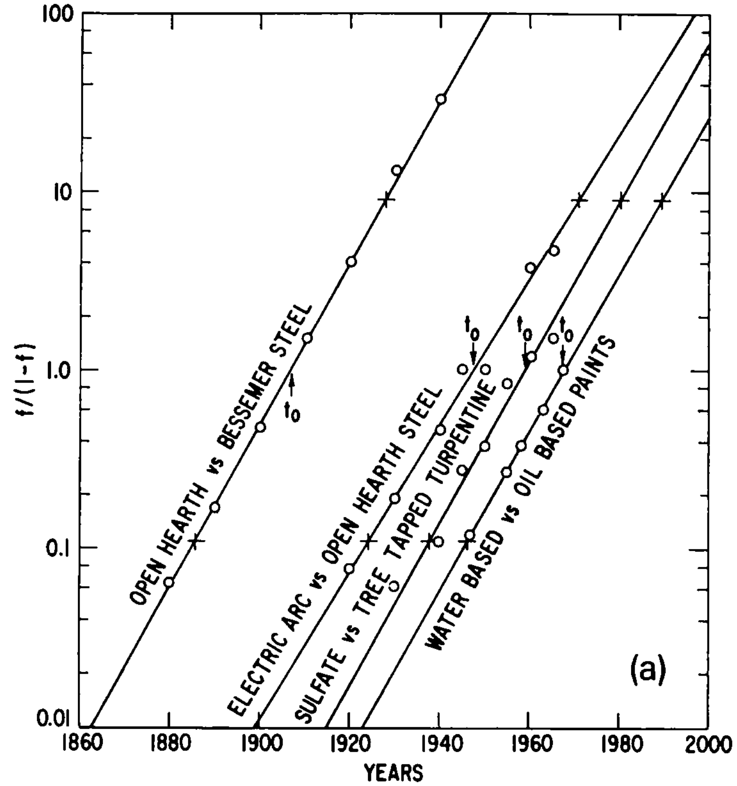


Fig. 7. U.S. consumption vs. years and fit to substitution model for three agriculture-based products.

forecaster. Second, the various elements of the forecast are separated; i.e., the fractional substitution competition, the per capita consumption, and the projected population growth. This not only allows, but demands, that independent projections be made for each. The substitution model is fatalistic in the sense that it projects a specific and undeviating future based upon past events. This is not to suggest that a particular future is inevitable, but that, in a normal competitive environment where no large forces are discontinuously brought into play, the future is predictable from past events. A demonstrable exception is the following case.

Synthetic vs. Natural Rubber

In the 1930s synthetic rubber was slowly being substituted for natural rubber. Natural rubber was largely imported from offshore plantations. Synthetic rubber was, at that stage, inferior in some ways to the natural product. However, very early in World War II, offshore sources of natural rubber were largely cut off while at the same time the demand for rubber as an essential material for the conduct of the war increased considerably. By this time, a large national effort was undertaken to substitute synthetic for



Figs. 8 (a–d). Substitution data and fit to model for a number of products and processes. All data United States except detergents for soap as noted.

natural rubber. During these years, progress was made in improving both the properties and the production cost of the synthetic product. After the war ended, the offshore sources of natural rubber again became available and, since purely synthetic rubber had not yet passed natural rubber in properties and cost, the relative use of the two products readjusted itself to a new substitute fraction. Then, in subsequent years, the substitution proceeded ahead at an orderly pace. Figure 7 shows the substitution competition of synthetic for natural rubber along with selected other agricultural product substitutions. It is interesting to note that the rate of substitution of synthetic for natural rubber after 1946 is nearly the same as those of oleomargarine for butter and synthetic for natural fibers, two other broad agricultural substitutions.

In order to examine the breadth of applicability of the substitution model, seventeen different cases of competitive substitutions have been considered, including those already described. They include the substitution of plastic for metal in cars, open-hearth steel for Bessemer steel, detergents for soap, and plastic floors for hardwood floors in houses.

In considering such a wide range of substitutions, a question arises as to the appropriate units to be used in each instance. Since the substitution of synthetic for natural fibers is reasonably direct, fiber weight was used as a basis for comparison. Weight will generally suffice when considering competing processes for the same end product, such as open-hearth for Bessemer steel and sulfate turpentine for tree-tapped turpentine. But what about substitutions like plastic floors for wood floors, or plastic for metal in cars, or

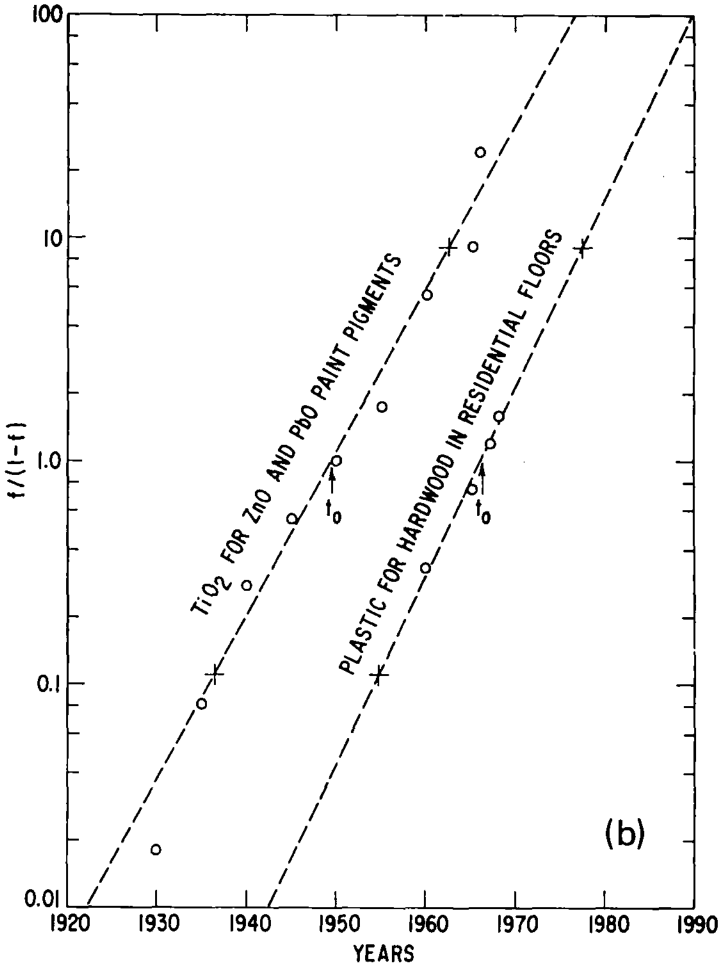


Fig. 8 (cont.)

fiberglass for other materials in pleasure boats? A weight comparison may be inappropriate in these cases. A comparison based upon dollars of sales is equally inappropriate when, as in the case of processes, cost saving may be the driving force for the substitution.

One must examine each case individually to determine the best equivalent units, and hope that data are available or attainable in these units. For example, in the case of plastic substituting for hardwood in floors, data were available for the number of pounds of plastic used in flooring new homes. In addition, data were available for the number of board feet of hardwood flooring used in new homes. Clearly the equivalent unit needed is the number of square feet used in homes. By converting the number of pounds of plastic into the equivalent number of pounds of filled plastic, dividing by the filled density and by the average thickness of a plastic floor covering, the pounds of plastic could be converted to square feet of plastic floor covering. Since the sum of this number plus the number of square feet of hardwood floor covering in new residential construction came within 10 percent or so of the total floor area of new housing starts for a number of years, confidence was increased in the validity of the data to be used in the substitution analysis.

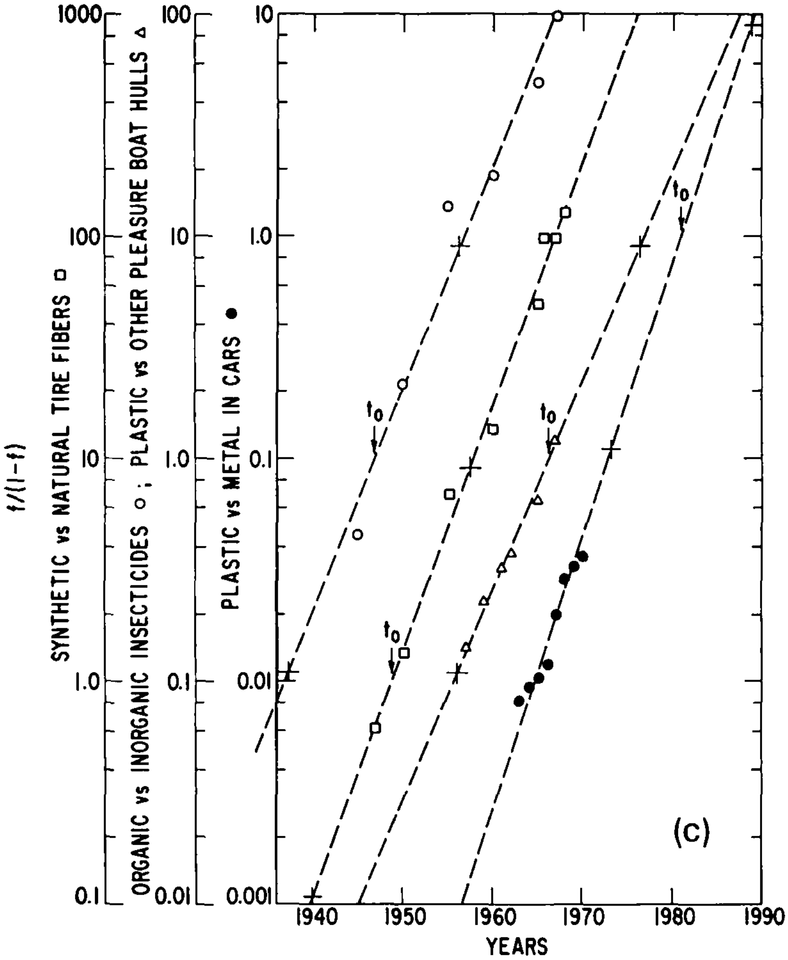


Fig. 8 (cont.)

In the case of substitution in materials for pleasure boats, numbers of boats of each type were used. In the case of plastics for leather, the surface area expressed in numbers of equivalent hides was used, and so on.

Data are given in Table II for a number of such substitutions. The takeover time Δt, the midpoint time t_0, and the units are given. Special problems exist for those items with an asterisk in the unit column: because the electric arc furnace is used primarily for the production of speciality steels, it was assumed to substitute for only 11 percent of steel production tonnage. Because the density of plastic is approximately one-eighth that of metal, but the strength and stiffness is much less, it was assumed that one pound of plastic would replace three pounds of metal in cars. In the case of detergents substituting for soap, approximately 15 percent of the total washing products are not considered available for replacement. These are mostly facial soaps and similar products. This is as true in Japan as in the United States. This amount was subtracted from the total in arriving at the fraction substituted in these cases. Figures 8(a) through (d) display the data and fit to the model for the cases of Table II using the function $f/(1-f)$ vs. time.

A further test of the degree to which the form of the model proposed fits the actual

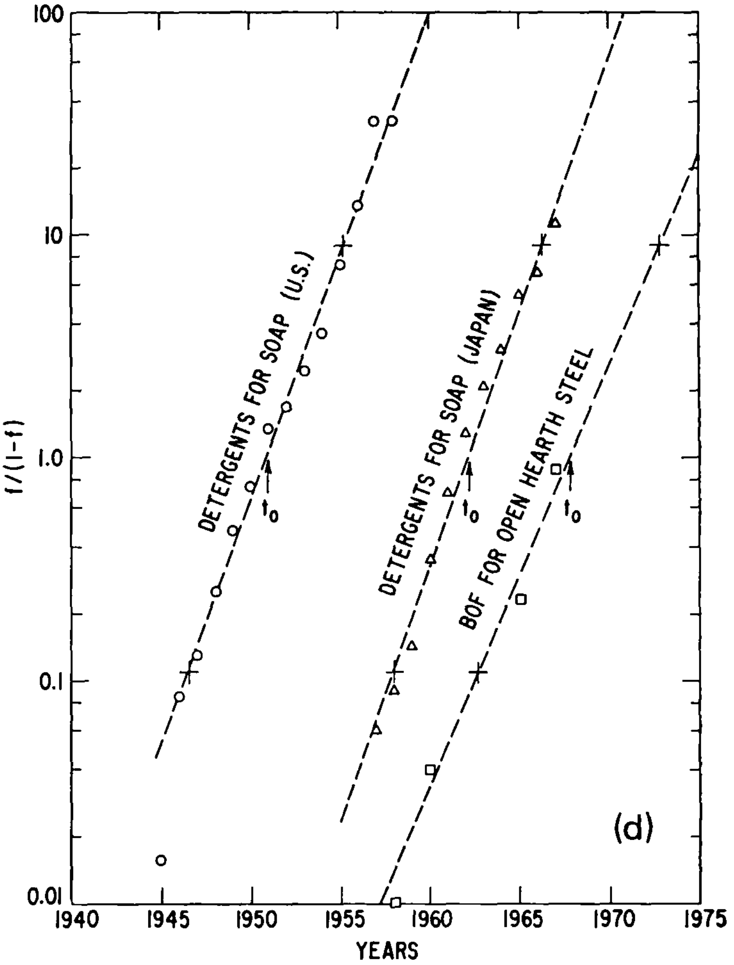


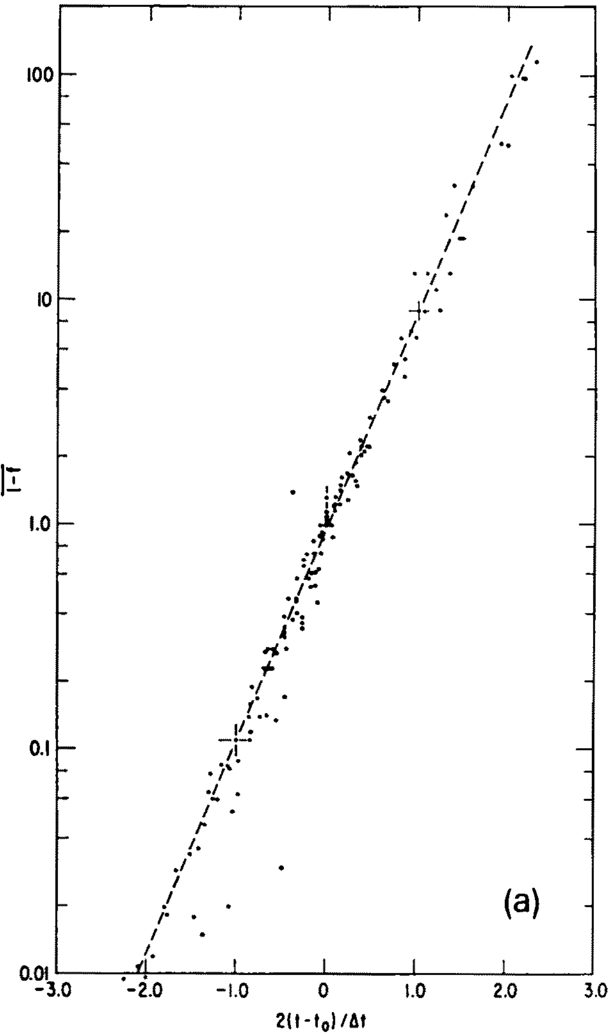
Fig. 8 (cont.)

history of many competitive substitutions taking place over the last nearly one hundred years is shown in Figs. 9(a) and (b). The ordinates used in these figures are $f/(1-f)$ and f, respectively. The abscissa used in both figures is the dimensionless parameter $2(t-t_0)/\Delta t$, which normalizes all of the data to a single mathematical form. All of the data points for the seventeen cases considered are plotted together in these figures. The solid curves shown are the theoretical curves for the substitution model, i.e.,

$$f=1/2\{1+\tanh (1.1)\ [(2)\ (t-t_o)/\Delta t]\}f/(1-f)=2.2[(2)\ (t-t_o)/\Delta t] \qquad (5)$$

The fit of the data to the mathematical form of the model is remarkably good, over this wide range of examples.

Although these data increase the confidence in the model for forecasting, the data displayed in this form raise many questions from the standpoint of understanding technological change. For example, is there an underlying reason for the great similarity in takeover time of the first four substitutions of Table II (particularly considering the major perturbation that occurred in synthetic rubber production during World War II)? Is their relationship to agriculture important? Noting that the takeover time of synthetic tire fibres for natural tire fibers is substantially shorter than that of all natural fibers,



Figs. 9 (a, b). Fit of substitution model function to substitution data for all 17 cases vs. normalized units of time.

how is this time related to the diversity of product of industry involved? How much of the very short time required for BASIC OXYGEN FURNACE takeover from open hearth, compared to open hearth takeover from Bessemer, is related to the fact that the BOF process was imported, fully developed, from Germany and Austria? How much of this difference is related to timing of equipment replacement and investment policy? Does the striking similarity between the detergent-from-soap takeover time in the United States and Japan, even with a midtime lag of a decade, have any particular significance? It is not within the scope of this report to attempt answers to these questions. Rather, the questions are raised to indicate the diversity of broad topics which may be addressed with the aid of this simple model.

It would be well to exercise some caution in drawing conclusions from a set of examples whose sole criterion for choice was the availability of data with which to perform the analysis. A few general remarks will be made, nonetheless. If one characterizes these

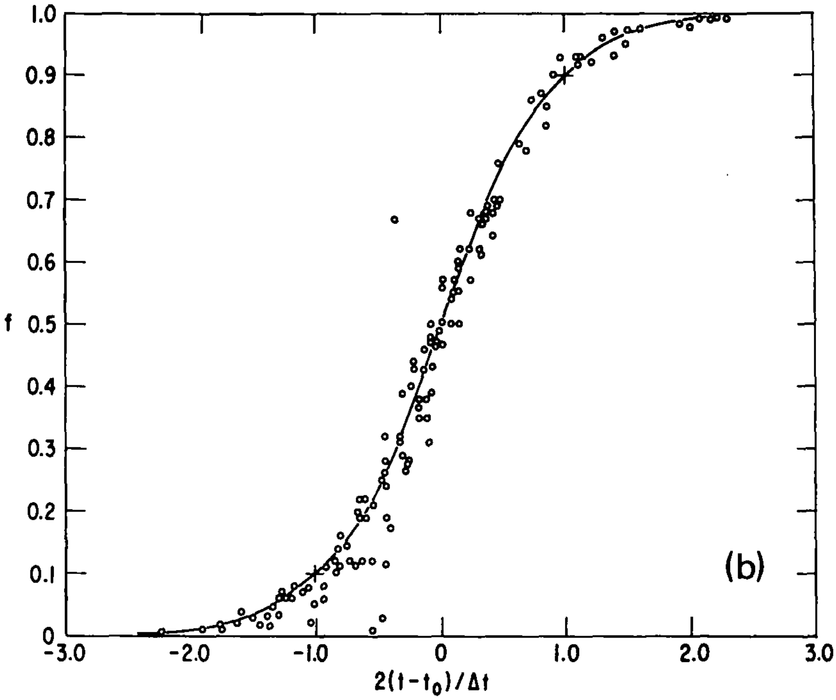


Fig. 9 (cont.)

examples by the date at which the substitution was 10 percent complete, then the set can be said to cover a span of time of about ninety years. In spite of the large variation in takeover times between examples in the set, there seems to be little correlation between the takeover time and the date at which the substitution started. On the other hand, it is

Table II

Takeover Times (Δt) and Substitution Midpoints, t_0, for a Number of Substitution Cases

Substitution	Units	Δt Years	t_0 Year	Reference source
Synthetic/Natural Rubber	Pounds	58	1956	1
Synthetic/Natural Fibers	Pounds	58	1969	1
Plastic/Natural Leather	Equiv. Hides	57	1957	1
Margarine/Natural Butter	Pounds	56	1957	1
Electric-Arc/Open-Hearth Speciality Steels	Tons[a]	47	1947	2
Water-Based/Oil-Based House Paint	Gallons	43	1967	3
Open-Hearth/Bessemer Steel	Tons	42	1907	2
Sulfate/Tree-tapped Turpentine	Pounds	42	1959	3
TiO_2/PbO-ZnO Paint Pigments	Pounds	26	1949	3
Plastic/Hardwood Residence Floors	Square Feet	25	1966	1
Plastic/Other Pleasure-Boat Hulls	Hulls	20	1966	4
Organic/Inorganic Insecticides	Pounds	19	1946	3
Synthetic/Natural Tire Fibers	Pounds	17.5	1948	1
Plastics/Metal Cars	Pounds[a]	16	1981	4
BOF/Open-Hearth Steels	Tons	10.5	1968	2
Detergent/Natural Soap (U.S.)	Pounds[a]	8.75	1951	5
Detergent/Natural Soap (Japan)	Pounds[a]	8.25	1962	5

[a] See text for qualifying comments.

commonly believed that the pace of technical change has increased dramatically in this century. The apparent discrepancy in these statements might be resolved by recognizing that the pace of change in a society is probably measured less by the speed with which a single isolated substitution occurs than by the number and magnitude of such substitutions taking place simultaneously. It might be enlightening to examine this question in a given country as a function of time or between countries to determine the correlation between the number of such substitutions and the abundance of technical, economic, educational, and other resources available.

The speed with which a substitution takes place is not a simple measure of the pace of technical advance, or of manufacturing, marketing, distribution, or any other individual substitution element. It is, rather, a measure of the unbalance in these factors between the competitive elements of the substitution. When a substitution begins, the new product, process, or service struggles hard to improve and demonstrate its advantages over the dominant product, process, or service. As the new substitution element becomes recognized by commanding a few percent of the total market, the threatened element redoubles its own efforts to maintain or improve its position. Thus, the pace of technical innovative effort—indeed, the competitive pace of all aspects of the substitution—may increase markedly during the course of the substitution struggle.

A major conclusion we draw from the successful application of the substitution model is that, all of these considerations notwithstanding, the rate constant of a substitution, once begun, does not change throughout its history. The rate at which a given substitution proceeds seems to be determined by the complex interplay of economic forces responding to the inherent superiority of a new method.

Summary

A substitution model of technological change based upon a simple set of assumptions has been advanced. The mathematical form of the model is shown to fit existing data in a wide variety of substitutions remarkably well.

It is suggested that the model can prove useful to a number of types of investigations, such as: forecasting technological opportunities, recognizing the onset of technologically based catastrophes, investigating the similarities and differences in innovative change in various economic sectors, investigating the rate of technical change in different countries and different cultures, and investigating the limiting features to technological change.

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