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The Making of Steam Power Technology: A Study of Technical Change during the British Industrial Revolution

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The Making of Steam Power Technology: A Study of Technical Change during the British Industrial Revolution

Writing in 1845 Friedrich Engels (and with him many other informed contemporaries) had few hesitations in pointing out the driving forces of the epochal transformation he was witnessing:

> The history of the proletariat in England begins with the second half of the last century, with the invention of the steam engine and the machinery for working cotton. These inventions gave rise, as is well known to an industrial revolution, a revolution which altered the whole civil society; one, the historical importance of which is only now beginning to be recognized.[1]

This dissertation was completed at the Eindhoven University of Technology, the Netherlands under the supervision of Bart Verspagen.

[1] Engels, *Condition of the Working Class,* p. 15

This view of the early phases of the industrial revolution, ascribing a central role to the steam engine, as a driver not only of economic growth, but also of other dramatic changes such as the rise of factory system was (and still is) resumed in a major part of the historical literature. Traditional accounts of the British industrial revolution have frequently adopted periodizations that tend to conflate the economic significance of steam power technology with its early development.[2]

More recent research has suggested that such a direct link between steam power technology and the early phases of industrialization is indeed spurious. The available shreds of evidence on the diffusion of the steam engine suggest that the late-eighteenth-century and early-nineteenth-century British economy was still dominated by the widespread use of animal, wind, and water power.[3] Furthermore, the economy-wide repercussions of the adoption of steam technology remained circumscribed until at least the 1840s.[4]

Against the background of this previous research, which has been mainly concerned with the economic and social impact of technical change, this thesis examines the process through which steam power technology first emerged and then grew into a major industrial technology over a period going approximately from the early eighteenth century to the mid nineteenth century. The focus of the thesis is on the *sources* and the *dynamics* of technical progress in steam engineering, rather than on its *effects*.

Chapter 1 and 2 of the thesis contain a broad overview of previous research in this field, which provides the reader with the necessary preliminary background for the inquiry that follows.

Chapter 3 employs an updated version of the data set of eighteenth-century steam engines compiled by J. W. Kanefsky to provide new estimates for the timing, pace and geographical spread of steam power adoption during the eighteenth century.[5]

Overall, the pattern of diffusion appears to be the outcome of a complex set of factors acting simultaneously both on the supply and the demand side. In coal mining and neighboring locations where coal was cheap, the most obvious choice of technique was for a long time represented by Newcomen type of engines by virtue of their simplicity of construction and low maintenance costs. In other areas, where coal was expensive, the low fuel efficiency of Newcomen engines severely limited their use. In these locations, in the last quarter of the eighteenth century, Watt engines rapidly became the favorite option because of their superior fuel efficiency. It should be noted that even if the global profile of engine adoption seems to have been by and large dictated by the level of coal prices, the growth of steam power in each individual county was clearly shaped also by a number of "idiosyncratic" factors, such as the economic structure of the county and the existing capabilities in mechanical engineering. The relative importance of these factors is assessed by means of the estimation of an econometric model of engine adoption.

On the basis of the findings of the diffusion study carried out in chapter 3, chapter 4 provides a general reinterpretation of the development of steam power technology during the eighteenth century.[6] The main contention is that in the second half of the eighteenth century, steam engine technology was characterized by the emergence of dis-

[2] See, in particular, Rostow, *Stages*, p. 60, which links explicitly Britain's industrial take-off (1783–1802) with the commercialization of the Boulton and Watt engine

[3] Kanefsky, *Diffusion*, especially pp. 188–233.

[4] Von Tunzelmann, *Steam Power,* chapter 6; and Crafts, "Steam."

[5] Kanefsky, *Diffusion.* For a condensed version of chapter 3, see Nuvolari, Verspagen, and von Tunzelmann, "Diffusion."

[6] Chapter 4 has been published as Frenken and Nuvolari, "Early Development."

tinct "design families," each adapted to the requirements of a specific application sector. Interestingly enough, over time this variety of designs, subjected to different sets of selection pressures gave rise to divergent technological trajectories. This persistent variety of designs is a feature that would characterize a good deal of the history of steam engine technology. In chapter 4 this process is accounted for by means of a formal evolutionary model in which technical change is represented as a "localized" search process on a rugged fitness landscape. [7]

A particularly good illustration of the influence of specific historical contexts on the development of the technology is provided by the case of the Cornish pumping engine, which is the subject of the second part of the thesis (chapters 5, 6, and 7).[8] The development of the Cornish steam engine can be studied in close detail because from 1811, Cornish mining entrepreneurs sponsored a monthly publication containing detailed reports on the performance of the engines at work in Cornish tin and copper mines. Joel Lean, a highly respected mine "captain," was entrusted with the compilation of the first reports, and the publication was generally known as *Lean's Engine Reporter.* Concomitantly with the publication of *Lean's Engine Reporter*, Cornish engineers, in an attempt of reaping further gains in fuel efficiency, experimented rather successfully with high pressure designs. These new designs were produced in a historical context that fits very well in R. C. Allen's notion of "collective invention."[9] The available evidence shows that Cornish engineers in the first half of the nineteenth century did not protect their inventions by means of patents. Instead, technical improvements were deliberately and actively popularized, not least also by means of *Lean's Engine Reporter.* This practice of knowledge sharing established by Cornish engineers exerted a very favorable impact on the rate of innovation. This process of "learning from others" was also reinforced by more familiar processes of "learning by doing" and "learning by using" leading to a sustained improvement of the thermodynamic efficiency of Cornish engines throughout the first half of the nineteenth centuries. Informed contemporary observers had no doubt in regarding Cornwall as the leading region in steam engineering in the first half of the nineteenth century. It is interesting to note that this remarkable progress was attained without the guidance of a full-fledged understanding of the working of the steam engine. Systematic collection and analysis of performance data allowed Cornish engineers to individuate a set of sound design principles that could successfully be used to project efficient steam engines, by-passing their imperfect understanding of the actual operation of the technology. [10]

Finally, the thesis examines the issue of the prolonged technology gap in steam engineering between Cornwall and the other steam using regions of Britain. Although Cornish achievements had been widely popularized, the high pressure expansive engine did not find widespread application in other steam-using regions (in particular in Lancashire), where the favorite option remained the Watt low pressure engine.

Although the delayed adoption of the high pressure engine can be seen to reflect, at least to a certain extent, a different set of economic conditions (specifically the lower price of coal prevailing in the manufacturing districts of the North), the thesis argues that the major obstacle was represented by factors of cognitive and engineering na-

[7] The model is an adaptation in the field of technical change of Stuart Kauffman's NK model, which represents the process of evolutionary adaptation of a complex system in theoretical biology, see Kauffman, *Origins of Order.*

[8] A condensed version of chapter 5 is published as Nuvolari, "Collective Invention."

[9] Allen, "Collective Invention."

[10] This procedure of extrapolation has also been pointed out by Vincenti in his studies of design activities in the aircraft industry, see Vincent, *What Engineers Know,* chapter 5.

tures. In other words, technological improvements matured along the Cornish technological trajectory could not be readily transplanted to other applications. In this sense, the delayed adoption is to be regarded as a period of "acclimatization" of Cornish innovations in new contexts.

The concluding chapter of the thesis is devoted to a consideration of the broader implications of the research. Recent research in economics has been devoted to the analysis of the development and diffusion of "general purpose technologies" (GPT), that is technologies that can be employed in a wide array of industrial sectors.[11] In this way, these technologies performs the function of "engines of growth" in specific historical phases. Steam, electricity, and information and communication technologies are most frequently put forward as clear-cut examples of GPTs. Although this conceptualization of economic growth has undoubtedly a historical appeal, in most models the development and diffusion of a new GPT is represented by means of rather mechanical schemes of innovation and diffusion. There is the risk that such deterministic abstractions may actually be too general for being useful in historical research. One of the salient features of the "making of steam power technology" that has emerged from our research is the fundamental role of local circumstances in generating technological variety. Over time, this variety led to the emergence of differentiated technological trajectories characterized by uneven rates of technical progress. The factors underlying progress along these trajectories were quite specific to local procedures of engineering knowledge accumulation, so that each trajectory tended to display an "evolutionary logic" of its own. This implies that accurate historical studies (aimed at reconstructing the procedures guiding the search for innovations in each application domain) are indeed a necessary prerequisite for the individuation of the "doors" through which pervasive technologies can spread across various application sectors. The implication of these considerations for modeling exercises is rather straightforward: it is necessary to incorporate into growth models a richer and more accurate representation of the process of accumulation of engineering knowledge in its multifarious forms.

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[11] See the essays collected in Helpman, *General Purpose Technologies.*

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The Business of Transatlantic Migration between Europe and the USA, 1900–1914

The relocation of Europeans across the North Atlantic during the first decade and a half of the twentieth century was the culmination of the longest-lived and most widely documented transoceanic migration of modern times. This enormous population transfer was a great human drama, a major international demographic shift, and a massive historical experiment in cultural transformation during a period of unprecedented globalization. This migration was also a complex and powerful travel business containing both risks and rewards for its three fundamental participants: the movers, the moved, and the sovereign authorities on either side of the borders being traversed. Prior studies have not adequately explained this business nor appreciated the extent to which the various strategies for dealing with its associated risks were crucial, largely congruent, and self-reinforcing elements of the overall migration process.

The mechanisms underlying mass migration across the North Atlantic from 1900 to 1914 incorporated accumulated experience and development built up over a "long nineteenth century" of relative political stability, rapid technological change, and persistent economic expansion. Between 1900 and 1914, the motivations for considerable human movement from a heavily populated Europe to a labor-scarce United States were strong and stable, while political and cost barriers to such movement were relatively predictable, stable, and low. This favorable environment for self-selected voluntary relocation on a massive, ethnically diverse, geographically broad, and transparently documented scale, makes the period and region excellent loci for isolating and explicating the essential causes of modern international mass migration.

The goal of this dissertation is to help improve our understanding of the general factors and processes shaping international migration, by comprehensively and systematically spotlighting the one indispensable common denominator of market-mediated mass transatlantic migration a century ago: the commerce in the physical relocation of people in large quantities across what was then regarded as vast distances.[1] This is a

This Ph.D. dissertation was completed at the University of California, Berkeley in May 2005 under the direction of Gerald Feldman, Jan de Vries, Jon Gjerde, Richard Sutch, and with substantial advice and assistance from many others.

[1] Other "businesses of migration" less vital or ubiquitous across the overall relocation (such as inland rail travel services and the activities of booking agents, labor agents and other intermediaries) are treated selectively in this study, whenever they strongly overlap with the business of the oceanic crossing.