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Technical choice, innovation, and British steam engineering, 1800–50[1]

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The development of the high-pressure expansive engine represented a watershed in the evolution of steam power technology, allowing the attainment of major fuel economies. In Britain, Cornish engineers took the lead in the exploration of this specific technological trajectory. Notwithstanding its superior fuel efficiency was immediately widely discussed, the high-pressure expansive engine did not find widespread application in other steam-using regions (in particular in Lancashire), where the Watt low-pressure engine continued to be the favourite option. This article provides a reassessment of the factors accounting for the precocious adoption of the high-pressure steam engine in Cornwall and for its delayed fortune in the rest of Britain.

Traditional accounts of the British industrial revolution have, more or less explicitly, assumed that a wide range of industrial sectors rapidly benefited from the development of steam power technology. Rostow's work can be considered representative of this view. Rostow dated the British 'take-off' to the years 1783–1802, linking it explicitly with the commercialization of the Boulton and Watt engine.[2] More recent research has suggested that such a direct link between steam power and early industrialization is actually spurious. The available shreds of evidence suggest that during the late eighteenth and early nineteenth centuries, the British economy was still dominated by the extensive use of animal, wind, and water power.[3] Furthermore, the economy-wide repercussions of the progressive adoption of steam technology remained circumscribed until at least the 1840s. Therefore, it seems that traditional accounts have improperly conflated the early development of the steam engine (and in particular the invention of the Watt engine) with its economic significance. In contrast, von Tunzelmann and Crafts point out that the widespread adoption of the steam engine had to await a number of improvements that progressively reduced its power costs relative to other energy sources.[4]

Crafts's recent calculations show that steam power began to contribute significantly to overall productivity growth only from the 1830s and that it exerted its major impact only in the second half of the nineteenth century. According to

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[1] This article has benefited from discussions with Nick von Tunzelmann, Bob Allen, Knick Harley, Christine MacLeod, and Dan Bogart, and from the comments of three anonymous referees. We would also like to thank participants at a seminar at St Antony's College, Oxford, and at a panel of the 2007 Economic History Society Conference in Exeter (in particular Jane Humphries, Avner Offer, John Kanefsky, Roger Burt, and Kate Hamblin) for useful suggestions. The financial support of the Netherlands Organization for Scientific Research (Veni Grant: 'Inventive activities, patents and the Industrial Revolution') is gratefully acknowledged.

[2] Rostow, *How it all began*, pp. 164–7. See also idem, *Stages*, p. 60, and, somewhat more cautiously, Landes, *Unbound Prometheus*, pp. 99–103.

[3] Kanefsky, 'Diffusion', esp. pp. 188–233.

[4] Von Tunzelmann, *Steam power*, pp. 116–73, and Crafts, 'Steam', pp. 344–8.

Crafts, the key factor accounting for this increasing economic impact was the reduction of annual costs per horsepower related to the adoption of the high-pressure expansive engine. The 'expansive use' of high-pressure steam (that is, cutting off the steam when the piston was at the beginning of its course and letting the expansion of the steam inside the cylinder complete the stroke) permitted the attainment of major fuel economies, increasing the cost effectiveness of steam power.[5]

Interestingly enough, already in the 1810s and 1820s, before the establishment of a consolidated theoretical understanding of the operation of the steam engine, Cornish engineers had systematically explored the technical and economic advantages of the high-pressure expansive engine. However, in the rest of Britain, although the gains in fuel efficiency related to the adoption of Cornish practices had been popularized in several engineering publications, the Watt low-pressure engine continued to be the favourite option at least until the mid-1840s.

The aim of this article is to examine the factors accounting for the precocious adoption of high-pressure expansive engines in the Cornish mining district and investigate the 'retardation' factors which may account for its delayed adoption in other contexts. Section I reconstructs technical progress in Cornish steam engineering, and introduces the potential factors behind the extraordinary performance achieved in Cornwall. In section II, a quantitative methodology is used to assess the relative contribution of the different factors driving improvements in engine performance, followed by discussion of how this relates to the peculiar context in which steam power was employed in Cornwall, and in particular the rapid growth of the Cornish mining industry in the first half of the nineteenth century. Section III contains an examination of the issue of the different choice of technique in Cornwall versus other steam-using regions, providing a re-assessment of the contemporary debate. Section IV contains our interpretation of the delayed adoption of the high-pressure expansive engine outside Cornwall, based on insights from some recent literature on the economics of technological change. Section V concludes.

I

The first technically successful use of high-pressure steam can be ascribed to the 'puffer' engines designed by Richard Trevithick around 1800. In these engines, high-pressure steam, after the stroke, was discharged into the atmosphere, rather than being conveyed into the separate condenser. The chief advantage of these engines was their compactness and cheaper cost of installation (due to the elimination of the condenser, the air pump, and the beam). However, this high-pressure non-condensing engine did not make use of early cut-off and was less efficient than the Watt low-pressure engine, as it tended to consume about 25 per cent more coal.[6] In Britain, the compactness of this engine design would make it the most natural option for railway use, but it did not find widespread use in industrial applications, where the Watt low-pressure engine remained dominant. Instead, in the US, the high-pressure non-condensing engine design (in the version developed

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[5] Crafts, 'Steam', esp. p. 345.

[6] Von Tunzelmann, *Steam power*, p. 22.

by Oliver Evans) soon became the standard form of mill engine.[7] Halsey has shown that this choice of technique reflected the peculiarities of many American locations in terms of relatively low fuel costs and high interest rates.[8]

The use of high-pressure steam for attaining fuel economies was the outcome of the parallel efforts of the Cornish engineers Richard Trevithick and Arthur Woolf. In the early 1810s, they developed engines in which high-pressure steam was employed expansively. These engines also made use of the separate condenser which permitted the exploitation of a larger range of operating temperatures (although the rationale for this design feature was not understood until the 1850s with the formulation of classical thermodynamics). The layout of the high-pressure condensing engine developed by Trevithick, making use of beam, separate condenser, and air pump, was substantially the same as a Watt low-pressure engine, with the key exception of a new form of tubular boiler for the generation of high-pressure steam.[9] Woolf instead adopted a so-called compound design in which steam was expanded subsequently in two cylinders.

It is not surprising that these pioneering developments of the high-pressure expansive engine took place in the Cornish mining district. By comparison with other locations, one of the distinctive features of the Cornish mining economy was the high price of coal. As a result, Cornish mining entrepreneurs were keenly interested in improvements in the fuel efficiency of steam engines which could curtail their costly fuel bills. From 1811, they sponsored a monthly publication containing detailed reports on the performance (measured in millions of lbs of water lifted one foot high per consumption of a bushel of coal, or, as it was termed by contemporary engineers, the 'duty' of the engine), technical details, and operating procedures of the steam engines at work in the county.[10] The explicit intention was two-fold. First, the publication would permit the rapid identification and diffusion of best-practice techniques. Second, it would create a climate of competition in the Cornish engineering community, with favourable effects on the rate of technical progress. Joel Lean, a highly respected mine 'captain', was entrusted with the compilation of the reports and the publication was generally known as *Lean's Engine Reporter*.[11]

In a previous article, one of the authors of the present article has argued that the Cornish mining district in the first half of the nineteenth century can be seen as an example of what Allen has termed 'collective invention settings'. Within 'collective invention settings', rival firms or independent individual inventors freely release to one another *pertinent* information concerning the solution of technical problems, rather than appropriating it by means of patents or secrecy. Each firm, in turn,

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[7] Hunter, *History*, pp. 118–72.

[8] Halsey, 'Choice'.

[9] Later on, this type of boiler would be termed 'Cornish' in contemporary engineering literature.

[10] Contemporary engineering measures of fuel efficiency such as duty or lbs of coal per h.p.-hour assessed the overall performance of the steam engine apparatus (boiler + engine). A more modern appraisal would distinguish between the performance of the boiler and that of the engine. In this paper, we will, by and large, adopt the contemporary practice of referring to the aggregate performance of the engine-boiler system.

[11] The first three reports were published in *West Briton*, a local newspaper. From 1812, *Lean's Engine Reporter* appeared as an independent publication. Joel Lean died in September 1812. After his death, the publication was first continued by his sons Thomas (I) and John, and other members of the Lean family later on. The final years (1897–1904) were covered by J. C. Keast. See Howard, *Mr Lean*, for biographical details of the various compilers of the reports. Also, the name of the publication changed over time. In this paper, for sake of convenience, we shall refer to the various reports simply as *Lean's Engine Reporter*.

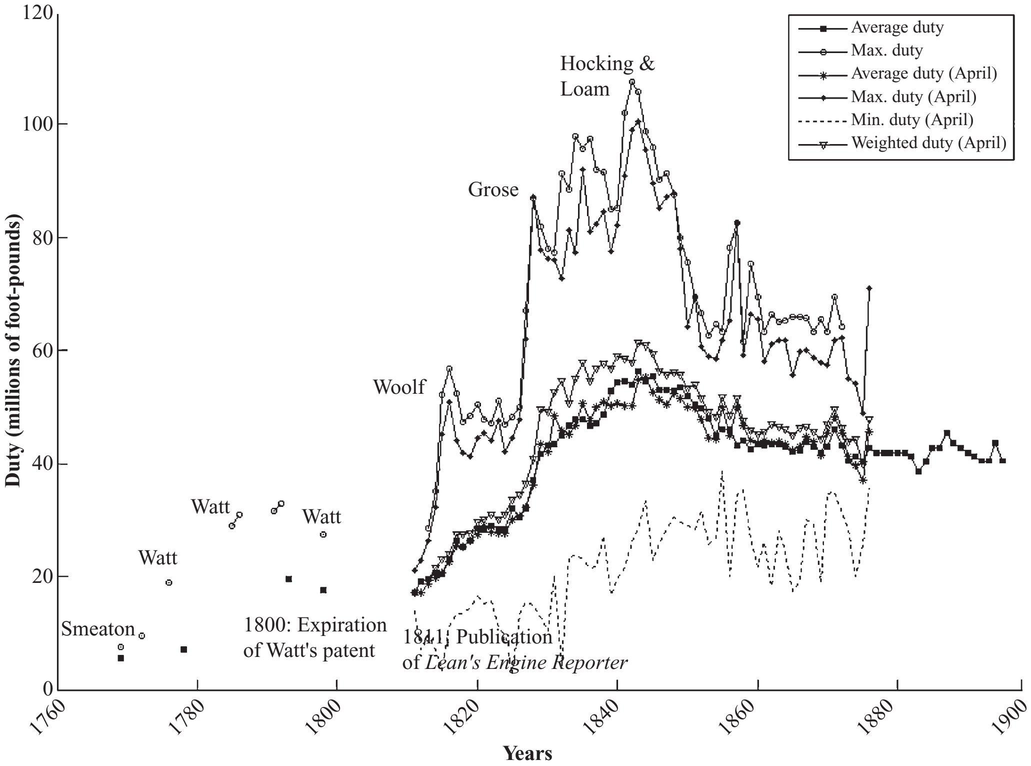

Figure 1. *Duty of Cornish pumping engines, 1769–1895*

Note: Duty is expressed in millions of foot-pounds per consumption of a bushel (94 lbs) of coal.

Sources: 1769, 1772, 1776, 1778: Lean and Brother, *Historical statement*, pp. 5–10; 1779, 1786, 1792: Dickinson and Jenkins, *James Watt*, pp. 329–32; 1798: Gilbert, 'On the progressive improvements', p. 126; 1811–72: Lean II, 'Comment', pp. 200–1; 1811–76 (April): *Lean's Engine Reporter*; 1873–95: Trestrail, 'Duty of the Cornish pumping engines', p. 15.

makes use of the received information to improve incrementally on a basic common technological design. In Cornwall, the chief channel through which information concerning the technological characteristics and the performance of the engines was released was clearly *Lean's Engine Reporter*.[12]

Figure 1 displays the duty of the pumping engines at work in Cornish mines over the period 1811–90, as reported in *Lean's Engine Reporter*.[13] The figure also contains some information on the duty of engines for earlier periods, collated from various sources. Throughout, this article makes use of the duty reported in the

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[12] Allen, 'Collective invention'. For a discussion of the operation of collective invention in Cornish mining district, see Nuvolari, 'Collective invention'. A different view in which the reporting of, sometimes inflated, engine duties is regarded as reflecting the attempt of some engineers such as Woolf to augment their reputation in the interest of their own business, is suggested in Howard, *Mr Lean*. For responses arguing that the duty figures reported should be considered as broadly accurate and that the chief motivation of *Lean's Engine Reporter* was a genuine desire to stimulate technical progress, see Cantrell, 'Review', and Nuvolari and Verspagen, '*Lean's Engine Reporter*', pp. 180–4.

[13] In 1857, the duty measure was changed in millions of lbs lifted one foot high per consumption of a cwt (112 lbs) of coal. In this article, all duty figures have been converted to a uniform standard of millions of lbs lifted one foot high per consumption of one bushel (94 lbs) of coal.

month of April as a general proxy for the duty performed in a given year.[14] Figure 1 shows that the behaviour of the April series is indeed very similar to the corresponding series for the entire year as calculated by the Leans.

Figure 1 indicates that the introduction of the practice of reporting went hand-in-hand with a sustained improvement in the fuel efficiency of the engines. The figure also suggests that the exploitation of the advantages of using high pressure expansively was not achieved instantly, but by means of a process of gradual technological learning. The 'weighted duty' series represents the average duty weighted by the share of the engines in the total horsepower delivered by the reported engine park. This series closely mirrors the simple average duty. The weighted average slightly outperforms the simple average, indicating that more efficient engines also tended to deliver more horsepower.

Figure 2 provides a comprehensive view of the evolution of the duty distribution of the engine park reported. In this figure, the density of the duty distribution in a particular year has been estimated using an Epanenchinkov kernel.[15] The duty performed is reported on the vertical axis. Darker (lighter) areas indicate higher (lower) concentration of engines. Initially, the distribution of the engines is rather concentrated (around a duty of about 20 millions). Then it is possible to distinguish a prolonged phase of increasing dispersion of the density coupled with a growth in average duty. From the 1840s, the 'width' of the distribution appears to narrow down and then remains stable.

Two main factors can account for the wide and growing dispersion of the distribution of duty around the mean. First, as the mining industry expanded, engines were forced to operate in a variety of contexts, ranging from very favourable to sub-optimal operating conditions. Second, since improvements in designs and operating procedures had been attained by extrapolation and guesswork, the actual performance of an engine continued to be surrounded by a good deal of uncertainty.

In a nutshell, the main technical developments responsible for the rapid growth of duty in the period 1810–40 can be summarized as follows: (i) adoption of tubular boilers for the generation of high-pressure steam; (ii) increasing use of early cut-off; (iii) adoption of force-pumps instead of suction pumps and stronger pitwork which permitted a more effective use of the expansive operation of the engine; and (iv) extensive use of steam jacketing and clothing of pipes.[16] These developments were coupled with a number of inventions of a more incremental and 'disembodied' character (improvements in the design of valves and water gauges for boilers, more effective management of the fires, and better cleaning of the engine and boilers).[17]

By the mid-1840s, the Cornish engine had probably reached its practical limits. Carried to the extreme with pressures reaching 50 pounds per square inch (p.s.i.), the expansion of steam produced an extremely powerful shock on the piston and the pitwork. Such an operating cycle increased the probability of breakages in the

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[14] The series for the month of April have been constructed using the almost complete collection of *Lean's Engine Reporter* conserved in the Cornish Studies Library (Cornwall Centre), Redruth. We have integrated some missing or unreadable pages, retrieving the figures from the collection of *Lean's Engine Reporter* conserved in the Science Museum Library, London.

[15] See Silverman, *Density estimation*, for an introduction to kernel density estimation techniques.

[16] Barton, *Cornish beam engine*, pp. 28–58, 88–117.

[17] Von Tunzelmann, 'Technological diffusion', pp. 94–5.

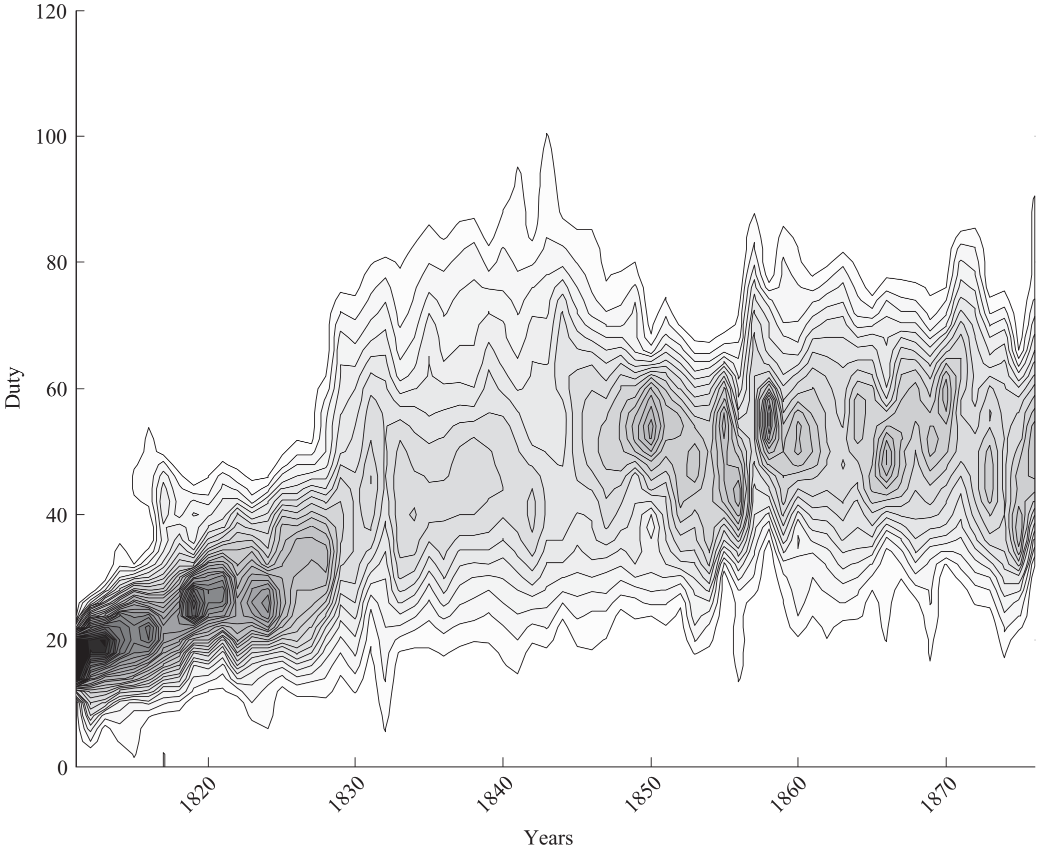

Figure 2. *Kernel density of duty*

Note: Darker shades indicate a higher density.
Source: Lean's Engine Reporter (April 1811–76).

pitwork, accelerating the wear and tear on the engine.[18] One can interpret this phase as one in which decreasing returns to further development of the Cornish expansive design set in. In fact, figure 1 shows that after the early 1840s, the duty of Cornish engines actually declined. This is startling because, at first sight, it might be interpreted as a curious form of 'technological retrogression'. Contemporaries debated the possible factors responsible for this decline of the duty. Overall, it is possible to identify three main factors responsible for the deterioration. First, over time, the number of diagonal, rather than perpendicular, pumping shafts increased. In particular, table 1 shows that, from the 1850s, the share of engines working 'diagonal' shafts grew steadily. This meant that an increasing amount of work was consumed by friction, leading to a deterioration of the duty. This also contributes to explaining the persistent wide dispersion of duty around the mean in figure 2.

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[18] Barton, *Cornish beam engine*, p. 59, cites an interesting passage from the *West Briton*: 'all the coal saved above 70 millions duty is paid for at too dear price in the racking of the engine and pump-work and the increased liability to breakage'. There is no date specified, but it is likely that the statement is referring to the late 1840s. See also Burt, *Short history*, p. 91.

Table 1. *Pitwork of the pumping engines reported*

Year	*Number of engines*	*Pumping perpendicularly*	*(%)*	*Pumping perpendicularly, then diagonally*	*(%)*	*Pumping diagonally*	*(%)*
1812	16	7	(43.75)	8	(50)	1	(6.25)
1822	51	32	(62.75)	18	(35.29)	1	(1.96)
1828	59	40	(67.8)	19	(32.2)	0	(0)
1834	62	44	(70.97)	17	(27.42)	1	(1.61)
1838	61	40	(65.57)	18	(29.51)	3	(4.92)
1840	62	35	(56.45)	24	(38.71)	3	(4.84)
1850	31	22	(70.97)	7	(22.58)	2	(6.45)
1855	22	11	(50)	10	(45.45)	1	(4.55)
1860	25	8	(32)	16	(64)	1	(4)
1868	24	7	(29.17)	16	(66.67)	1	(4.17)
1876	20	5	(25)	15	(75)	0	(0)

Source: Lean's Engine Reporter (April, various years).

A second factor that contributed to the deterioration of duty was the lower quality of the coal used in Cornwall from the early 1840s, an interpretation put forward in a number of contemporary accounts.[19] Finally, the progressive decline of the duty also coincides with stagnation in Cornish mining, which began in the 1850s. As we shall see in the next section, one of the main forces that had driven the growth of duty in the first half of the nineteenth century was a sustained wave of investment in new engines which had been fuelled by the expansion of mining production. In the second half of the nineteenth century, the investment in new engines became sluggish and this had negative repercussions for further improvements in duty.[20]

As Vincenti has suggested, engineers tend to make use of systematic data collection to *bypass* the absence of an adequate scientific understanding of the operation of a technology.[21] This was exactly the situation in early nineteenth-century steam power technology, when no fully-fledged understanding of the working of the steam engine was available. Systematic collection and analysis of performance data allowed Cornish engineers to determine guidelines that could successfully be used to design efficient steam engines.

Unfortunately, *Lean's Engine Reporter* does not include information on a number of important technical characteristics and operating procedures that are intimately linked with the performance improvements described above (for example, steam pressure in boilers,[22] rate of expansion, or cut-off point). In this respect, we should take into account that much more information, besides the tables of the reporter, was shared by Cornish engineers, by means of informal contacts, visits to particularly interesting engines, correspondence, and so on.[23] We can surmise the role played by *Lean's Engine Reporter* in guiding the search for effective design prin-

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[19] See Farey, *Treatise*, vol. II, pp. 180–1, and Sims, 'Cornish engine', pp. 175–7. The use of coal of lower quality could be justified in economic terms, as it was cheaper; see von Tunzelmann, 'Technological diffusion', pp. 97–8, and Burt, *Short history*, p. 91.

[20] A similar link between expansion of productive capacity and performance improvement was also noted by Allen in his study of the Cleveland iron industry; see Allen, 'Collective invention', pp. 14–15.

[21] Vincenti, *What engineers know*, pp. 137–69.

[22] Boiler steam pressures began to be reported by the Leans in the late 1840s.

[23] Farey, *Treatise*, vol. II, pp. 177–82. This is also confirmed in accounts provided by Thomas Wicksteed ('On the effective power') and William Pole (*Treatise*, pp. 150–61), who on their visits to Cornwall had the possibility of having free access to all the installed engines.

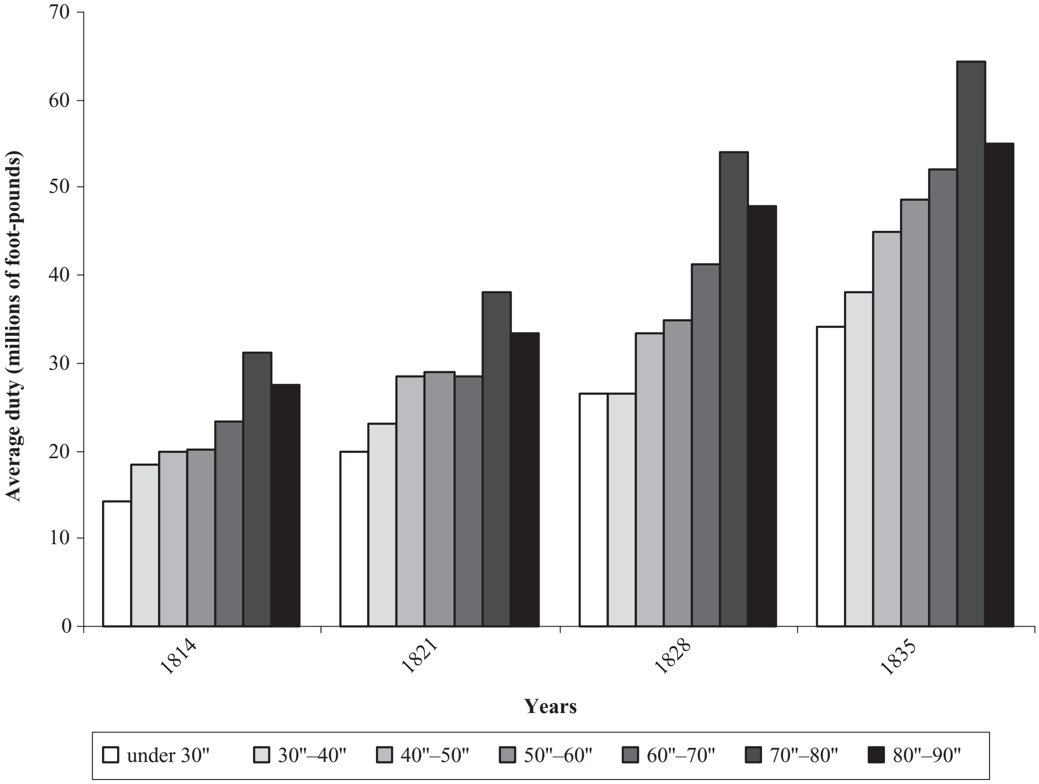

Figure 3. *Average duty of pumping engines of various sizes*
Source: Lean and Brother, *Historical statement*, p. 140.

ciples by considering the development of the cylinder size of the engines. In 1859, in a paper read to the South Wales Institution of Civil Engineers, James Sims presented a detailed description of dimensions, proportions, and operating procedures of an 'ideal' Cornish engine.[24] The overall tone of the paper suggests that Sims was expounding a fairly well-established conventional wisdom. Sims recommended 85 inches as the optimal size of cylinder diameter (if more power was needed, Sims suggested installing two engines, rather than erecting one with a larger cylinder diameter). It is likely that the definition of this optimal size was the result of the elaboration of the performance data of the *Reporter*. Writing in 1839, the Leans constructed tables containing the average duty of engines of different cylinder size, showing that 'the duty performed advances with the size of the engine, till it reaches a certain point (namely, 80″ cylinder) and then recedes'.[25] Farey also made analogous remarks on the basis of a table constructed with the data for the year 1835.[26] Figure 3 reports as histograms the tables constructed by the Leans illustrating the existence of scale economies in duty up to an approximate cylinder size of 80 to 85 inches, with diseconomies of scale taking place

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[24] Sims, 'Cornish engine', pp. 178–9.
[25] Lean and Brother, *Historical statement*, p. 139.
[26] Farey, *Treatise*, vol. II, p. 259.

Table 2. *Distribution of cylinder sizes of the pumping engines reported*

Cylinder size (diameter in inches)	*1811 (%)*	*1821 (%)*	*1831 (%)*	*1841 (%)*	*1851 (%)*	*1861 (%)*	*1871 (%)*
20–9	0	4.65	0	1.72	0	0	0
30–9	8.33	11.63	14	15.52	25.81	17.86	0
40–9	25	16.28	12	10.34	3.23	10.71	9.09
50–9	16.67	20.93	12	8.62	6.45	10.71	4.55
60–9	50	34.88	30	18.97	12.90	25.00	13.64
70–9	0	6.98	14	15.52	22.58	21.43	40.91
80–9	0	0	8	24.14	22.58	10.71	27.27
90–9	0	4.65	10	5.17	6.45	3.57	4.55
Total	100	100	100	100	100	100	100
Number of engines	12	43	50	58	31	28	22

Source: Lean's Engine Reporter (April, various years).

beyond that point. It is interesting to note the abrupt transition to diseconomies of scale above 85 inches. Speculatively, this was probably due either to problems of heat conservation in engines with the largest cylinders, or to difficulties in operating the largest engines with a rate of expansion that would optimize fuel consumption. Although noted by contemporaries, this peculiar 'scaling' behaviour of the Cornish engine has received very little attention from modern historians of technology.

This case provides a good illustration of how the data of the *Reporter* were employed to refine the design of the Cornish engine (in the example, the data permitted the identification of the optimal cylinder size). Table 2 shows the evolution of the distribution of the engines reported by cylinder size. The table indicates that in the initial period (the 1810s), the bulk of the reported engine park is constituted by engines with a cylinder diameter of 60–9 inches. Over time the share of engines of larger sizes (70–9, 80–9, and 90–9 inches) becomes predominant. This is not surprising, as the progressive deepening of mining operations required the use of larger engines. However, in the light of the evidence discussed here, the shift towards larger engines can, at least partially, be interpreted also as a reallocation of productive capacity towards better performing engines, following the extrapolation of the data published in the *Reporter*.

In Cornwall, a great part of the engineers' attention was without doubt devoted to pumping engines. This was the application for which the high-pressure expansive engine was designed and progressively refined. However, from the late eighteenth century, Cornish mines were also employing steam power for drawing ore to the surface (so called 'whim' engines), and from the early 1800s for driving the stamping machinery that was used for crushing mineral ores (stamping engines). Figure 4 shows the evolution of average and maximum duty for these two types of engines. Both whim and stamping engines were delivering rotative power and for this reason the use of duty as an indicator of performance is somewhat capricious. Duty was calculated by converting the amount of work performed by the engines in foot-pounds and then dividing by the amount of coal consumed. It is likely that the calculation was very imprecise. For this reason, it is necessary to interpret these figures with more caution than those of pumping engines.

In figure 4, two points merit attention. First, it is clear that the acceleration in the improvement of performance (which began in the mid-1830s) was delayed in

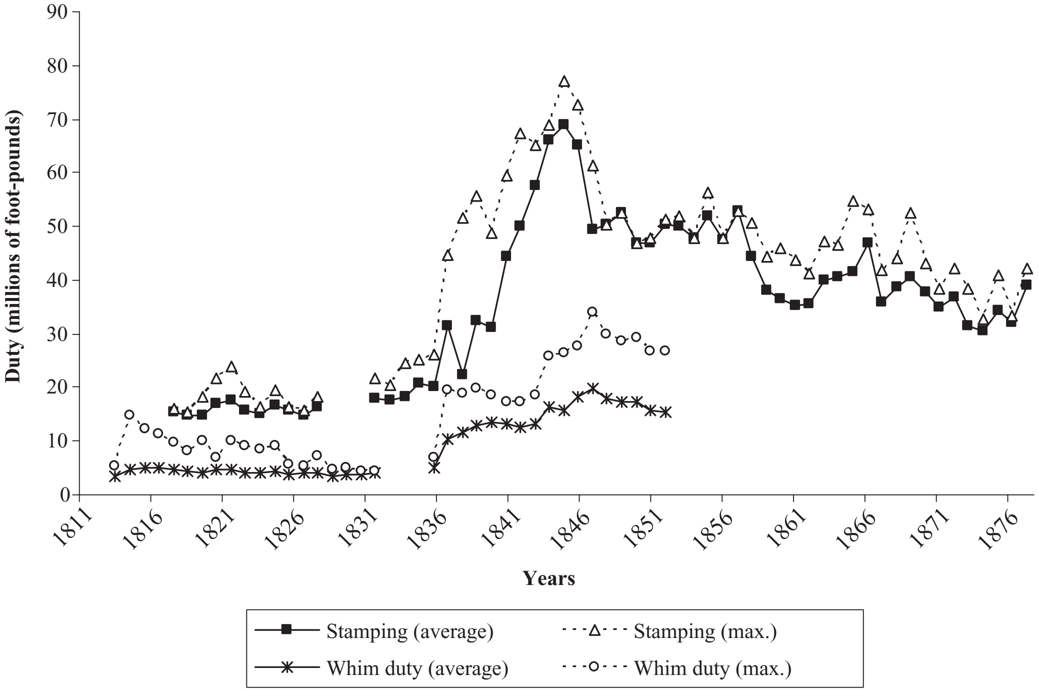

Figure 4. *Duty of Cornish rotative (whim and stamping) engines, 1811–76*
Note: Duty is expressed in millions of foot-pounds per consumption of a bushel (94 lbs) of coal.
Source: Lean's Engine Reporter (April 1811–76).

comparison to pumping engines. The second point is that the maximum performances attained throughout the period were lower than those of pumping engines. Cornish pumping engines were operated by means of a very irregular cycle that allowed the full exploitation of the expansion of high-pressure steam in the cylinder. This means of operation was not particularly suited for delivering rotative power to machinery that required a smoother action and a consequent reduction of the rate of expansion. Further, it is also worth noting that, given their relatively small share in the overall coal costs of a mine, efficiency was a somewhat minor concern for this type of engine (this explains their relative neglect in the 1810s and 1820s), the main goal being the maximization of the power delivered by the rotative engine.[27]

II

It is possible to probe the forces underlying the improvement of the high-pressure expansive pumping engine in Cornwall by carrying out an accounting exercise that examines the behaviour of different segments of the engine population (more

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[27] Burt, *Short history*, pp. 96–7. In 1835, the amount of coal consumed by stamping and winding engines in Cornwall was about one-fifth of the coal consumed by pumping engines; see Lean and Brother, *Historical statement*, p. 146.

specifically, we distinguish between existing and new engines). It is important to note that some innovations could, to some extent, be retrofitted into existing engines. Von Tunzelmann has specifically argued that this continuous upgrading of installed capacity permitted a rapid diffusion of technical improvements and was one of the main factors responsible for the sustained improvement of the average performance of Cornish engines in the first half of the nineteenth century.[28]

The analytical tool that we will use resembles the decomposition exercises that, in the industrial economics literature, are employed to single out the factors contributing to productivity growth in 'longitudinal' data sets of industrial plants or firms.[29] In our case, we will consider the weighted average of duty as an aggregate indicator of the technological performance of our engine park. The weighted average duty in a given year is given by:

$$\bar{D}_t = \sum_{i=1}^{J} S_{i,t} D_{i,t} \tag{1}$$

where J = number of engines in operation at time t; $S_{i,t}$ = share of horsepower delivered by engine i in year t in the total horsepower employed in the same year; and $D_{i,t}$ = duty performed by engine i in year t.

Using the following decomposition formula, it is possible to identify the main contributing factors underlying the growth of weighted average duty:

$$\frac{\bar{D}_t - \bar{D}_{t-1}}{\bar{D}_{t-1}} = \frac{\sum_{i \in C} (D_{it} - D_{it-1}) S_{it-1}}{\bar{D}_{t-1}} + \frac{\sum_{i \in C} (S_{it} - S_{it-1}) \left(D_{it-1} - \bar{D}_{t-1}\right)}{\bar{D}_{t-1}} + \frac{\sum_{i \in C} (S_{it} - S_{it-1}) (D_{it} - D_{it-1})}{\bar{D}_{t-1}} + \frac{\sum_{i \in N} \left(D_{it} - \bar{D}_{t-1}\right) S_{it}}{\bar{D}_{t-1}} - \frac{\sum_{i \in X} \left(D_{it} - \bar{D}_{t-1}\right) S_{it}}{\bar{D}_{t-1}} \tag{2}$$

In the formula, C represents the set of 'continuing' engines, N the set of new engines (that is, engines installed in year t), and X the set of 'exiting' engines (that is, engines active in year $t - 1$ that were scrapped in year t).

The first term on the right-hand side represents a 'within' engine component accounting for the improvement of 'continuing' engines weighted by their initial share. This term captures the more efficient operation of installed productive capacity (arising from learning by using or from technical improvements that were retrofitted into existing engines, and so on). The term may be regarded as a measure of the 'disembodied' component of technical progress. Note that whenever the physical deterioration of the engines is not counterbalanced by maintenance and repairs and by the 'disembodied' component of technical change, the term will assume a negative value.

The second term on the right-hand side represents a 'between' engine component. This term reflects the increase of the average duty due to the reallocation of the installed capacity from worse to better engines (or vice versa). Note that the term is expressed as a deviation from the mean. Overall, this term can be consid-

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[28] Von Tunzelmann, 'Technological diffusion', pp. 93–5.

[29] Bartelsman and Doms, 'Understanding productivity'.

Table 3. *Decomposition of duty growth in Cornish pumping engines, 1814–74*

Period	*Within engine*	*Between engine*	*Cross engine*	*Entry*	*Exit*	*Overall growth*
1814–24	0.046	–0.007	–0.012	0.401	–0.009	0.436
1824–34	0.153	–0.006	–0.042	0.641	–0.029	0.775
1834–44	–0.004	–0.001	0.003	0.104	–0.005	0.107
1844–54	–0.021	–0.021	–0.024	–0.125	0.016	–0.208
1854–64	–0.022	–0.010	0.012	–0.037	–0.013	–0.044
1864–74	–0.025	–0.010	–0.018	0.021	0.007	–0.040

Source: Lean's Engine Reporter (April 1814–74).

ered to reflect the degree of efficiency in the management of the existing engine park (an effective management of installed productive capacity would require the most efficient engines to deliver more horsepower). By virtue of the 'rigidities' involved in the use of steam power for draining mines, we may expect this term to be relatively small.

The third term on the right-hand side represents a 'cross' effect, capturing the growth of the average duty determined by the reallocation of productive capacity towards more 'dynamic' engines, that is, engines showing higher duty growth rates (note that the 'between' engine component reflects the reallocation of capacity towards engines with higher duty *levels*). Also this term can be seen as representing a technology management aspect, and we expect it to be relatively small.

The fourth term on the right-hand side measures the improvement of the average duty due to the introduction of new engines, which can be regarded as the contribution of 'embodied' technical change. This term is, again, expressed as a deviation from the mean, so, to give a positive contribution to average duty growth, a 'new' engine should perform a higher duty than the average duty of the previous period. As engines were sometimes moved from one mine to another, in some cases, it is difficult to identify whether an engine that appears in the columns of the *Reporter* is new or an existing engine transferred from another mine. This can bias the decomposition exercise, introducing an overestimation of the 'entry effect' and an underestimation of the 'within' effect.

Finally, the fifth term represents the effect due to the scrapping of existing capacity. Also in this case the term is expressed as a deviation from the mean. Accordingly, only the scrapping of engines with below-average performance contributes positively to duty growth.

Table 3 reports the results of the decomposition exercise. We have considered 10-year intervals.[30] The first three intervals, from 1814 to 1844, cover the phase of sustained duty improvement in figure 1. In this phase the predominant contribution to duty growth is given by the 'entry' effect (the installation of new engines). The 'within' engine effect is also positive, indicating the existence of possibilities for improving the performance of existing engines by means of processes of learning by using, and other forms of 'disembodied' technical change.

In fact, our results indicate that—although the 'upgrading' of installed engines, throughout the years 1814–34, made a positive contribution to duty growth—the installation of new engines represented the *major* factor accounting for duty

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[30] Alternative periodizations (3, 5, 7, and 12 years) were tried, leading to very similar results.

growth.[31] In other words, our results suggest that technical progress in Cornish steam engineering in the first half of the nineteenth century assumed essentially an 'embodied' form and could be realized only when investment for expanding or replacing existing capacity was taking place. It would seem that von Tunzelmann has probably overestimated the contribution of the 'within' effect to the average improvement in performance.

Additionally, it is also clear that, given the initial composition of the engine park where the bulk of engines had a cylinder size of 60–9 inches (see again Table 2), the installation of new engines was necessary to reallocate productive capacity towards engines of larger size which were able to score higher duties. This strong contribution of the entry effect is also a factor accounting for the relatively wide dispersion of engine performances shown in figure 2.

The 'between' and 'cross' effects, throughout the whole period from 1814 to 1870, appear to affect duty growth in a relatively minor way, as expected. This can be accounted for by the existence of 'rigidities'; in other words, there was a rather narrow scope for adjusting the horsepower delivered by the engine, once this was installed.

As shown in figure 1, the period 1844–74 is a phase of relative stagnation in the historical evolution of the duty. Again, the major contributing factors to (negative) duty growth are the 'within engine' effect, which shows a deterioration of installed capacity (this may well be a consequence both of the decline in the quality of coal used and of a diminished rate of expansion) and the 'entry' effect. Note that since the entry effect is taken in deviation from the mean, this indicates that new engines tended to have *lower* duty than the average of the installed capacity.

In summary, our analysis suggests that the precocious development and refinement of the high-pressure engine in Cornwall was the outcome of a process of technological learning taking place in a very favourable context. Our results show that the main driver of technical progress in Cornish steam engineering was a powerful wave of 'innovative investment' which took place throughout the first half of the nineteenth century, following the sustained expansion of the Cornish mining industry.[32] In the Cornish context, the expansion of productive capacity was coupled with an experimentation with design modifications and with the discovery of many improvements related to the use of high-pressure expansive steam for pumping applications, resulting in an effective exploration and extension of the technological frontier. Furthermore, in the Cornish context, the diffusion of these innovations was enhanced by an institutional set-up that stimulated the rapid dissemination of technological knowledge and that had no counterpart in the rest of Britain.[33] Finally, the accumulation of technological knowledge was further reinforced by 'disembodied' processes of learning by doing and by using (accounted for by the within effect of our decomposition) that allowed some improvement of installed capacity.

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[31] As noted above, our estimation of the 'entry' effect can contain some upward bias to the detriment of the 'within' effect. However, for each of the three periods 1814–24, 1824–34, 1834–44, the difference between the magnitudes of the two effects is so large that we can conclude that, notwithstanding some possible overestimation, our decomposition is probably correct in determining the relative contribution of the two effects.

[32] See Barton, *History of copper mining*, pp. 45–74.

[33] In several instances, there were proposals for introducing similar systems of reporting for steam engines at work in textile areas, but nothing followed; see Hills, *Power*, p. 131.

III

In retrospect, it is not surprising that competent contemporary observers paid great attention to technological developments in Cornwall as portrayed in the engine reports. A large body of contemporary engineering literature on steam technology was precisely informed by the debate on the different choice of technique characterizing the use of steam power in Cornwall (where the high-pressure expansive engine was adopted) versus the rest of Britain, especially the manufacturing districts of the north, where the Watt low-pressure engine continued to be the favourite option.

The superior fuel efficiency of the Cornish practice led some contemporary observers to describe this situation as a case of 'entrepreneurial failure', with the rest of country unduly hesitant in their transition to the high-pressure expansive engine. For example, William Fairbairn, an authoritative member of the Lancashire engineering community, and one of the leading advocates of the merits of the high-pressure expansive engine whose pleadings remained for a long period unfulfilled, wrote in 1849:

> For a great number of years a strong prejudice existed against the use of high-pressure steam and it required more than ordinary care in effecting the changes which have been introduced: it had to be done cautiously, almost insidiously, before it could be introduced. The author of this paper believes he was amongst the first in the Manufacturing Districts who pointed out the advantages of high-pressure steam when worked expansively, and for many years he had to contend with the fears and prejudices of the manufacturers.[34]

Similarly, John Farey vigorously denounced a widespread and culpable 'state of apathy as to consumption of fuel' in the 'great manufacturing districts of the North'.[35]

According to James Nasmyth, the inventor of the steam hammer, the actual beginnings of the adoption of high pressure with expansion in Lancashire could be reasonably dated to the late 1840s, when 'timid and prejudiced traditions' had been finally dissipated. In a letter of 1852 cited by Factory Inspector Leonard Horner, Nasmyth wrote:

> The engine power of this district [Lancashire] lay under the incubus of timid and prejudiced traditions for nearly forty years, but now we are happily emancipated. During the last fifteen years, but more especially in the course of the last four years [since 1848] some very important changes have taken place in the system of working condensing steam engines . . . The result has been to realize a much greater amount of duty or work performed by identical engines, and that again at a very considerable reduction of the expenditure of fuel . . .[36]

These passages suggest that, despite numerous solicitations, many engineers and practitioners had remained extremely sceptical, at least till the late 1830s, about the fuel advantages of using high-pressure steam expansively. Since the superior fuel efficiency of the high-pressure expansive engine had remained theoretically mysterious, the dramatic early rise of the duty of the (best-practice)

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[34] Fairbairn, 'On the expansive action', pp. 23–4.

[35] Farey, *Treatise*, vol. II, p. 307.

[36] *Reports of Inspectors* (P.P. 1852–3, XL), p. 484.

Cornish expansive engines (in the 1810s up to more than 40 million and by the late 1820s to more than 80 million) was not easily accepted outside Cornwall. In fact, several doubts were voiced on the actual levels of efficiency achieved by Cornish engines, actually denying the existence of a Cornish technological lead. In 1838, G. H. Palmer published an article in the authoritative *Transactions of the Institutions of Civil Engineers*, in which he contended that the levels of fuel efficiency claimed for the Cornish engine were undoubtedly exaggerated (because they were in open contrast with the caloric theory of heat):[37]

> If the statements given to the public by the Cornish engineers, whose sincerity I cannot doubt are correct, I dare not trust to call nature to account for the undue favouritism she confers upon our Cornish friends by enabling them to perform results that the London, Manchester and Birmingham engineers cannot approach . . . Upon what principle then, permit me to ask, can the Cornish engines perform so much more than all other engines. Strong, indeed, should be the evidence that ought to outweigh or cancel the . . . laws of nature, and induce this Institution to sanction statements of duty more than double of the best Watt engine, and still more, surpassing the limits Nature has assigned steam to perform.[38]

The most strenuous defender of Lancashire technical practice was perhaps Robert Armstrong. In his *Essay on the boilers of steam engines*, published in 1839, he declared that the Cornish duty figures were undoubtedly 'gross exaggerations', the real duty probably being about 30 million. He concluded that 'there is nothing in their [Cornish] system of management that can be profitably imitated here [Lancashire]'.[39]

Alternative explanations for the different technical choice have also been put forward. It is frequently held that concerns about safety delayed the adoption of the high-pressure engine. According to this view, the reluctance to shift to the high-pressure engine was a manifestation of different propensities towards risk between Cornwall and other areas of Britain (with Cornish engineers being more inclined to bear the risks of boiler explosions). In fact, the available data on the number of boiler explosions indicate that in Cornwall high-pressure steam was employed very safely throughout the first half of the nineteenth century.[40] On the other hand, the evidence also suggests that, when it occurred, the transition to high-pressure expansive steam in the rest of Britain did take place *notwithstanding* the increased risks of explosions. In fact, in the 1840s, in Lancashire it was not infrequent to increase steam pressure by placing bricks on safety valves, with few concerns for the increased risks of explosions.[41] These considerations, in our

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[37] In the same article, Palmer ('On the application of steam', p. 46), on the basis of the caloric theory of heat, fixed the maximum duty attainable by a steam engine at 44 million.

[38] Ibid., pp. 44–6.

[39] Armstrong, *Essay*, p. 76.

[40] See Marten, *On boiler explosions*. Most apprehensions over boiler explosions in the first half of the nineteenth century were related to the engines of steamboats. See Hills, *Power*, pp. 144–7, and Hunter, *History*, pp. 648–52. Public concerns over the safety of steam boilers in industrial applications actually only emerged from second half of the 1840s, concomitantly with the transition to high-pressure steam in manufacturing districts. See in particular the statements of William Fairbairn in front of the Select Committee of Parliament on steam boiler explosions; *S.C. on Causes* (P.P. 1870, X), pp. 467–8.

[41] Bartrip, 'State and the steam boiler', p. 80.

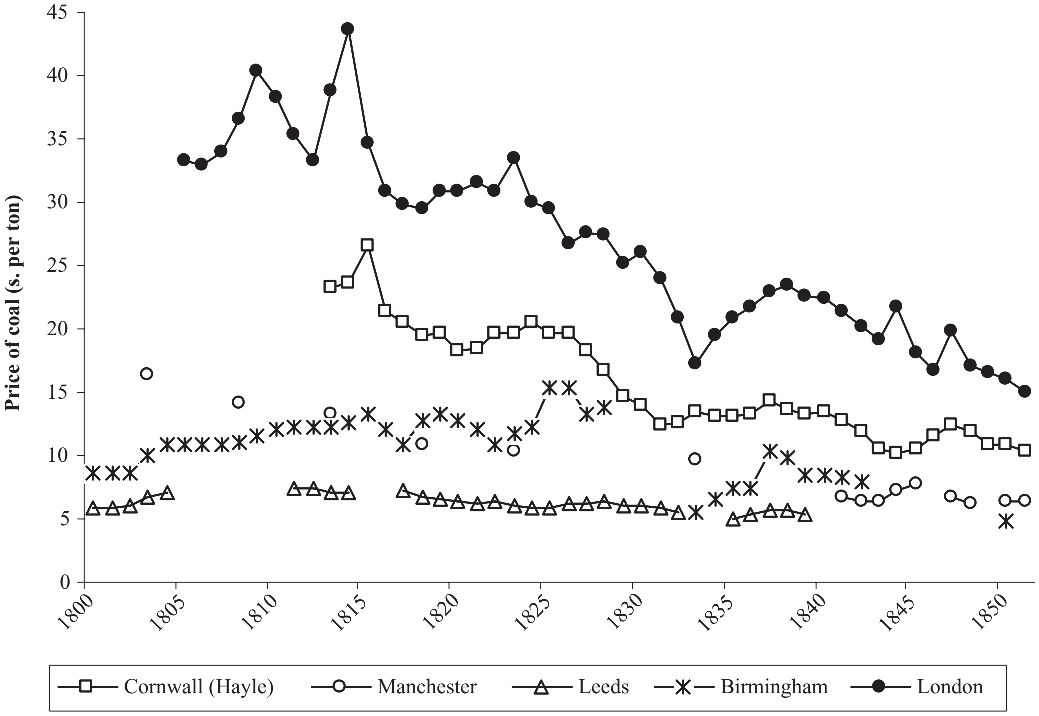

Figure 5. *Coal prices, 1800–50*

Sources: Manchester, Leeds, Birmingham, and London: von Tunzelmann, *Steam power*, p. 97; Hayle: von Tunzelmann, 'Some economic aspects', pp. 199–200.

judgement, circumscribe the possible role that fears of boiler explosions might have played in delaying the adoption of high-pressure steam outside Cornwall.[42]

Another possible explanation is that the different technical choice in Cornwall compared with the rest of Britain reflected factor prices prevailing in each location (in particular, the price of coal). This interpretation turns the argument of 'entrepreneurial failure' on its head.

Figure 5 displays series of coal prices in various locations for the period 1800–50. In this time-span, the price of coal in Cornwall appears to have been higher than those prevailing in Lancashire (Manchester), Yorkshire (Leeds), and in the midlands (Birmingham). The price of coal in London, instead, was higher than in Cornwall. We do not have systematic information on the rental cost of capital. Some evidence suggests that interest rates were lower in the south-west than in the north, providing further incentive to substitute capital for coal, but it is very difficult to formulate an estimate of the differential.[43] Here we will mostly focus on differences in coal prices, which are probably the main factor affecting the choice of technique.

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[42] See also von Tunzelmann, *Steam power*, pp. 88–9. Hunter, *History*, p. 649, notices that '[i]n the discussions of the Cornish pumping engine that led to their introduction in the London area in the late 1830s there was virtually no reference to the hazards of the high pressures used'.

[43] Von Tunzelmann, *Steam power*, p. 85.

Following this line of inquiry, it is possible to examine in some detail two cases of adoption of the high-pressure engines in the late 1830s and early 1840s and carry out some simple profitability assessments. In the case of the purchase of a new engine, an entrepreneur will be indifferent between a high-pressure and low-pressure engine when

$$K_H(i+d)+C_H\cdot H\cdot p_c=K_L(i+d)+C_L\cdot H\cdot p_c \tag{3}$$

In the formula, K_H represents the capital costs per horsepower (h.p.) for the high-pressure engine, i is the annual interest rate, d is the depreciation rate, C_H is the consumption of coal per h.p.-hour for the high-pressure engine, H is the amount of working hours in the year, P_c is the price of coal, K_L is the capital cost per h.p. for the low-pressure engine, and C_L is the coal consumption per h.p.-hour of the low-pressure engines.[44] The formula can be used to calculate the 'threshold' coal price for the technical choice between the two types of engines, P_c.[45]

$$p_c=\frac{(K_H-K_L)(i+d)}{(C_L-C_H)H} \tag{4}$$

In other words, if the price of coal is equal to P_c, an entrepreneur will be indifferent between a high-pressure and low-pressure engine. If the price of coal is higher than P_c, it will be economic to adopt the high-pressure engine; and vice versa, if the price is lower, the low-pressure engine represents the optimal choice.

In case there is a low-pressure engine already installed, an entrepreneur will be indifferent between installing a new high-pressure one and keeping the old one when

$$K_H(i+d)+C_H\cdot H\cdot p_c=C_L\cdot H\cdot p_c. \tag{5}$$

In this case, the threshold coal price is given by

$$p_c=\frac{K_H(i+d)}{(C_L-C_H)H} \tag{6}$$

We will examine first the profitability of adopting a high-pressure expansive engine for pumping applications (the user context most similar to the Cornish case). One of the first high-pressure expansive pumping engines installed outside Cornwall was erected at the East London Waterworks as late as 1838. The installation was preceded by a journey made by Thomas Wicksteed to Cornwall where he conducted detailed research on the merits of the Cornish engine.[46] Although Wicksteed heartily encouraged the adoption of Cornish engines, the management

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[44] Clearly, the formula assumes that labour costs per h.p. and maintenance costs are the same for the two types of engine. See ibid., pp. 79–91, and also Halsey, 'Choice', pp. 727–8. The profitability assessments consider only the cost of engines and boilers and do not include engine house and foundations. These omitted costs are not likely to introduce major biases in the results; again see von Tunzelmann, *Steam power*, pp. 57–9.

[45] For a discussion of the threshold approach to the adoption of new technologies, see David, *Technical choice*, pp. 195–287. For two earlier applications to the study of steam power technology, see von Tunzelmann, *Steam power*, pp. 47–97, and Halsey, 'Choice'.

[46] Wicksteed, 'On the effective power', pp. 117–20; idem, *Experimental inquiry*, pp. 1–8.

Table 4. *Profitability of a high-pressure engine for pumping applications, 1839*

	Cornish	*Boulton & Watt*	*Coal price (s. per ton)*	*Coal price (s. per ton)*
Duty (millions of foot-pounds)	90.809	40.049		
Coal consumption (lbs per h.p.-hour)	2.05	4.65		
h.p.	135	71.50		
Total costs (£)	7,600	(—)		
Capital costs per h.p. (£)	56.30	(45)		
Capital costs per h.p. per annum (£)	5.63	4.50		
Threshold coal price for replacing an already working engine (s. per ton)				
(4,500 hrs)			21.58	
(5,000 hrs)			19.42	
(5,500 hrs)			17.65	
(6,000 hrs)			16.18	
(6,500 hrs)			14.94	
Threshold coal price for a new engine (s. per ton)				
(4,500 hrs)				4.33
(5,000 hrs)				3.90
(5,500 hrs)				3.54
(6,000 hrs)				3.25
(6,500 hrs)				3.00

Notes and sources: Duty, total costs, and h.p. delivered are from Wicksteed, *Experimental inquiry*, pp. 36–40. Coal consumption per h.p.-hour is calculated as 186.12/duty (see Pole, *Treatise*, p. 171); the hypothetical cost per h.p. of a Watt pumping engine is based on von Tunzelmann, *Steam power*, p. 54; interest + depreciation rate set at 10% (see discussion in Kanefsky, 'Diffusion', pp. 167–70).

of the waterworks remained reluctant. Finally, in 1838, a second-hand Cornish engine was purchased for £7,600 on the condition that it would perform a duty of 90 million over 12 consecutive months, otherwise a penalty had to be paid.[47] Once the engine was installed, Wicksteed made a systematic comparison of the performance of the new Cornish engine with that of a Boulton and Watt engine.[48] In table 4, we assess the profitability of adopting high-pressure expansive engines for pumping applications in the late 1830s using Wicksteed's data. As it is hard to estimate a typical number of working hours for engines employed in waterworks, we have computed the threshold coal price for a reasonable range of possible values.[49] The upshot of the results of table 4 is rather striking (although probably not fully surprising for a reader acquainted with the contemporary engineering discussions). At the high price of coal (around 20 s.) prevailing in London, it would have been worthwhile to scrap all the installed low-pressure engines and replace them with new high-pressure engines.

As mentioned earlier, some technical teething problems hampered the adoption of high-pressure steam expansively in engines employed to power machinery. The Cornish practice of expansive operation could not be easily transferred to mill operations, where the application of the steam engine to industrial processes generally required a smooth and regular piston movement.[50]

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[47] Barton, *Cornish beam engine*, p. 258.

[48] Wicksteed, *Experimental inquiry*.

[49] Von Tunzelmann, *Steam power*, p. 73. In several cases steam engines in waterworks were worked around the clock for long periods; thus the most plausible estimates are those on the high side. For example, the Cornish engine of East London Waterworks for the first 18 months worked 24 hours per day with only occasional stoppages; see *Civil Engineer and Architect Journal*, Feb. 1840, p. 66.

[50] Parkes, 'On steam boilers', p. 67.

Table 5. *Profitability of a compound high-pressure engine for a textile mill, 1841*

	Low-pressure condensing engine			*Woolf compound*				
Coal consumption (lbs per h.p.-hour)	*14*			*5*				
h.p.	*Engine (£)*	*Boiler (£)*	*Capital costs per h.p. p.a. (£)*	*Engine (£)*	*Boiler (£)*	*Capital cost per h.p. p.a. (£)*	*Threshold coal price for a new engine (s. per ton)*	*Threshold coal price for replacing an existing engine (s. per ton)*
6	330	50	8.33	335	65	8.88	0.71	11.63
10	435	65	6.58	450	100	7.38	1.05	9.66
12	480	80	6.17	510	120	7.06	1.17	9.25
16	550	100	5.39	620	150	6.48	1.43	8.49
20	630	120	4.99	720	180	6.08	1.42	7.96
25	710	150	4.60	800	220	5.54	1.23	7.26
30	770	180	4.26	870	260	5.14	1.16	6.74
40	960	240	4.05	1,130	320	4.93	1.15	6.46
50	1,170	280	3.91	1,350	400	4.78	1.14	6.25

Notes and sources: Coal consumption and data on engine and boiler costs are from Hills, *Power*, p. 119. In calculating capital costs p.a., following von Tunzelmann, *Steam power*, p. 72, we have made these assumptions: depreciation rate set at 7.5% p.a. for the engine and at 12.5% p.a. for the boiler; interest rate set at 5%. For calculating the threshold coal price, we have assumed 3,800 working hours per year; see ibid., p. 73.

Some of the problems created by the irregular power cycle could be solved by expanding the steam in two separate cylinders, thus reviving the Woolf double cylinder compound design, which had not met with much success in Cornwall. This, however, involved some loss of fuel efficiency. We can safely assume that this technical solution was feasible because the Woolf compound expansive engine had become the favourite technical choice in France in many industrial applications from the 1820s.[51]

Von Tunzelmann has calculated the 'threshold' coal price at which, for rotative applications around 1835, it would have been economically worthwhile to install a new high-pressure expansive engine, instead of a low-pressure one, at 12 s. per ton.[52] This result, according to von Tunzelmann, goes some way in the direction of rehabilitating Lancashire entrepreneurs from the allegations of entrepreneurial failure to which contemporaries, such as Farey, had condemned them.

We can provide a new calculation of this threshold coal price in manufacturing applications in 1841 using a list of prices for the engines produced by Benjamin Hick. Hick was one of the pioneers of the introduction of compound high-pressure expansive engines on the Woolf plan into the textile industries, and his engines should probably be considered as best practice for the time.[53]

In table 5, we report Hick's prices and estimates of coal consumption and our calculation of the threshold coal prices.[54] When installing a new engine, for the

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[51] The compound design was imported into France by Woolf's former partner Edwards, and it became very popular in industrial applications in the period 1815–50; see Payen, 'La technologie', pp. 384–5.

[52] Von Tunzelmann, *Steam power*, p. 91.

[53] A glowing appraisal of Hick's compound engines was given in Farey, *Treatise*, vol. II, p. 306.

[54] Hick's estimates of coal consumption are consistent with those reported in other sources. Zachariah Allen estimated the average fuel consumption of the steam engines installed in Manchester in 1831 as 13 lbs. About 10 years later in 1842, Fairbairn considered this to be about 10.5 lbs; see Hunter, *History*, p. 600. In the same year Josiah Parkes ('On steam boilers', p. 67) estimated average coal consumption in industrial applications at 15 lbs.

most common sizes in this period (that is, 40 and 50 h.p.),[55] it would have been economically justified to adopt high-pressure expansive engines even in locations with a low coal price. The calculated threshold coal price for engines of 30, 40, and 50 h.p. is equal to slightly more than 1 s. a ton, which is even lower than the cost of 'slack' coal at the colliery pithead.[56] When a low-pressure engine was already installed, results are less clear-cut and possibly consistent with maintaining the low-pressure engine as the favourite technical choice if coal prices were lower than 7 s. Overall, our results indicate a greater cost effectiveness of the high-pressure expansive engine than was originally estimated by von Tunzelmann.[57]

In figure 6, we generalize our findings by plotting the threshold function (4) for both pumping and rotative engines in the space of factor prices. The horizontal axis is expressed in terms of rental cost of capital $(i + d)$, so that the threshold function is represented by a line through the origin. For factor price combinations above the line, the high-pressure expansive engine is the optimal choice, while below the line the low-pressure option is better. The threshold functions are calculated using data that can be considered as representative for 'best practice' engines around 1840. Interestingly enough, the threshold line for rotative engines lies below that for pumping engines. This is because, as also indicated by Wicksteed's data in table 4, the differential in coal consumption between high-pressure and low-pressure engines was lower in pumping than in rotative engines.[58] We can probably consider a rental cost of capital ranging between 8 and 20 per cent as a suitable approximation for most of the areas in question.[59] Figure 6 suggests that, when installing a new pumping engine, given the savings in coal costs, in locations with high coal prices such as London and the south-east, it would have been clearly economically advantageous to adopt high pressure.[60] This result fully vindicates the allegations of technological conservatism voiced in the contemporary engineering literature discussed above, *as far as pumping applications are concerned.* In this sense, the slow diffusion of Cornish practices in pumping applications in areas

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[55] See, for example, Hills, *Power*, p. 116.

[56] Von Tunzelmann, 'Some economic aspects', p. 63, gives a price of 2 s. 8 d. for slack coal for a Staffordshire colliery in the period 1828–36.

[57] Our calculation suggests that threshold price computed by von Tunzelmann for 1835 is overrated. The source of this overestimation is in the estimated increase in capital costs resulting from the adoption of the Cornish high-pressure boiler, which von Tunzelmann assumes to increase in direct proportion with heating surface (this amounts to multiplying the price of the 'corresponding' low-pressure boiler by 7.5). Thus, for a 30 h.p. engine, he puts total boiler cost at £1,500. Casual evidence shows that this errs far too much on the high side. In 1838, *three* boilers for a 60-inch engine for the Fresnillo Mine in Mexico were sold for £963 (Barton, *Cornish beam engine*, p. 280). In 1841, James Sims offered, in an advertisement published in the *West Briton*, an 80-inch pumping engine for £2,600, *inclusive of boilers* (Barton, *Cornish beam engine*, p. 52). These figures are broadly consistent with the prices in tab. 3. In this respect, one has to take into account that in low coal price regions, steam engine manufacturers like Hick generally avoided constructing the full-size Cornish boiler, opting for a 'shortened' and cheaper version of the elongated Cornish cylindrical boiler; see von Tunzelmann, *Steam power*, pp. 83–4.

[58] In the first half of the nineteenth century, Watt pumping engines did actually make use of some expansion of steam in the cylinder. However, the use of low-pressure steam did not allow a full exploitation of the expansive operation; von Tunzelmann, *Steam power*, p. 76.

[59] Annual interest rates were likely to range between 5% and 10%. For depreciation, a range of variation between 3% and 12% is probably adequate; see Kanefsky, 'Diffusion', pp. 169–70. See also Jenkins, 'Wool textile industry', pp. 135–6. Fairbairn, *Treatise*, pp. 92–3, uses a total rental cost of capital of 10% (covering 'interest of capital, repairs and renewals') when discussing the profitability of a 100 h.p. steam engine for cotton mills.

[60] In 1840, William Fairbairn published a paper ('On the economy') advocating the adoption of the Cornish engine to drain *collieries* in the north-east.

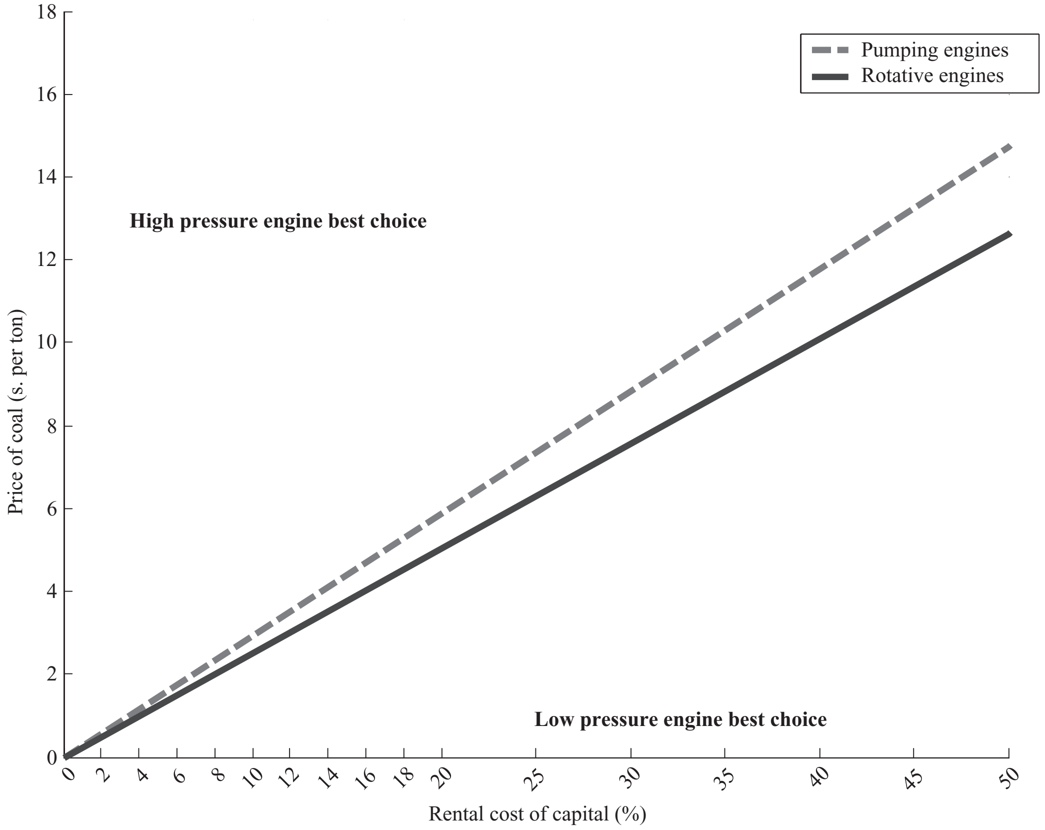

Figure 6. *Steam engine profitability in 1840*

Notes and sources: We have assumed 6,000 hours worked per year for the pumping and 3,800 hours for the rotative engine (see von Tunzelmann, *Steam power*, p. 73). With regard to capital costs per h.p. (engine plus boiler), we have assumed £60 for the high-pressure pumping engine (see Kanefsky, 'Diffusion', pp. 159–61, and Wicksteed, *Experimental inquiry*, p. 3), £45 for the low-pressure pumping engine (see von Tunzelmann, *Steam power*, p. 54), £50 for the high-pressure rotative engine, and £35 for the low-pressure rotative engine (von Tunzelmann, *Steam power*, pp. 84–7; Kanefsky, 'Diffusion', p. 158). Coal consumption is assumed to be 2.2 lbs per h.p.-hour for the high-pressure pumping, 6 lbs per h.p.-hour for the low-pressure pumping, 5 lbs per h.p.-hour for the high-pressure rotative pumping, and 12 lbs per h.p.-hour for the low-pressure rotative pumping (von Tunzelmann, *Steam power*, pp. 69–70, 76).

with high coal prices may be said to reflect entrepreneurial failures or information delays.[61] When looking for possible causes of this outcome, two considerations are in order. First, the engineering reputation of Boulton and Watt was particularly strong among waterworks engineers (especially in London) and this can account for scepticism towards Cornish achievements.[62] Second, water supply by statutory

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[61] In other mining areas such as North Wales and Derbyshire, where coal prices were more moderate than in London, Cornish engines, by virtue of the recommendations of John Taylor and other Cornish engineers, had begun to be installed in the late 1820s (North Wales, see Howard, *Mr Lean*, pp. 67–72) and in the late 1830s (Derbyshire, see Kirkham, 'Steam engines').

[62] Boulton and Watt's reputation was linked to the successful installation of a number of large pumping engines in several London waterworks companies at the beginning of the nineteenth century. See Dickinson, *Water supply*, pp. 34–8. This had allowed the company to establish a number of strong connections with influential members of waterworks companies.

companies was a peculiar economic environment in which competitive pressures were not particularly strong and this may have led to some complacency in the adoption of new technologies.[63]

For rotative engines, the results are less straightforward. Figure 6 suggests that in the early 1840s, many industrial areas were located just above the relevant threshold line. This may indicate some delay in realizing the cost effectiveness of the high-pressure expansive design, but clearly its significance is relatively minor when compared with the case of pumping engines in high coal price areas. Thus, notwithstanding our revision of the profitability assessment, we tend to agree with von Tunzelmann that the hesitancy in taking up the high-pressure expansive engine in factories was actually grounded in some sound economic and technological considerations.

In fact, from the late 1830s, manufacturing areas had actually begun to install high-pressure expansive engines.[64] These cases of early adoption did not amount to a slavish imitation of the Cornish practice. Lancashire engineers tried to 'acclimatize' the high-pressure engine to local circumstances and to strike a balance between gains in fuel efficiency and the higher capital costs involved in the use of high pressure. Accordingly, the shift to high pressures was coupled with the introduction of a number of adaptations/modifications, such as the 'compounding' of existing low-pressure engines with the addition of a high-pressure cylinder (this practice was known as 'McNaughting'), or the employment of smaller versions of tubular boilers.[65]

IV

In our interpretation, the discussion of the previous sections suggests that, in British steam engineering, technical progress was to a major degree *localized* and *path-dependent*, *taking place around specific designs and with minimal diffusion across applications*.[66] The analysis of this peculiar 'topography' of technical change (which is at odds with a smooth shift of *all* points of a unit isoquant assumed by the traditional neoclassical view of technical change) can be further articulated using Dosi's paradigm/trajectory approach.[67] Dosi defines a technological paradigm as a ' "model" and a "pattern" of solution of *selected* technological problems, based on *selected* principles derived from natural sciences and on *selected* material technologies'.[68] The term 'paradigm' is borrowed from Thomas Kuhn's philosophy of science and indicates a cognitive framework, jointly adhered to by a significant group of innovators, guiding the search for technical advances in a particular historical context. A technological paradigm defines the boundaries of the domain in which future technological developments will take place. Dosi suggests that it should be possible to 'deconstruct' each technological paradigm into a set of particular engineering 'heuristics'. These represent the accepted rules prescribing

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[63] Ibid., p. 47.

[64] Fairbairn, *Treatise*, pp. 247–57.

[65] See again the letter of James Nasmyth in *Report of Inspectors* (P.P. 1852–3, XL), p. 488.

[66] In this context, 'local' means that the development of new technologies will take place in the proximity of the factor combinations presently in use. For a theoretical discussion, see Atkinson and Stiglitz, 'New view'.

[67] Dosi, 'Technological paradigms'.

[68] Ibid., p. 152, original emphasis.

the procedures adopted in the search for innovations (that is, 'in order to develop a more efficient engine, try to increase the rate of expansion'). In Dosi's view, technological heuristics are the product of the combination of what might be termed the 'autonomous drift' of a technology (that is, the 'compulsive sequences' of technical challenges and solutions individuated by Rosenberg, which are typically insensitive to market signals)[69] with 'inducement factors' of a genuinely economic type (such as current and expected factor prices).

The heuristic search process practised by the inventors' community, by channelling inventive activities in specific and finalized directions, generates relatively ordered paths of improvement, called 'technological trajectories'.[70] Improvements along a trajectory are strongly cumulative, in the sense that they are tightly related with previous attainments. In this way, technical progress ought to be conceived as an inherently path-dependent process in which specific innovations are to be understood in terms of the state of the art that preceded them.

The application of this interpretative framework to the case of British steam engineering seems relatively straightforward and consistent with the evidence discussed above. The Cornish context of high coal prices confronted steam engineers with a very specific and clear-cut technical problem, that is, how to raise the maximum quantity of water consuming the minimum amount of coal. In this context, the performances of the engines designed by Trevithick and Woolf in the early 1810s were rightly perceived as providing the opportunity to embark on a more steeply inclined trajectory of improvement, resulting in the development of a pumping high-pressure steam engine particularly fit for mining operations. Thus, Cornish engineers, induced by local circumstances, set out to explore the trajectory outlined in section I above.

From a wider perspective, we should recognize that these developments represented an exception by comparison with the trends of evolution characterizing the 'mainstream trajectory' of British steam engineering. In industrial applications the search for inventions was guided by different concerns. Engineers were trying to maximize the amount and quality (in terms of smoothness and reliability) of the power delivered by the engine. In the first half of the nineteenth century, this led to a focus of inventive activities on valves, control systems, and transmission, and on a general improvement of manufacturing methods. Over time, some attention was also paid to increasing pressure and stronger boilers, but importantly, this was related to attempts to increase the power of engines of a given size, rather than for reasons of fuel efficiency.[71]

For example, Hills has shown that the early adoption of high-pressure expansive steam and compounding in the textile industries in the early 1840s had more to do with the superior quality of motion delivered by the compounds (relative to low-pressure single cylinder engines) than to their improved fuel efficiency.[72] In this context, the squeeze on profits during the 1840s (originating from various

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[69] Rosenberg, *Perspectives*, pp. 108–26.

[70] The evolution of duty charted in fig. 1 represents a technological trajectory in the sense defined by Dosi, 'Technological paradigms', pp. 153–4.

[71] See Hills, *Power*, pp. 70–94.

[72] Ibid., pp. 158–9.

sources, including the Factory Act of 1847 which limited factory work to 10 hours per day) spurred the shift to the high-pressure trajectory.[73]

The technological history of the steam engine, therefore, suggests that, until the 1840s, the Cornish paradigm of using high pressure expansively had been unable to replace the low-pressure paradigm in applications where some fruitful use of the expansion action could be made. During the 1830s, high-pressure direct-acting horizontal engines were increasingly employed in several industrial applications by virtue of their compactness, and high-pressure engines were the dominant design for railways, but there was no systematic adoption of the practice of using high-pressure steam expansively. This entrenchment of the low-pressure paradigm can account for some of the scepticism with which information on the superior efficiency of the high-pressure expansive engine was received outside Cornwall.[74] In each application, the search for innovations was guided by very specific and idiosyncratic engineering heuristics, leading to the emergence of distinct trajectories of improvement with little cross-fertilization. Accordingly, the adoption of high-pressure steam expansively was the outcome of semi-autonomous innovative processes taking place within each sector in different moments, rather than emerging from diffusion and spill-overs between applications. An upshot of these considerations is that the issue of 'entrepreneurial failure' is especially relevant when comparing similar types of application (for example, pumping) and less so when considering the spread of innovations across contexts where technologies had to satisfy different requirements.

Interestingly enough, the adoption of high pressure expansively for marine engines (another domain which until the late 1840s had remained dominated by low pressure) followed yet another independent route. John Elder (who was a close associate of Rankine) was probably one of the first engineers to realize the advantages of compounding and of using high pressure expansively from a fully scientific point of view.[75] From the 1850s, in marine engineering, Elder's compound expansive design became the norm and quite soon the average engine would expand the steam in three steps using as many cylinders.[76]

V

One of the features of the economic history of the steam engine that has attracted the attention of historians is the prolonged resilience of the low-pressure design in the first half of the nineteenth century. The evidence presented in this article indicates that it is likely that the initial choice between low-pressure and high-pressure expansive designs was dictated by the economic conditions prevailing at different locations. Thereafter, the search for improvements in each location proceeded 'empirically' and semi-autonomously on the basis of particular sets of

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[73] See von Tunzelmann, *Steam*, pp. 209–25.

[74] Another factor, pointed out by Hills ('Development', pp. 187–9), among others, accounting for the hesitancy in developing the high-pressure expansive design for industrial applications was the influence of James Watt's authority, which had sanctioned the low-pressure engine as the optimum. This helps to explain the strong 'legitimacy' of the low-pressure 'paradigm'.

[75] Smith, *Science*, pp. 151–5.

[76] Griffiths, *Steam*, p. 46. On the critical role of these improvements in marine engines for the transition from sailing ships and steamships, see Harley, 'Shift from sailing ships', pp. 219–22.

engineering heuristics geared to specific sectoral requirements.[77] In the Cornish context, a peculiar institutional set-up and the expansion of the mining industry promoted the creation and dissemination of a body of practical knowledge that led to the early development of high-pressure expansive engines. However, notwithstanding the fact that these remarkable Cornish achievements had been popularized, the diffusion of these new technological practices remained minimal. In this article, it has been argued that the localized and path-dependent nature of the processes of technological learning taking place in the various sectors constrained the 'transferability' of the high-pressure expansive practice across applications. The ultimate outcome was a pattern of technical change characterized by *uneven* rates of technological advance across the various applications of steam power. As hinted at by Crafts, it is this peculiar pattern of technical change that we should consider in order to understand the restricted impact of steam power on productivity growth throughout the first half of the nineteenth century.[78]

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[77] See Cardwell and Hills, 'Thermodynamics', pp. 7–11.
[78] Crafts, 'Steam', p. 345.

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