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Sporadic Innovation and Historical Continuity[1]

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Abstract *This article argues that, by appealing to technological factors, one can compare different innovations, even different economies, over time. An application is made to the development of steam engines and turbines over their history from 1700 to 2000, for which it is shown that four types of physical variables—temperatures, pressures, thermal efficiencies and power ratings—provide common measures of succeeding devices. Such measures can be incorporated in a technological analogue of an input–output system. In principle, an entire economy could be represented in technological form; and, since scientific variables are invariant through time, its evolution could be depicted in quantitative terms.*

Keywords: innovation, technical change, economic history, input–output analysis.

Introduction

History is recorded movement. In order to make sense of what might otherwise be disassociated events historians conceive of social or political vehicles in which the events can hitch-hike. Such conceptual aids can be physical processes (such as territorial expansion), economic institutions (such as competition or exploitation), or human aggregations (such as empires or civilizations): the vehicle is successful to the extent that it provides common carriage for diverse elements. In its voyage through time, the vehicle imposes an order upon events, which remain fixed within its confines.

Some vehicles are so capacious that they can pick up almost every event; others are very selective: some historians prefer to use the former, some the latter. Generally, the larger is the vehicle, the more diffuse is the movement that it reveals; smaller vehicles can be followed with more precision and display a clearer passage. Smaller vehicles may also lie within the historian's focus throughout their entire voyage, enabling him or her to track them continuously.

My objective in this paper is to introduce such a small vehicle, whose chief merit is that it carries its complement of passengers along a single route in full view. It is neither a social nor a political construct, but a technological one; and it is not singular but numerous, as many as there are technologies in existence. The simile is with motor cars, which have certain common characteristics—four wheels, an

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engine, a body, etc.—but which come in a dizzying variety of styles. Yet, the term 'motor car' is sufficiently familiar and comprehensive to serve as a convenient catch-all: technology is a similar device.

The outline of the paper is as follows: first, we shall select a technology, one which has been applied for a considerable length of time. Second, we shall record the changes that have occurred in this technology from the date of its introduction to the present, in such a fashion as to make the changes comparable one with another. The result is a series of observations through time—a history—all lying along a fixed dimension, like time itself. By joining the observations, as one could join, on a route map, the successive points reached in a journey, a continuous record is obtained of the distance travelled. Third and finally, we shall draw the implications for the many journeys that make up the larger and more general movement that we call technological progress, and try to determine what portion of all events technology captures. It will not surprise any reader that the portion of all events captured is disappointingly meager; after all, technology is not the only vehicle on the road of history. Nonetheless, it may carry us further than we might otherwise guess.

The Steam Engine

Three centuries is a respectable interval of time historically. For that long a period, the steam engine has been ubiquitous in industry, and the products whose manufacture it has made possible have become necessary ingredients of our lives. If only for its familiarity, the steam engine should be a worthy item for investigation.

To the historian of science and technology the steam engine has a particularly attractive characteristic—that it is a relatively simple device. The basic principle that motivates its application is that steam, expanding against a movable barrier, can do work. The movable barrier can be a piston, or the blade of a turbine, or any object impermeable to steam; pressing against the barrier, the molecules of the steam exert a force that transforms some of the energy in the steam into motion. The motion can be harnessed, driving a pump or an electric generator or some other apparatus. In the process of transferring energy from heat to motion, steam is not altered chemically, and its physical changes—in pressure and temperature—are easily observed and measured.

At this simple level, the device within which the latent energy in the steam is transformed into motion is irrelevant, although the conditions under which it performs its function are not. Whatever the device, it must conform to the conditions of nature, as expressed in the Laws of Thermodynamics. These laws, derived by Carnot and his successors, were formulated in the middle third of the nineteenth century, well after the power of expanding steam had been recognized and exploited in machinery, a not uncommon sequence of technological events.

The formulae underlying the conversion of the energy in steam to work are not so difficult as to confound the historian. Two terms are required, enthalpy and entropy. Enthalpy is the measure of the heat contained in steam at any stage of its passage through the engine; entropy is a measure of the heat accumulated in the steam at the particular temperature being observed. Enthalpy is commonly measured in British Thermal Units (BTUs) per pound of steam; entropy in BTUs per pound of steam per degree Rankine (degrees Celsius plus 273: Standard tables of enthalpy and entropy at various temperatures and pressures can be found in

ASME, 1967). Enthalpy is a workman-like concept, useful in the analysis of devices generating or utilizing heat; entropy is a profound concept, hinting at the degree of order or disorder in a system. The two concepts—one mundane and the other ephemeral—complement each other nicely, like all symbolic pairs.

We can calculate the enthalpy of steam at any point, but two points stand out as crucial—the point at which the steam first exerts its pressure upon the movable barrier and the point at which its impulse ends. In between the two points, the steam transfers its innate energy to the piston or to the turbine blades or whatever. We shall assume that no additional heat is supplied to the steam in the course of its expansion (a sensible assumption) and that no heat is lost to the surroundings (a less sensible assumption). (The thermodynamicist has a word for expansions without the addition or subtraction of heat: they are called 'adiabatic', from the Greek *adiabatos* meaning impermeable—impermeable, that is, to the transmission of heat either into or out of the container within which the potential energy in the steam is converted into motion.) Later, we shall relax the assumption that the expansion is adiabatic, so as to be able to account for the heat losses that arise in practice.

Temperature and pressure are phenomena common to all steam engines, regardless of their design or their operation or their originators or their historical and economic contexts: they provide universal, timeless, if abstract, descriptions of the devices. In Table 1 we have listed some of those temperatures and pressures that are appropriate for our analysis; they describe the several innovations for which the data are available in terms of a common set of characteristics. The common set involves pairs of steam temperatures and pressures, designating the temperature and pressure of the steam upon entering into the chamber where its expansion occurs (this is the cylinder in the case of a piston engine). These pairs of temperature and pressure represent the energy potentially available in the steam; other pairs of temperature and pressure not tabulated but used in the calculations include those describing the temperature and pressure of the steam leaving the expansion chamber and those describing the conditions of the steam or condensed water at the end of the cycle. The ratio of the potential energy that is converted into useful work, derived from the calculations, is tabulated in the third column of Table 1, and the total power generated by the engine in the last column.

In designing and building a steam engine, the objectives can be thought of as injecting steam of as high energy as possible and converting as much of this energy into work as possible. Attainment of the former objective is measured by the usable enthalpy of the steam (that is, the enthalpy of the steam on entering the artefact less the enthalpy of the steam on leaving), multiplied by the rate at which it is provided to the engine; attainment of the latter by the efficiency of the engine. Both measures together—usable enthalpy times charge rate, and efficiency—describe the productivity of the engine. These two measures occupy the last two columns of Table 1.

Tables of numbers are hard to read, and the progression of the numbers themselves difficult to visualize. It is not surprising that such tables do not command our attention, nor do they remain vividly in our memories. Fortunately, there is a figure in which the two pairs of temperature and pressure can be displayed, for any particular steam engine. This figure is called a Mollier diagram, after the French chemist who was its originator.

In the Mollier diagram are plotted the two fundamental properties of steam, its enthalpy and its entropy, for varying steam temperatures and pressures. As is evident, the usefulness of steam increases as its temperature rises, and also as its

Table 1. Inlet temperatures and pressures, power ratings and efficiencies of steam engines, 1700–2000

Description	**Year**	**Temperature (° Centigrade)**	**Pressure (MN/m^2)**	**Power (KW)**	**Efficiency (%)**
Savery	1700	113	0.131	0.75	N.A.
Newcomen	1712	100	0.096	3.75	0.5
Smeaton	1740	N.A.	N.A.	17	0.9
Smeaton	1775	116	0.147	38	1.5
Watt	1780	113	0.135	43	2.1
Watt	1782	N.A.	N.A.	76	2.6
Watt	1792	N.A.	N.A.	100	4.3
Trevithick	1800	145	0.4	N.A.	N.A.
Cornish	1840	>145	0.36	220	15
Corliss	1876	N.A.	N.A.	1,100	16
Corliss	1880	N.A.	N.A.	3,000	17
Corliss	1900	N.A.	0.69	3,500	20
Triple Expansion Engine	1910	N.A.	1.38	4,200	23
Parson's Turbine	1888	N.A.	N.A.	75	N.A.
Parson's Turbine	1891	N.A.	N.A.	100	N.A.
Warship Turbinia	1897	N.A.	N.A.	1,500	N.A.
Advanced Turbines	1906	190	0.9	3,500	5
Advanced Turbines	1930	430	9	150,000	15
Advanced Turbines	1955	605	25	150,000–200,000	28
Advanced Turbines	1970	640	26	1,000,000–1,500,000	45
G.E. 'H' System	2000	N.A.	N.A.	>500,000	50

Sources: Temperatures and pressures: *Encyclopaedia Britannica*, 1960, Vol. 21, p. 357ff. and Vol. 22, p. 366ff; A. W. Skempton (ed.), *John Smeaton, FRS*, Thomas Telford, London, 1981, p. 187. Power and efficiency 1700–1970: Vaclav Smil, *Energies: An Illustrated Guide to the Biosphere and Civilization*, MIT Press, Cambridge, MA, 1999, pp. 145, 148; 2000: 'Go-ahead given for £300m gas-fired power station', *Financial Times*, 8 April 1999, p. 28.

pressure rises. This usefulness of steam is represented in the Mollier diagram by associated higher values of enthalpy. But there is always a cost implicit in raising temperature or pressure and subsequently lowering it. (The common example is the 'cost' incurred in blending hot and cold water; taking the lukewarm water resulting from the mixing, one cannot re-establish the original hot portion without additional energy. The 'cost' is measured as a gain in entropy, or increase in disorder.) As a consequence, as lower steam pressures occur (say, through a decrease in pressure at the end of the stroke of a piston), the entropy of the system increases. Reflecting the inescapable gain in entropy through the conversion of potential energy (in steam) into work, the lines of (constant) pressure on a Mollier diagram shift to the right as lower pressures are encountered.

What the Mollier diagram enables one to do is to identify, on a chart displaying the properties of steam at elevated temperatures and pressures, the three points consistent with the condition of the steam at its entry into the engine; with the condition of the steam at its discharge from the engine, after completing its work; and with the condition of the steam (or, in the earlier engines, the steam condensed to water) as it is exhausted or returned for re-heating. When these three points are connected they depict the cycle of heating, working and condensing, which describes in the abstract all steam engines. The two points on a Mollier

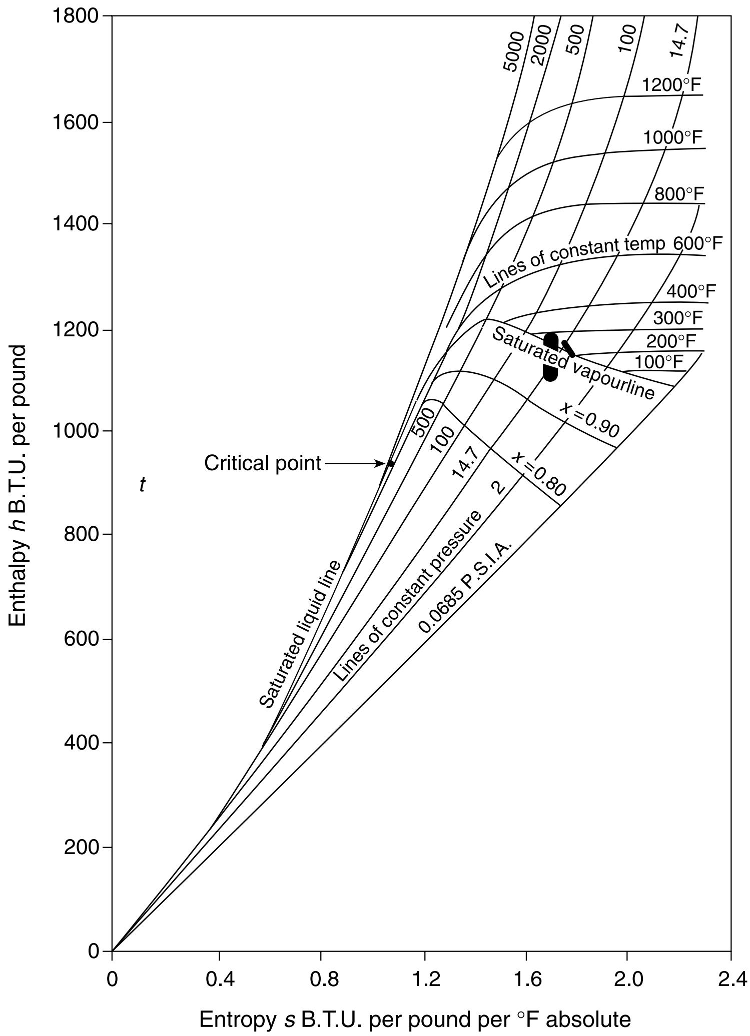

Figure 1. Mollier diagram for Smeaton's atmospheric engine in theory (solid line) and in practice (dot, from apex), circa 1775.
Source: A. W. Skempton (ed.), *John Smeaton FRS*, Thomas Telford, London, 1981, p. 187.

diagram representing steam at the beginning and end of the expansion phase can be plotted for any steam engine; in our case, for each engine in the historical sequence, from the first to the last.

Figure 1 displays a Mollier diagram, within which the performance, in both theory and practice, can be observed visually for one of the first steam engines invented—that of John Smeaton. The enthalpy loss and entropy gain for Smeaton's steam engine of 1775 appear in Figure 1, the short solid line representing the theoretical and the dot the actual values. Because there is no loss in heat in theory, there is no entropy gain and the short line is vertical; because there is a gain in entropy in practice, the dot is at an acute angle to the origin (just above the saturated vapour line).

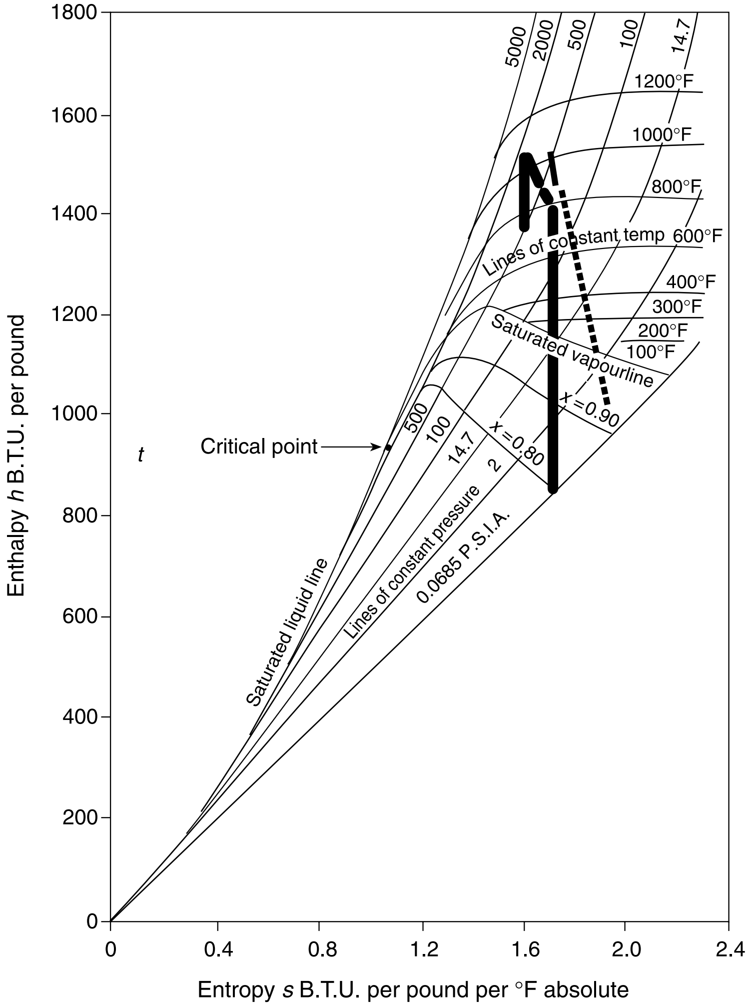

Figure 2. Mollier diagram for a compound steam turbine, circa 1950.
Source: *Encyclopaedia Britannica*, 1960, Vol. 21, Fig. 21, p. 357; and Fig. 12, p. 365.

The next figure, Figure 2, displays the same four loci for a compound steam turbine, circa 1950. Again, the work carried out by the engine, in theory, is indicated by vertical lines, a pair in this case because the steam is re-heated after its first pass through the turbine blades, whence it makes a second pass. The actual work performed is indicated by the (two) dotted lines.

There are two implications to be drawn from a comparison of the Mollier diagrams for Smeaton's engine and for the steam turbine: one regarding the extent of the work performed; and the other regarding efficiency. In both figures, the vertical lines depict what work can be done in theory, on the assumption that all the potential energy in the system is converted into useful work. Such perfection is not attained in practice, for there are losses of energy attributable to such phenomena as friction in the operation of pumps and pistons and turbine shafts and blades, convection of heat to the atmosphere, and, in the case of Smeaton's engine, the heat lost in restoring the cylinder to its operating temperature after the injection of the water used to condense the steam at the end of the expansion phase. In Figures 1 and 2, the work lines depict the actual work done; for the two-stage turbine it is the sum of the work on the first pass and the work done on the second pass—the combined length of the two sets of dots. For Smeaton's engine, the work done is the much smaller amount indicated by the position of the dot just below and to the right of its apex. The two figures permit the same comparison, between the performance of the turbine of 1950 and that of Smeaton's engine of 175 years earlier, in the columns of Table 1.

The second implication from the comparison of Figures 1 and 2 involves the relative efficiency of the two engines. Not surprisingly, one of the great merits of successive innovations in steam engines has been their reduction in heat losses; that is, in their abilities to capture as useful work greater proportions of the potential in the steam entering the expansion chambers. In terms of the Mollier diagrams, these improvements are seen, as time passes, in work lines closer and closer to the vertical. Nonetheless, the cumulative reduction in heat losses is only one of the factors that have contributed to increases in the efficiency of steam engines via successive innovations. The higher temperatures and pressures at the beginning of the cycle is another; so is the longer phase of expansion, and so is the withdrawal of steam for reheating and for recharging in subsequent phases. Altogether, these improvements have led to the increases in overall efficiency indicated in the final column of Table 1.

Figures 1 and 2 present a visual comparison of the efficiency of the two steam engines—Smeaton's and the advanced turbines—via the slopes of the two work lines. The slope of Smeaton's is approximately 30° from the vertical; that of the turbine 10°: the larger the deviation of the work line from the vertical, the less efficient is the engine. From the two measures—length and slope—combined, one can make a single quantitative comparison of any two engines. The enthalpies and entropies, and their changes, can be read off scaled equivalents of Figures 1 and 2. Labelling the initial and final enthalpies h_i and h_f respectively, the work line of any engine would be $[(h_i - h_f)$ cotangent (alpha)$]$, where alpha is the angle subtended between the theoretical and the actual work lines in a Mollier diagram. (The work lines are those of the pumps or turbines alone; the contributions of the boilers that generate the steam and the machinery that utilises the work provided by the pump or turbine are excluded.) Applying the formula to Smeaton's engine of 1775, we obtain a work load of approximately 173 BTUs: to the turbine of 1950, one of approximately 2,211 BTUs, both per pound of steam. The compound rate of growth of productivity over the 175 years, from 1775 to 1950, is almost exactly 1% per year. If these two measures of work, in BTUs per pound of steam, are multiplied by the total provision of steam to the engine, a measure combining productivity and volume is obtained. For Smeaton's engine and the turbine 1950, the steam ratings are 5.6 lb/hr and 500,000 lb/hr respectively, yielding combined measures of productivity and power of 970 and 3,300,000,000 BTU/hr. (These can be converted to horsepower through multiplication by 2.931×10^{-4}, giving values of 0.1 and 30,000 hp.) These measures are isomorphic to the values of efficiency and power in Table 1.

The ratio of the combined measures, 1 to 3.3 million, gives an indication of technical progress in steam engines over 175 years, for it measures both the increase in energy input to the artefact and the efficiency with which that energy is transformed into useful work. In terms of the average rate of increase, this amounts to a little under 6% per year. (This compares relatively closely with the author's estimate of 5.6% per year for a series of chemical innovations extending over a period of 52 years.)[2]

The Continuity of History

Looking at photographs of any succession of steam engines, we see what seems at first a great and confusing variety: comparability would appear to be beyond the ability of even the most impetuous of economic historians. The task of comparing is made more difficult still for the historian distracted by the intriguing forces, personalities and events surrounding the individual innovations. Immersed in the story of innovation, the historian can, at best, compare successor and predecessor; comparisons of greater historical extension are, in all the panoply of customary inquiry, nearly impossible.

Restricting ourselves to the austere relations of science, however, we can make comparisons. In the case of steam engines, the relations are those of the science of thermodynamics, and the comparisons are those incorporated in Table 1 and in Figures 1 and 2. In particular, we notice in Figure 1 how much shorter is the work line for Smeaton's engine than the sum of the two work lines for the turbine in Figure 2. Thus, using the Mollier diagram, we have made a comparison, or two comparisons really (one in theory and a second in practice), between two very different steam engines, two engines separated by nearly two centuries.

So, continuity is the first claim that we can make, and this is continuity in the face of great variety of engine types and applications. Most significantly, there is continuity from one broad technology—the piston-impelled steam engine—to its successor—the steam turbine. It is only by examining the technologies on the basis of their fundamental characteristics that comparability can be obtained. [Even such an apparently useful index as Watt's indicator diagram is not valid for turbines, which lack the convenient correlation between piston movement and (de)compression.] Continuity becomes visible only in successive realizations of a common phenomenon; in this case, a technological phenomenon.

The second claim that we can make is that different innovations have different consequences (a simplistic statement), and that the differences are quantifiable (an equally simplistic statement, but one with content). Table 1 provides the most obvious indication of the differences in outcomes: certain innovation yielded relatively small increases in power and improvements in efficiency (for example, those of 1782 and of 1900), whereas other innovations (those of the late 1870s and the 1930s) yielded great increases in power and improvements in efficiency. In particular, the innovation of the compound Corliss engine in 1876 and of the combined cycle in the 1930s provided substantial gains in both measures of performance. Attention to fundamental changes in the characteristics of machines gives the economic historian insight into their relative significance.

To be sure, the historical progression of machine productivity cited above makes no allowance for the cost of securing the increases in productivity. It is possible that the larger accomplishments, such as the innovation of the steam turbine, cost as much in proportion as they yielded in increases in productivity. Extraordinary benefits might have required extraordinary efforts. Although this statement might be correct for individual innovations, we do not believe that it holds true for individual innovations followed by the improvements that exploit their potential. If the original innovation and its subsequent improvements are considered as a single event rather than a series of independent events—that is, if the benefits and costs are accumulated over an extended time horizon (or compiled into a 'trajectory'[3]), there may be little association between the immediate benefits, on the one hand, and the immediate costs, on the other. Our experience, for the narrower set of process innovations in a single industry, is that there is no consistent relationship between the two. The benefits from a single innovation and the costs thereof seem to display no direct correlation.

We are content, though, to associate the magnitude of the gain through a single innovation in steam engines to the increases in the two measures of productivity displayed in Table 1, and, thereby, to infer that the increases in the numbers display not only a relatively continuous path of historical progress, but also the relative importance of the individual incidents. Nor need the statement hold true if the scope of the analysis is extended beyond the innovations in steam engines themselves so as to include all the applications of, and constraints on, the power that an engine generates (excluded therefore are such applications as prime movers and electric generators, and constraints such as safety). That the existence of applications of steam power did affect the development and utilization of steam engines can be seen in, for instance, von Tunzelmann's history of the early history of steam power in Britain's mining and textile industries.[4]

The Past in the Future

In spite of its familiarity to economic historians, the example of the steam engine was not chosen for that reason. Rather it is its scientific simplicity—the expansion of steam, so as to utilize its latent energy—that recommended it for inquiry. Steam is an inert substance chemically, so in the expansion of steam there are no complicated chemical reactions to take into account. Steam, in its expansion, does not alter the physical shape or properties of the metal that confines it, so there are no difficult mechanical changes to describe. Such analytic felicities make steam an ideal medium for analysis.

But such has been recent progress in the description of more complex industrial processes that we do not have to rely on steam alone for illustration of historical continuity. The author himself has investigated a much more complicated process—that of the catalytic cracking of heavy hydrocarbon oils over the 60 years that the process has been in operation.[5] Depending upon how one defines the word 'innovation', this complicated set of events can be thought of as one innovation followed by six decades of improvements, or as a connected sequence of major and minor innovations extending over 60 years; but the analytical significance of the cracking process is that there is a precise description of the process, equivalent to the Mollier diagram in the case of steam, that yields fundamental measures of productivity. One measure is the analogue of the steam engine's work, and indicates the scale at which a single plant is operated; another set of measures (the kinetic coefficients) is the analogue of efficiency, and indicates the rates at which the various chemical reactions proceed.

Although this study of technical progress in petroleum refining is, to the author's knowledge, the only case in which a mathematical model of an industrial technology has been applied for historical research, it represents by no means the only opportunity that has arisen for such application. Many, many other models now exist, awaiting attention. Their availability is the outcome of recent research by scientists and engineers in universities and industry taking advantage of parallel advances in knowledge of industrial processes and in computation. The field has various names, as is customary in a new discipline—'systems analysis' is one, 'systems engineering' is another, 'optimal systems control' is an ambitious third. Already there have appeared a few textbooks, addressed to engineers,[6] and numerous scholarly and trade journals (for example, *Journal of Process Control, International Journal of Control, IEEE Transactions on Control Systems and Technology*). Every day, additional industrial processes are being described in the precise form of mathematical models and data assembled, in laboratories and pilot plants and in the operations of productive facilities employing the most modern techniques. These inquiries satisfy firms keen to improve their current operations; economic historians may also be able to utilise the models, although for comparisons they will have to search through records of previous industrial operations to discover the characteristics of the techniques exploited in the past.

The Micro-Technics of Historical Change

Let us imagine for the moment that there has occurred a grand series of such historical inquiries, with the consequence that a very large number of continuous series of technical change has become available in forms similar to that of ours for the steam engine. What will they look like and to what purposes could they be put? There are not one but two answers to these questions: one answer derived from micro-economic investigations and the other from macro-economic. We shall take these in turn, concentrating on their theoretical bases.

The basis in theory for micro-economic investigations of an historical nature is the engineering production function. The idea came from Hollis Chenery, who argued that there exists a scientific/engineering intermediary to every economic production function.[7] Just as the economic production function is a rule which relates the flows of inputs to the flows of outputs, both inputs and outputs expressed in their appropriate physical dimensions—man-hours, or units of services of capital for inputs; and units of product for outputs—so the engineering production function is a rule which relates the flows of fundamental technical inputs to the flows of economic outputs, where the inputs of the engineering production function are the outputs from the economic production function. Illustrating this link between the engineering and economic production functions by the steam engine, the economic production function would relate the capital and energy and man-hour flows (the inputs) to the temperatures and pressures that could be maintained in the engine (the outputs), and the engineering production function would relate the availability of steam at elevated temperature and pressure (the inputs) to the amount of useful work that would result (the output) via the employment of the engine. Mathematically, if the economic production function could be written as $f(\mathbf{x},\mathbf{y};\,\mathbf{z}) = 0$, where $\mathbf{x}$ is the vector of flows of inputs, $\mathbf{y}$ is the vector of flows of outputs, and $\mathbf{z}$ is the vector of the prices that value the inputs and outputs, the engineering production function would be written as $g(\mathbf{y},\mathbf{q},) = 0$, where $\mathbf{y}$ is the vector of technical inputs (from the economic production function), and $\mathbf{q}$ is the vector of outputs derived from the application of the (technical) inputs. Just as the economic production function is based on the premise that the scarce inputs are combined efficiently, so the engineering production is based on a premise, namely that the transformation that takes place, from inputs to outputs, adheres to the fundamental scientific/engineering principles underlying the process. Nature ensures that the function $q(.)$ is extreme-valued (in economic language, that all its points lie on, but not inside, the isoquants). Under certain mathematical conditions [that $f(.)$ and $g(.)$ be complete, continuous and convex], it is possible to combine the two into a single function $g\{f(\mathbf{x,y,q; z})\} = 0$ which relates the (economic) inputs, $\mathbf{x}$, to the (physical) outputs, $\mathbf{q}$, via the two activities represented in the functions f and g.

Chenery suggested that there were some relatively simple processes, well enough known technically, which could be expressed quantitatively by the combination of economic and engineering production functions, but to our knowledge only three such applications have been made. The most extensive application, to the transport of crude oil in a pipeline, was carried out by Cookenboo.[8] From fundamental scientific principles governing the flow of an incompressible fluid, and economic estimates of the costs of providing the physical inputs necessary to contain the crude oil within a large-diameter pipe and to overcome the friction incurred in the flow of the liquid through the pipe over a long distance, Cookenboo derived the interesting relationships (isoquants, cost curves and expansion paths) that, drawn from theory only, adorn micro-economic textbooks.

Cookenboo's application of engineering/economic production functions to a real situation covered only one instant in time, but a study inspired by Chenery and Cookenboo extended their analysis through time, so as to determine the consequences of technical progress in the construction and operation of crude oil pipelines.[9] The results were what an economist would expect—a reduction in cost of transport at all rates of throughput, an extension of the range over which economies of scale were manifest, and a reduction in the elasticities of factor substitution—but from our point of view here the important consequence was that some features of a particular set of micro-economic changes were revealed through an investigation of the technical aspects of the technology employed. In the future, such investigations could be made with increasing ease, as more technologies yield their properties to scientific and engineering inquiry.

The Macro-Technics of Historical Change

In principle, we could move from a micro-economic to a macro-economic world by aggregating all the economic and engineering production functions describing economic activities; such are the ways the Walrasian general equilibrium model is formulated and computable general equilibrium models solved. But in practice the functions describing economic activities accurately are extremely complex, violating the conditions that must be fulfilled if aggregation is to proceed. The approach of the general equilibrium theorist cannot be followed by the historian, who describes real events.

One way of avoiding the problem of aggregation is to linearize all the functions, as is done in input–output analysis and social accounts matrices. This is the approach that we shall adopt. Let us follow this approach first in the abstract. We commence by linearizing the economic and engineering production functions for a single 'final product', where the term 'final product' is used in the sense in which it is used in input–output analysis—a good that is consumed without further processing. Entering into the economic production function of this product, as inputs, are purchased goods and services from all the economy's 'industries', in value terms—that is, so many pounds sterling of labour, of capital, of fuel and so on. Following Chenery's analysis, the results of the total expenditure on inputs are quantities of 'products' in technical terms—that is, so much temperature and pressure and catalysis, etc.

The relation between the economic inputs and the technical outputs—the linear version of the economic production function—is represented by a sort of transactions matrix, the individual coefficients of which measure the expenditure on the output of a single industry needed to produce a single unit of input to the consuming industry. We could call this matrix the 'eco-technical matrix', but that is an ugly term so we shall christen it the 'facilitating matrix'.

In analogous fashion we could express the relation between the technical inputs from the economic production function as inputs to the engineering production function, and the physical outputs of goods that these technical inputs yield by a transformation matrix the individual coefficients of which would measure the quantities of technical inputs—so much temperature, pressure, etc.—needed to produce a single unit of the industry's output. Since the dimensions of the industry's good are physical, we must multiply the quantity of the good by its price, so as to obtain the value of industry output. With this conversion of physical quantities of output into values, we have consistency between the units in which industry inputs—the initial purchases by the industry—are expressed, and those of the industry outputs. This second matrix of coefficients could be called the 'techno-economic matrix', but we prefer the term 'fundamental matrix', since it represents the amounts of technical inputs required, according to scientific and engineering principles, to produce a unit of physical output. The fundamental matrix is illustrated, in the case of the steam engine, by the Mollier diagram, which indicates how much useful work is obtained from inputs of steam at elevated temperature and pressure.

Equipped with the facilitating and fundamental matrices, and with the prices of the goods, inputs and outputs, we can state the overall relationship between the total values of inputs from the economy's industries and the values of the outputs that the economy can produce from those inputs—the equivalent of the conventional model of input–output analysis. In the conventional model, the relationship is written in vector form as: $\mathbf{x}–\mathbf{Ax} = \mathbf{f}$, where $\mathbf{x}$ is the vector of gross inputs, $\mathbf{A}$ is the matrix of Leontief coefficients (whose elements a_{ij} *indicate the value of purchases of the product of industry* i by industry j in producing one unit of j's output), and $\mathbf{f}$ is the vector of 'final' demands (i.e. final consumption).

In our macro-technics, the vectors $\mathbf{x}$ and $\mathbf{f}$ are unchanged, but the coefficient matrix $\mathbf{A}$ is subdivided into two matrices, the facilitation matrix and the fundamental matrix. Labelling the former $\mathbf{H}$ and the latter $\mathbf{K}$, we have an equality between the product of $\mathbf{H}$ and $\mathbf{K}$ and the coefficient matrix $\mathbf{A}$. There is also an equality between the product of $\mathbf{H}$ and $\mathbf{K}$, pre-multiplied by the inverse of the diagonal matrix of product prices, $\mathbf{P}^{-1}$, and post-multiplied by the diagonal matrix of product prices, $\mathbf{P}$, on the one hand, and the conventional transactions matrix $\mathbf{Ax}$, on the other. Mathematically,

$$\mathbf{HK} = \mathbf{A}; \text{ and } \mathbf{x}–\mathbf{P}^{-1}\mathbf{HKPx} = \mathbf{f}.$$

It is the two matrices $\mathbf{H}$ and $\mathbf{K}$ that interest us, since these link initial (economic) inputs and final quantitative (economic) outputs via the fundamental scientific and engineering variables. As far as the order of the two matrices is concerned, $\mathbf{H}$ will be of order $n \times m$, where n is the number of industries in the economy and m is the number of fundamental variables. (If the number of industries into which the economy is subdivided on the basis of available statistics is relatively few, we would expect m, the number of fundamental variables, to be greater. If the economy's industries are enumerated in great detail, n might well exceed m since there is only a finite number of fundamental scientific and engineering phenomena.)

We can illustrate these principles by referring once again to the two steam engines, Smeaton's and the turbine of 1950. Since we will be restricting ourselves to power generation by steam engines, we will be reducing an entire economy (which is reflected in input–output analysis by the matrix **A**, or **HK**, and the output vector **x**) to a single 'industry'. We shall label this industry m. The inputs to this industry, measured in terms of transactions of so many dollars purchased by industry m from each of the n industries $1, 2 \ldots m{-}1, m, m{+}1 \ldots n$, will be represented by a column vector $\mathbf{a}_m\mathbf{x}_m$. If the elements in $\mathbf{a}_m\mathbf{x}_m$ are divided by their prices **p**, purchases are converted from monetary to physical units: the vector product $\mathbf{a}_m\mathbf{x}_m\mathbf{p}^{-1}$ represents the physical quantities of inputs purchased by industry m from each of its supplying industries.

Next, the physical quantities of inputs are converted into engineering inputs (steam at the appropriate temperature and pressure in our case) via the appropriate portion of the facilitation matrix $\mathbf{H}_m$; whose dimensions are physical inputs per technological unit (the technological unit in our case is pounds of steam, at certain temperature and pressure). Thereafter steam is converted into output per technological unit (BTUs per pound of steam). This last transformation is via the appropriate portion of the fundamental matrix $\mathbf{K}_m$, which in our case is simply the Mollier diagram (where changes in temperatures and pressures determine enthalpies and entropies, which in turn determine the work lines, 173 BTU/lb for Smeaton's engine and 2,211 BTU/lb for the turbine). If the reduction from total input of steam to input per pound is designated by the scalar y, the total transformation of the inputs, to industry m, into the value of the output of steam engines (the value of the output of industry m) is written, in vector form, as $\mathbf{a}_m\mathbf{x}_m\mathbf{p}^{-1}\mathbf{H}_m y^{-1}\mathbf{K}_m y\mathbf{p}$. This vector product is equal to the total output of 'industry' m, namely $\mathbf{x}_m$. Technical change in the unit conversion of steam to power in the centuries from Smeaton's engine to the turbine is measured by the change in the fundamental matrices $\mathbf{K}_m(\text{turbine}) - \mathbf{K}_m(\text{Smeaton})$.

At this point, we bring the mathematics to a close for we want to examine changes in the individual coefficients comprising the fundamental matrices in order to determine how they have progressed through time. In other words, we want to compare again single coefficients—the elements of $\mathbf{K}_m$—over time. This is what we did when we observed the historical changes in the temperature and pressure at which steam has been charged to steam engines and turbines, and the power that the steam has generated. One difficulty in comparison arises in the case of the steam engine, however, because temperature and pressure are not combined linearly—the curves in the Mollier diagram are not straight lines. Yet, input–output analysis depends on that assumption for its furtherance. What is to be done? There are two possible ways of resolving, partially, this difficulty; one involves simplifying the economic and engineering production functions, the other limiting observations to the neighbourhood of the ultimate solution.

In our own work, we have followed both approaches; it is the second that we shall discuss here. This approach is considerably more complicated than the first, both in principle and in practice. It requires a reasonably accurate mathematical model of the industrial process (obtained by systems engineering), the optimization of this model (so as to represent efficient industrial practice), and the linearization of the equations describing the solution in the neighbourhood of the optimum.[10] Comparing the linearized versions of successive solutions through time, set up in the form of linear programmes, one can isolate the changes in individual parameters.[11] In principle, this approach could be followed for the major processes constituting the core of an industrial economy. Altogether, it would yield a sequence of paired input–output tables, each with their appropriate matrices of input–output coefficients representing the economy's technology at the date of each table. But the resulting matrices would not be complicated by changes in non-technological variables, such as relative factor prices or demand elasticities, since the changes would be restricted to those in fundamental scientific and engineering phenomena. To be sure, innovations would be expected to have non-technological consequences, but these would appear primarily in the diagonal price matrices. The technical consequences (rather than the economic) would appear as changes in the coefficients of the facilitating and fundamental matrices. There, they would be measured in dimensions constant through time, for the units in which temperature and pressure and other fundamental phenomena (such as enthalpies and entropies) are measured remain the same through the ages. How fortunate since so few historical data exhibit the same continuity.

Conclusion

We have submitted three ideas, the first of which is a hypothesis concerning one objective of historical inquiry; the second of which is an empirical statement about the degrees of complexity of individual events; and the third of which is a modest contribution to the resolution of the difficulties arising out of the first two. The first idea is that history becomes more nearly comprehensible when it is displayed as a continuous movement through time, continuity being expressed, like time itself, in dimensions common to the major events. Measured along the same dimensions, with the same metrics, some of the wrinkles of history are ironed out.

The second idea is that histories of innovations, whatever their nature, generally lack continuity, partly because of the complexity of the individual observations and partly because of the passage of time between the original events themselves and their effects on the economy within which they have been assimilated. An innovation may have been achieved by one generation of entrepreneurs, but its extensive exploitation is likely to be in the hands of the next generation, or the next generation after that.

The third idea is that focusing on the technology underlying the innovation may go part way to resolving the difficulties preventing historical continuity. The reason is that technologies abound in phenomena expressed along common dimensions (in scientific and engineering terms). Linked innovations are not a sequence of independent events, but progressions along a single path, a path whose blazes are familiar signs, like temperature and pressure and velocity. Moreover, there are not so many different blazes as to cause confusion; when the units of inquiry are scientific and engineering phenomena, apparent complexity may resolve itself into orderly display.

It is the third of these ideas—that of the consistency of technology in the course of progress—that we have characterised as a vehicle to carry a load of history. We illustrated the concept of technology as a useful focus for the history of material advance in economies with the steam engine, which has exhibited through time both a confusing sequence of physical forms and human achievements, and a measurable progression of technical advance. When reduced to their common elements—temperatures and pressures, or their derivatives (enthalpies and entropies)—the crowd of engines and turbines fits conveniently into the commodious vehicle of technology.

In theory, the extension of such analysis as that of the steam engine to other artefacts is possible, via the subdivision of the economist's production function into economic and engineering components, and the two components' expression through time, on the basis of common scientific and engineering principles. In theory, such analysis as that of the steam engine could be proliferated so as to describe the development of an entire economy as it grows, via changing technology matrices within an overall input–output system.

In practice, such proliferation would have been impossible in the past, for accurate and precise descriptions of technologies, in terms of their fundamental scientific and engineering elements, were not available. But in recent years, control systems engineering has been applied to many industries, yielding results illustrated in the cases of crude oil pipelines and catalytic cracking, and hinting that results covering other industries may become available. In consequence, technology has become a vehicle for historical research that is road-worthy, and has been test-driven. In the future, it could enter into regular commuting.

Notes and References

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