Les archives de l'invention, pp. 211-226.

Data for engineering design: *Lean's engine reporter* and early nineteenth century steam technology*

Alessandro Nuvolari**

One of the salient features of the Industrial Revolution was the transition from an economic system based on the exploitation of «organic» natural resources to another centered on the intensive use of inorganic minerals. In this sense, the Industrial Revolution consisted in a dramatic increase of the energy potential susceptible of effective economic utilization[1]. If we consider the cluster of technological innovations commonly associated with the Industrial Revolution in this perspective, the steam engine, allowing the transformation of thermal energy (heat) into kinetic energy (work), assumes paramount importance. Traditional accounts of early industrialization have, more or less explicitly, considered that a wide range of application sectors *rapidly* benefited from the development of steam power technologies[2]. This seems, however, to be generally unwarranted. When carefully examined, the diffusion of steam power appears to have been a delayed and particularly prolonged affair. The late eighteenth century and the early nineteenth century economies were still dominated by the pervasive use of animal, wind and water power[3]. In fact, the widespread utilization of steam power had to await a number of cumulative improvements that progressively reduced the power costs of the steam engine. A major part of the power costs associated with the

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1 This interpretation of the Industrial Revolution is clearly presented in WrigleyE. A., *Continuity, chance and change,* Cambridge, Cambridge University Press, 1988.

2 See among many others, LandesD. S., *The unbound Prometheus*, Cambridge, Cambridge University Press, 1969.

3 TunzelmannG. N. von, *Steam power and British industrialization to 1860*, Oxford, Clarendon Press, 1978.

utilization of the steam engine was determined by the degree of fuel-efficiency of the machine.

In the first half of the nineteenth century a drastic improvement in the fuel efficiency of the steam engine was achieved by adopting the «principle of expansion» in combination with increasing steam pressures. Interestingly, these technological developments were introduced before the attainment of a consolidated theoretical understanding of the working principles of the steam engine. In Britain, Cornish engineers took the lead in the exploration of the potentialities of high pressure steam used expansively. In other parts of the country, Watt's low pressure engine remained the favourite technological choice at least until the late 1840s.

Accordingly, a large body of contemporary engineering literature was informed by the debate on the different choice of technique characterizing the employment of steam power in Cornwall versus the rest of Britain, especially the manufacturing districts of the North.

The superior fuel efficiency of the Cornish practice led some contemporaries to describe this situation as a manifestation of a «technology gap». Thus, N.P. Burgh, in *A practical treatise on the condensation of steam* published in 1871, described the general complacent attitude towards the adoption of technical novelties in steam engines prevailing in the textile manufacturing districts in the early nineteenth century in these terms: «The matter before them was all-sufficient because it answered up to a certain point of working duty, and thus *mutual contentment* reigned where an equal desire for further knowledge ought to have been» [4].

William Fairbairn, a highly influential member of the Lancashire engineering community, was one of the leading advocates of the technical merits of the high pressure expansive engine. However his pleadings remained for a long period unfulfilled:

> 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.[5]

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4 Cited in HillsR. L., *Power from steam. A history of the stationary steam engine*, Cambridge, Cambridge University Press, 1989, p.113 (italics added).

5 FairbairnW., «On the expansive action of steam, and a new construction of expansion valves for condensing steam engines», *Proceedings of the Institution of Mechanical Engineers*, 1847-1849, n°1, p.23-24.

Similarly, John Farey denounced a widespread and culpable «state of apathy as to consumption of fuel» in the «great manufacturing districts of the North» [6].

However, other commentators remained rather sceptical, at least till the late 1830s, regarding the fuel efficiency achieved by Cornish engines, actually denying the existence of a Cornish technological lead. This was also partially due to the fact that the superior fuel efficiency stemming from the expansive use of high pressure steam remained theoretically unaccounted for. As a consequence, the dramatic improvement in fuel efficiency brought about by the adoption of high pressure steam expansively was not easily accepted outside Cornwall. In 1836 there was a heated debate in *Mechanic's magazine* on the general reliability of the measured performances of Cornish engines. Two years later, G.H. Palmer published an article on *Transactions of the institution of civil engineers*, in which he contended that the levels of fuel efficiency claimed for the Cornish engine were undoubtedly exaggerated (because in open contrast with the caloric theory of heat):

> 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 favoritism 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.[7]

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 duty figures voiced for the Cornish high pressure engines

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6 FareyJ., *A treatise on the steam engine. Historical, practical and descriptive,* Newton Abbot, David & Charles, 1971, vol. 2, p.307. Nick von Tunzelmann has made explicitly the case for considering Farey's book as «the finest monograph on technology produced during the Industrial Revolution», von Tunzelmann, *op.cit.* note 3, p.2. The second volume of Farey's *Treatise…* was still not finished when the author died in 1851. The existing proofs of the second volume were published by David & Charles in 1971. On Farey's *Treatise…*, see WoolrichA. P., «John Farey and his *Treatise on the steam engine*», *History of technology*, n°22, 2000.

7 PalmerG. H., «On the application of steam as a moving power, considered especially with reference to the economic of atmospheric and high pressure steam», *Transactions of the institution of civil engineers,* 1838, n°2, p.44-46. In the early nineteenth century the fuel efficiency of steam engines was measured in terms of «duty» (a measured devised by Watt). «Duty» consisted in the *weight* of water lifted 1 foot high consuming 1 bushel of coal, or millions of foot-pounds per bushel of coal consumed. In the same article Palmer, on the basis of the caloric theory of heat, calculated that the maximum duty attainable by a steam engine to 44millions. PalmerG. H., *ibid.*, p.46.

were undoubtedly «gross exaggerations». He concluded that «there is nothing in the Cornish system of management that can be profitably imitated by… [Lancashire engineers]» [8].

This paper aims at reconstructing the peculiarities of the Cornish context, in order to identify the factors accounting for the early use of high pressure steam expansively in the county and, in turn, for the emergence of a Cornish technological lead in steam engineering in the early nineteenth century.

Lean's engine reporter and the development of the high pressure expansive engine

What were the forces that had shaped Cornish technical practice in such a peculiar direction, leading Cornish engineers to the precocious use of high pressure steam?

The Cornish mining district was endowed with very rich lodes of tin and copper, whose exploitation, however, was severely hampered by flooding problems. The development of steam power technology (in this case in the form of steam pumping engines) provided an effective solution to mine drainage. In Cornwall, coal had to be imported from Wales by sea and, for this reason, was particularly expensive. As a consequence, Cornish mine entrepreneurs were eagerly interested in improvements in the efficiency of the steam engine that could curtail their dear fuel bill. Starting in 1811, they sponsored a monthly publication containing detailed reports on the performance (measured in terms of 'duty'), technical details and operating procedures of the steam pumping engines at work in the county. Joel Lean, a highly respected mine engineer, was entrusted with the compilation of the reports and the publication was known as *Lean's engine reporter*[9]. A page of the reporter is here reproduced as figure1.

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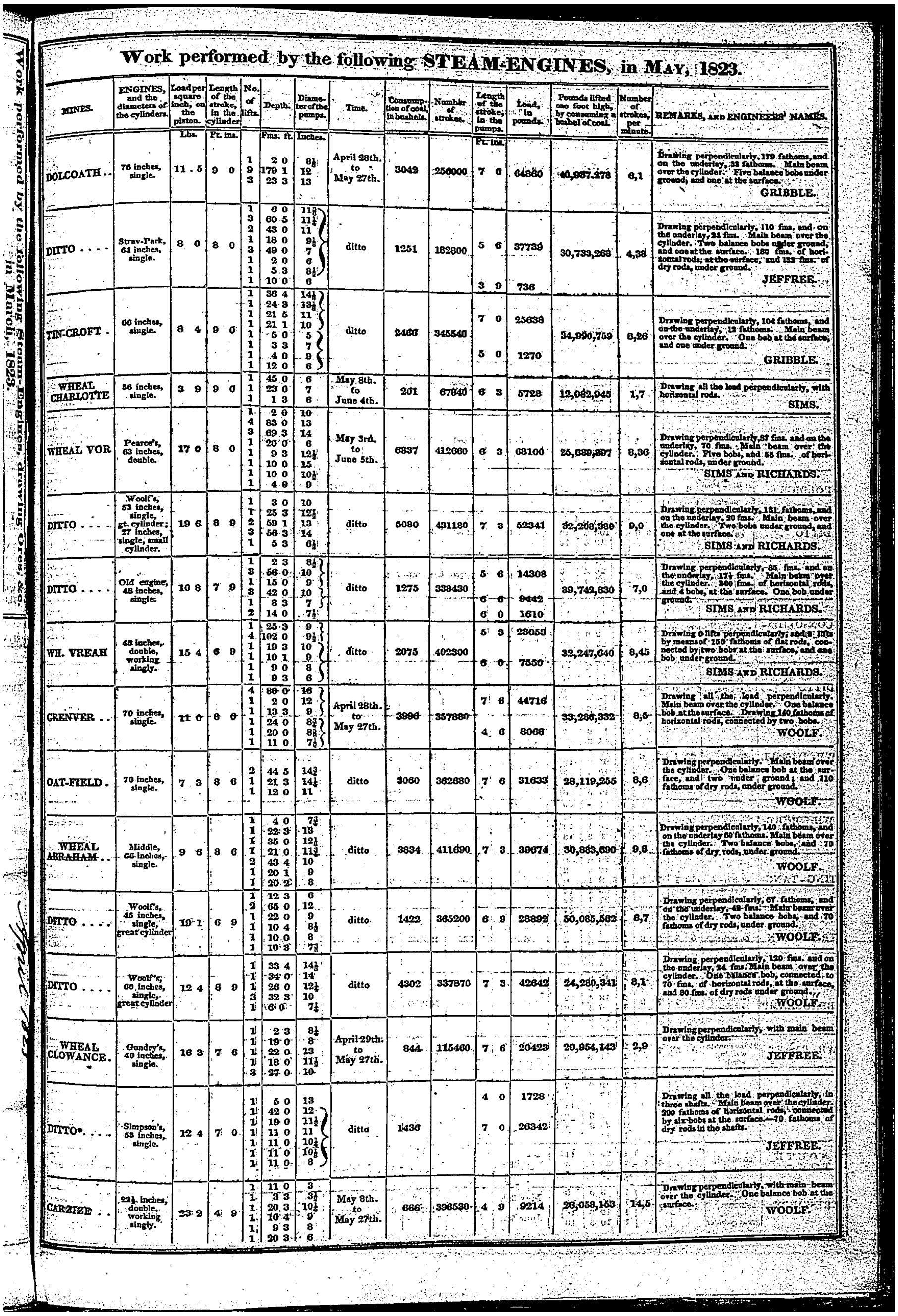
8 Cited in PoleW., *A treatise on the Cornish pumping engine*, London, 1844, p.59.

9 After Joel Lean's death, the publication was continued by his sons, and later on by other members of the Lean family. An almost complete set of *Lean's engine reporter* is conserved in the Cornish Studies Library in Redruth.



Work performed by the following Steam-Engines, drawing Ores, &c. in March, 1823.

Work performed by the following STEAM-ENGINES, in MAY, 1823.

MINES.	ENGINES, and the diameters of the cylinders.	Load per square inch, on the piston. Lbs.	Length of the stroke, in the cylinder. Ft. ins.	No. of lifts.	Depth. Fms. ft.	Diameter of the pumps. Inches.	Time.	Consumption of coal, in bushels.	Number of strokes.	Length of the stroke, in the pumps. Ft. ins.	Load, in pounds.	Pounds lifted one foot high, by consuming a bushel of coal.	Number of strokes, per minute.	REMARKS, AND ENGINEERS' NAMES.
DOLCOATH ..	76 inches, single.	11 . 5	9 0	1 9 3	2 0 179 1 23 3	8½ 12 13	April 28th. to May 27th.	3042	256000	7 6	64860	40,987,278	6,1	Drawing perpendicularly, 179 fathoms, and on the underlay, 33 fathoms. Main beam over the cylinder. Five balance bobs under ground, and one at the surface. GRIBBLE.
DITTO	Strav-Park, 64 inches, single.	8 0	8 0	1 3 2 1 3 1 1 1	6 0 60 5 43 0 18 0 49 0 2 0 5 3 10 0	11½ 11¼ 11 9½ 7 6 8½ 6	ditto	1251	182800	5 6 3 9	37739 736	30,733,268	4,38	Drawing perpendicularly, 110 fms. and on the underlay, 24 fms. Main beam over the cylinder. Two balance bobs under ground, and one at the surface. 180 fms. of horizontal rods, at the surface, and 132 fms. of dry rods, under ground. JEFFREE.
TIN-CROFT .	66 inches, single.	8 4	9 0	1 1 1 1 1 1 1 1	36 4 24 3 21 5 21 1 5 0 3 3 4 0 12 0	14½ 13½ 11 10 5 7 9 6	ditto	2466	345540	7 0 5 0	25638 1270	34,990,759	8,26	Drawing perpendicularly, 104 fathoms, and on the underlay, 12 fathoms. Main beam over the cylinder. One bob at the surface, and one under ground. GRIBBLE.
WHEAL CHARLOTTE	36 inches, single.	3 9	9 0	1 1 1	45 0 23 0 1 3	6 7 6	May 8th. to June 4th.	201	67840	6 3	5728	12,082,945	1,7	Drawing all the load perpendicularly, with horizontal rods. SIMS.
WHEAL VOR	Pearce's, 63 inches, double.	17 0	8 0	1 4 3 1 1 1 1 1	2 0 83 0 69 3 20 0 9 3 10 0 10 0 4 9	10 13 14 6 12½ 15 10½ 9	May 3rd. to June 5th.	6837	412660	6 3	68100	25,689,897	8,36	Drawing perpendicularly, 87 fms. and on the underlay, 70 fms. Main beam over the cylinder. Five bobs, and 55 fms. of horizontal rods, under ground. SIMS AND RICHARDS.
DITTO	Woolf's, 53 inches, single, gt. cylinder; 27 inches, single, small cylinder.	19 6	8 9	1 1 2 3 1	3 0 25 3 59 1 56 3 5 3	10 12½ 13 14 6½	ditto	5080	431180	7 3	52341	32,208,389	9,0	Drawing perpendicularly, 131 fathoms, and on the underlay, 20 fms. Main beam over the cylinder. Two bobs under ground, and one at the surface. SIMS AND RICHARDS.
DITTO	Old engine, 48 inches, single.	10 8	7 9	1 3 1 3 1 2	2 3 56 0 15 0 42 0 8 3 14 0	8½ 10 9 10 7 7½	ditto	1275	338430	5 6 6 6 6 0	14308 9442 1610	39,742,830	7,0	Drawing perpendicularly, 85 fms. and on the underlay, 17½ fms. Main beam over the cylinder. 200 fms. of horizontal rods, and 4 bobs, at the surface. One bob under ground. SIMS AND RICHARDS.
WH. VREAH	48 inches, double, working singly.	15 4	6 9	1 4 1 1 1 1	25 3 102 0 19 3 10 1 9 0 9 3	9 9½ 10 9 8 6	ditto	2075	402300	5 3 6 0	23053 7550	32,247,640	8,45	Drawing 6 lifts perpendicularly, and 3 lifts by means of 150 fathoms of flat rods, connected by two bobs at the surface, and one bob under ground. SIMS AND RICHARDS.
CRENVER ..	70 inches, single.	11 0	8 0	4 1 1 1 1 1	80 0 2 0 13 3 24 0 20 0 11 0	16 12 9 8¾ 8½ 7½	April 28th. to May 27th.	3996	357880	7 6 4 6	44716 8066	33,286,332	8,5	Drawing all the load perpendicularly. Main beam over the cylinder. One balance bob at the surface. Drawing 140 fathoms of horizontal rods, connected by two bobs. WOOLF.
OAT-FIELD .	70 inches, single.	7 3	8 6	2 1 1	44 5 21 3 12 0	14¾ 14½ 11	ditto	3060	362680	7 6	31633	28,119,255	8,6	Drawing perpendicularly. Main beam over the cylinder. One balance bob at the surface, and two under ground; and 110 fathoms of dry rods, under ground. WOOLF.
WHEAL ABRAHAM ..	Middle, 66 inches, single.	9 6	8 6	1 1 1 1 2 1 1	4 0 22 3 35 0 21 0 43 4 20 1 20 2	7¾ 18 12½ 11¾ 10 9 8	ditto	3834	411690	7 3	39674	30,883,690	9,8	Drawing perpendicularly, 140 fathoms, and on the underlay 60 fathoms. Main beam over the cylinder. Two balance bobs, and 70 fathoms of dry rods, under ground. WOOLF.
DITTO	Woolf's, 45 inches, single, great cylinder	19 1	6 9	1 2 1 1 1 1	12 3 65 0 22 0 10 4 10 0 10 3	6 12 9 8½ 8 7½	ditto	1422	365200	6 9	28892	50,085,562	8,7	Drawing perpendicularly, 67 fathoms, and on the underlay, 48 fms. Main beam over the cylinder. Two balance bobs, and 70 fathoms of dry rods, under ground. WOOLF.
DITTO	Woolf's, 60 inches, single, great cylinder	12 4	8 9	1 1 1 3 1	33 4 34 0 26 0 32 3 6 0	14½ 14 12¼ 10 7¼	ditto	4302	337870	7 3	42642	24,280,341	8,1	Drawing perpendicularly, 120 fms. and on the underlay, 24 fms. Main beam over the cylinder. One balance bob, connected to 70 fms. of horizontal rods, at the surface, and 80 fms. of dry rods under ground. WOOLF.
WHEAL CLOWANCE.	Gundry's, 40 inches, single.	16 3	7 6	1 1 1 1 3	2 3 19 0 22 0 18 0 27 0	8¼ 8 13 11½ 10	April 29th. to May 27th.	844	115460	7 6	20423	20,954,143	2,9	Drawing perpendicularly, with main beam over the cylinder. JEFFREE.
DITTO*	Simpson's, 53 inches, single.	12 4	7 0	1 1 1 1 1 1 1	5 0 42 0 19 0 11 0 11 0 11 0 11 0	13 12 11½ 11 10½ 10½ 8	ditto	1436		4 0 7 0	1728 26342			Drawing all the load perpendicularly, in three shafts. Main beam over the cylinder. 200 fathoms of horizontal rods, connected by six bobs at the surface.—70 fathoms of dry rods in the shafts. JEFFREE.
CARZIZE ..	22½ inches, double, working singly.	23 2	4 9	1 1 1 1 1 1	11 0 3 3 20 3 10 4 9 3 20 3	3 3½ 10½ 9 8 6	May 8th. to May 27th.	666	396530	4 9	9214	26,058,153	14,5	Drawing perpendicularly, with main beam over the cylinder. One balance bob at the surface. WOOLF.

Fig. 1 : page of *Lean's engine reporter*

In our interpretation, the publication of *Lean's engine reporter* marked the transition of the Cornish mining district to a peculiar form of innovation process which Robert Allen has termed «collective invention». In collective invention settings, rival firms prefer to reciprocally share technological knowledge rather than protecting it using patents. When innovations are highly cumulative, regimes of collective invention are likely to yield higher rates of technical progress than those based on «closed» and proprietary knowledge. In collective invention settings, competing firms freely release *pertinent* technical information on the construction details and the performance of the technologies they have just introduced to one another[10]. Allen has noticed this type of behaviour in the iron industry of Cleveland (UK) over the period 1850-1875. In the Cleveland district, iron producers devoted few resources to the discovery of new technical knowledge, instead they freely disclosed to their competitors technical information concerning the construction details and the performance of the blast furnaces they had erected. In the words of Allen:

> [...] if a firm constructed a new plant [more specifically, a blast furnace] of novel design and that plant proved to have lower costs than other plants, these facts were made available to other firms in the industry and to potential entrants. The next firm constructing a new plant build on the experience of the first by introducing and extending the design change that had proved profitable. The operating characteristics of the second plant would then also be made available to potential investors. In this way fruitful lines of technical advance were identified and pursued.[11]

Information was normally released through both formal (presentations at meetings of engineering societies and publications of design details in technical journals) and informal channels (such as visits to plants, conversations, etc.). Additionally, new technical knowledge was normally not protected by patents, so that competing firms could *liberally* make use of the released information when they had to erect a new plant[12].

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10 AllenR. C., «Collective invention», *Journal of economic behavior and organization*, 1983, n°4. A similar notion, «open technique», has been proposed by A.-F. Garçon and L.Hilaire-Pérez, «Open technique between community and individuality in eighteenth century France», in GoeyF. de and VeluwenkampJ. W., *Entrepreneurs and institutions in Europe and Asia, 1500-2000*, Amsterdam, Aksant, 2002.

11 AllenR. C., *op.cit.* note 10, p.2.

12 It is important to note that the notion of «coll ective invention» and «open technique» do not refer to the exchange of information between users and producers studied by LundvallB. A., «Innovation as an interactive process: from user-producer interaction to the national system of innovation», in DosiG., Freeman, NelsonC. R., SilverbergG. and SoeteL.ed., *Technical change and economic theory*, London, Pinter, 1988. In fact, Allen is describing an exchange of information among *competing* entities. «Collective invention» also differs from «know-how trading» described by HippelE. von, «Cooperation between rivals: informal know-how trading», *Research policy,* 1987, n°16. In «know-how trading», engineers «trade» proprietary

In Cornwall, *Lean's engine reporter* was the main vehicle for the exchanges of information which constitute the basis of the collective invention processes described by Allen. The reporter allowed engineers to promptly identify the respective merits and pitfalls of different design solutions. As Donald Cardwell has aptly noticed:

> The publication of the monthly *Engine Reporter* seems to have been quite unprecedented, and in striking contrast to the furtive secrecy that had surrounded so many of the notable improvements to the steam engine. It was a cooperative endeavor to raise the standards of all engines everywhere by publishing the details of the performance of each one, so that everybody could see which models were performing best and by how much.[13]

Interestingly enough, in the contemporary engineering literature, engines built on the basis of Cornish design principles were not ascribed to this or that particular engineer, but simply known as «Cornish» engines, properly acknowledging the cooperative and cumulative character of this particular form of technological development.

The patenting behaviour of Cornish steam engineers provides additional confirmation of the existence of an institutional setting that strongly encouraged the free circulation of technical knowledge rather than its private appropriation and commercialization. Table 1 reports the geographical distribution (measured using the stated addresses of the patentees) of patents in steam power technology over the period 1698-1852.

County	N.of Patents 1698-1852	% 1698-1852	N.of Patents 1698-1812	% 1698-1812	N.of Patents 1813-1852	% 1813-1852
Cheshire	14	1.23	0	0.00	14	1.39
Cornwall	17	1.50	8	6.25	9	0.89
Cornwall*	21	1.85	12	9.38	9	0.89
Derby	11	0.97	1	0.78	10	0.99
Durham	13	1.15	0	0.00	13	1.29
Essex	6	0.53	0	0.00	6	0.60
France	21	1.85	0	0.00	21	2.09
Gloucester	20	1.76	8	6.25	12	1.19
-Bristol	12	1.06	4	3.13	8	0.79
Hampshire	9	0.79	0	0.00	9	0.89

know-how in the sense the information is exchanged on a bilateral basis (non-participants to the transaction in question are excluded). Within collective invention, *all* the competing firms of the industry have free access to the potentially proprietary know-how.

13 CardwellD. S.L., *From Watt to Clausius. The rise of thermodynamics in the early industrial age*, London, Heinemann, 1971, p.156.

Ireland	13	1.15	1	0.78	12	1.19
Kent	31	2.73	1	0.78	30	2.98
Lancashire	145	12.78	5	3.91	140	13.90
-Liverpool	35	3.08	1	0.78	34	3.38
-Manchester	58	5.11	2	1.56	56	5.56
London & Middlesex	395	34.80	40	31.25	355	35.25
Northumberland	22	1.94	2	1.56	20	1.99
-Newcastle-up.-Tyne	11	0.97	1	0.78	10	0.99
Nottingham	13	1.15	1	0.78	12	1.19
Scotland	47	4.14	6	4.69	41	4.07
-Edinburgh	9	0.79	0	0.00	9	0.89
-Glasgow	22	1.94	3	2.34	22	2.18
Shropshire	6	0.53	3	2.34	3	0.30
Somerset	4	0.35	2	1.56	2	0.20
-Bath	2	0.18	1	0.78	1	0.10
Stafford	27	2.38	5	3.91	22	2.18
Suffolk	5	0.44	0	0.00	5	0.50
Surrey	88	7.75	10	7.81	78	7.75
USA	13	1.15	2	1.56	11	1.09
Wales	12	1.06	1	0.78	11	1.09
Warwick	58	5.11	8	6.25	50	4.97
-Birmingham	55	4.85	6	4.69	49	4.87
Worcester	11	0.97	1	0.78	10	0.99
York	63	5.55	11	8.59	52	5.16
-Bradford	11	0.97	0	0.00	11	1.09
-Kingston-up.-Hull	9	0.79	2	1.56	7	0.70
-Leeds	17	1.50	3	2.34	14	1.39
-Sheffield	6	0.53	0	0.00	6	0.60
Others	71	6.26	12	9.38	70	6.95
Total	1135	100.00	128	100.00	1007	100.00

Table 1: Geographical distribution of British steam engine patents, 1698-1852

* Cornwall including the patents taken by Arthur Woolf.
Source: The list of steam engine patents is taken from *Abridgments of specification relative to the steam engine*, London, 1871. In order to retrieve the stated residence of the patentees, these patents have been matched with those contained in WoodcroftB., *Titles of patents of invention chronologically arranged*, London, 1854.

The London and Middlesex area holds the predominant position. In this respect the pattern of patenting in steam technology mirrors that for overall patenting outlined by Christine MacLeod[14], and it is likely that this high number is mainly explained both by the growth of the metropolis as a commercial and manufacturing centre and by the proximity to the patent office, which gave would-be patentees the possibility of following closely the administrative procedures related to the granting of the patent. Surrey also has a quite high concentration of steam patents. This case, besides the proximity to the patent office, may also be accounted for by the presence in the area of a number of engineering firms specialized in the production of capital goods[15]. Other notable locations with high numbers of steam patents are Warwickshire, Lancashire and Yorkshire, where patents were probably related to the increasing use of steam power by the industries there located. Again, one should take into account that in this case as well, patents were essentially an urban phenomenon and so they were concentrated in major towns such as Birmingham, Liverpool, Manchester and Leeds. The table also reports the number of patents in major urban centres.

Over the entire period 1698-1852, the share of Cornwall in total patenting is 1,85 per cent, which does not reflect at all the major contribution of the county to the development of steam power technology. Breaking down the period 1698-1852 into two sub-periods (1698-1812 and 1813-1852), in order to take into account the publication of *Lean's engine reporter* is even more revealing. In the first period, Cornwall (including in the count also the patents taken out by Arthur Woolf who, at the time, was working for the Meux & Reid brewery in London) is the county with highest number of patents after the London and Middlesex area, with a share of 9,38 per cent. In the second period, the share of Cornwall drops to a negligible 0,89 per cent and this is exactly the period during which the Cornish pumping engine was actually developed. In our view, this finding is indicative of the widely perceived awareness in the county of the benefits stemming from the adoption of a collective invention regime for the rate of innovation. Accordingly, it seems quite clear that in the Cornish steam engineering community, an *ethos* prescribing the full release of technical innovations into the public domain emerged and became progressive established.

The case of Arthur Woolf is particularly illustrative. Woolf was one of the leading figures in the Cornish engineering community[16]. Born in Cornwall, he had an initial apprenticeship with steam engineering by working with Jonathan Hornblower. In the first decade of nineteenth century he moved to London, where he was entrusted with the steam engines of the Meux & Reid brewery. In this period Woolf took out four patents for innovations in steam engines (in particular his famous compound engine patented in 1804). In 1812,

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14 MacLeodC., *Inventing the Industrial Revolution. The English patent system, 1660-1800*, Cambridge, Cambridge University Press, p.119-124.

15 MacLeodC., *ibid.*, p.124, and Hilaire-PérezL., *L'invention technique au siècle des Lumières*, Paris, Albin Michel, 2000, p.111.

16 HarrisT. R, *Arthur Woolf, the Cornish engineer, 1766-1837*, Truro, D.B.Barton, 1966.

he moved back to Cornwall, where he tried to commercialize his compound engine by means of an agreement similar to the one proposed by Boulton & Watt for their patented engines (royalties paid as a proportion of fuel savings). His initiative was unsuccessful. Most mine adventurers awaited the expiration of the patent in 1818 before installing this type of engine[17]. Later on, in 1823, Woolf invented a new valve for steam engines (the double-beat valve). The adoption of this type of valve greatly facilitated the operation of the engine. He did not claim any patent right for this invention. In the same period, he also introduced notable improvements in the cataract regulator which he did not patent[18]. Similarly, Samuel Grose did not patent the system of thermal lagging that he introduced in 1826, even when Davies Gilbert had advised him to do so[19].

Another example that confirms the negative attitude towards patents existing in the Cornish mining district is the limited diffusion of the two-cylinder compound engine patented by the Cornish engineer, James Sims, in 1841. The first engine of this type erected at the Carn Brea mine performed particularly well in terms of duty (it was the second best engine in the *Reporter* in the early 1840s). However, being a patented design made the engine quite unpopular with other engineers and mine-owners, who, in the end, preferred not to adopt it[20].

One can point to other Cornish inventions in steam technology which were not patented. The «Cornish water gauge», an instrument which allow a prompt check of the height of water in the boiler, invented by Richard Hosking in 1833, is a noteworthy case. In his *Treatise*, William Pole describes it as «a very ingenious apparatus […] almost unknown out of the county» [21]. The invention was awarded a prize by the Royal Cornwall Polytechnic Society and a detailed description was published in the Society's Reports. In fact, since its foundation the Royal Cornwall Polytechnic Society, a local learned society, in 1833 awarded a yearly prize for «Inventions and workmanship». A perusal of the yearly reports *Reports* of the society reveals that many inventions were related to steam engineering. For the period 1833-1841, none of them was patented. It is also interesting to note that leading mine entrepreneurs, such as John Taylor, tried to steer the direction of inventive efforts by instituting prizes for inventions aimed at specific purposes (such as water meters for boilers, stroke counters, etc.). Overall, it assess hard to tell the technological significance of these inventions. Remarkably, William Pole found a number of them worthy to deserve a description in his *Treatise*, which indicates that at least some of them were not of trifling importance[22].

17 FareyJ., *op.cit.* note 6, p.188-189.
18 PoleW., *op.cit.* note 8, p.89.
19 ToddA. C., *Beyond the blaze. A biography of Davies Gilbert*, Truro, D.B.Barton, 1967, p.101.
20 BartonD. B., *The Cornish Beam Engine*, Truro, D.B.Barton, 1969, p.110-112.
21 PoleW., *op.cit.* note 8, p.109.
22 PoleW., *ibid.*, p.122.

Patterns of technological learning in Cornish steam engines

Walter Vincenti has argued that engineers typically make use of systematic data collection and analysis to *bypass* the absence of an adequate scientific understanding of the operative principles of a technology[23].

This was exactly the situation in early nineteenth century steam engine technology. At that time, the steam engine was still conceived as a vapour-pressure engine and not as a heat engine, so that there were no theoretical principles that could account for the impact on the efficiency of the engine of the use of high-pressure steam and of the principle of expansion. Systematic collection and analysis of performance data allowed Cornish engineers to consistently individuate fruitful lines of technical advance, so that, between 1820 and 1840, the Cornish pumping engine represented the highest engineering achievement in steam power technology. As a matter of fact, immediately afterwards the publication of the engine reports, the thermodynamic efficiency of Cornish engines began to improve steadily. Figure2 displays the behaviour of the «duty» of Cornish pumping engines as portrayed in *Lean's engine reporter.*

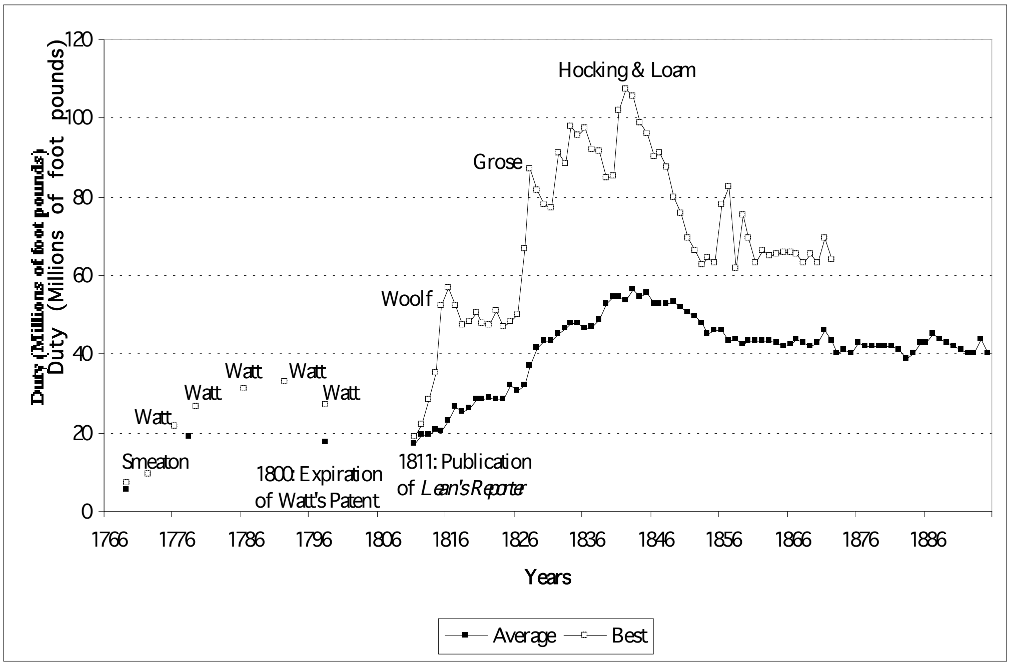

Fig.2: duty of Cornish engines, 1769-1895

23 VincentiW. G., *What engineers know and how they know it. Analytical studies from aeronautical history*, Baltimore, John Hopkins University Press, 1990, especially chapter 5.

Sources:
1769, 1772, 1776, 1778: LeanT., *Historical statement of the improvements made in the duty performed by the steam engines in Cornwall*, London, 1839.
1779, 1786, 1792: DickinsonH. W. and JenkinsR., *James Watt and the steam engine*, Oxford, Clarendon, 1927; 1811-1872: LeanT., II, «Comment» on RichardsonJ. «On the application of portable engines for mining purposes», *Proceedings of the institution of mechanical engineers*, 1873.
1873-1895: TrestrailN., «The duty of the Cornish pumping engines, past and present, and as compared to others», *Transactions of the federated institution of mining engineers*, 1896.

Figure2 clearly indicates that the practice of information sharing resulted in a marked acceleration in the rate of technical advance (both of best and average practice). This phase of rapid growth of technological performance appears to cover approximately the period 1811-1846. After that, Cornish technological practice seems to run into diminishing returns[24].

As we have already mentioned, at the beginning of the nineteenth century established scientific theory could provide very limited assistance in engineering design activities. Therefore the design of a steam pumping engine was a rather risky undertaking from an engineering point of view. Technology was much ahead of scientific understanding and complex – that is to say that the overall performance could be affected by a host of factors (boilers, steam pressure, engine, pitwork, etc.). Engineers could not rely on sound theoretical principles when they had to design a new engine. In this situation, the best engineers could do was to extrapolate from the relative performance of existing designs, attempting some small trial-and-error modifications. In such cases, one can expect that information disclosure will enhance the exploration of the space of technological opportunities. By pooling together all the accumulated experience, it was possible to gain a deeper understanding of the connections between specific designs features and engine performance and, consequently, focus the search process in the most promising directions. Furthermore, Cornish engines like the Cleveland blast furnaces are «complex capital goods». Rosenberg has argued that for this type of products learning by using constitutes the main sources of improvement:

> [L]earning by using refers to a very different locus of learning than does learning by doing. There are various reasons why this should be so. Perhaps in most general terms, the performance characteristics of a durable capital good often cannot be understood until after prolonged experience with it. For a range of products involving complex, interdependent components or materials that will be subject to varied or prolonged stress in extreme environments, the outcome of the interaction of these parts cannot be precisely predicted. In this sense, we are dealing

[24] Here we are mainly concerned with the growth in fuel efficiency in the first half of the nineteenth century. For an analysis in the second half of the nineteenth century, see BartonD.B., *op.cit.* note 20, p.59-88.

> with performance characteristics that scientific knowledge or techniques cannot predict very accurately. The performance of these products therefore is very uncertain. Moreover many significant characteristics of the products are revealed only after intensive or, more significantly prolonged use.[25]

Cornish engines were run 24 hours a day. The use of high pressure in such conditions put under considerable strain the pit-work and many components of the engine itself (e.g. valves, beam). In these circumstances, the evaluation of the merits and pitfalls of a design modification might have needed a prolonged phase of experience. Furthermore, interdependence between components often meant that the introduction of a design modification often required adjustments and modifications of other parts of the engine. Again, the type of modifications required very often became evident only after a period of experience with the new design. In the Cornish context, sharing of information related to engine operating experiences reinforced the feedback loop from learning by using to the further development and refinement of the original invention outlined by Rosenberg.

Cornish engines and Cornish mining

Since the first systematic exploitation of copper and tin lodes, the Cornish mining economy was characterized by a peculiar form of industrial organization, centered around the so-called «cost book system» [26]. Under such a system, mine entrepreneurs or investors («adventurers») had first to obtain the grant for working the mine from the owner of the land. This was a normal renting contract (usually for a period of twenty-one years). The rent (called «dues») was paid in terms of a proportion of the ore extracted. This proportion varied according to the profitability of the mine. In deep and expensive mines, the lord's dues comprised between 1/18 and 1/15 of the ore excavated. In more profitable mines this proportion could rise to between 1/12 and 1/10.

Before starting up the mining operations, adventurers met and each of them subscribed shares of the mine venture (normally the mine venture was divided into 64 shares). Shares were annotated in the mine cost book. One of the adventurers was appointed as the administrator of the venture («purser»). At the same time, one or more mine captains were put in charge of the day-to-day management of the mine. Every two or three months, adventurers met and examined the accounts. If necessary a «call» was made and the adventurers had to contribute (in proportion to their share) to the coverage of mining costs until the next meeting. Failure to meet the call implied immediate forfeiture of the mine shares. Shares could be easily transferred, the only formality being notification to the purser. When the mine

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[25] RosenbergN., *Inside the black box*, Cambridge, Cambridge University Press, 1982, p.122.

[26] RoweJ., *Cornwall in the age of the Industrial Revolution*, Liverpool, Liverpool University Press, 1953, p.23-25.

became productive and ore was sold, profits were divided in proportion to shares in the mining venture. The «cost book» system had the advantage of allowing mine adventurers a limited financial liability.

Adventurers were usually not tied to the fortunes of a single mine, but they often acquired shares of different mine ventures. Consequently, they tended to be more interested in the overall profitability of the district than in that of individual mines. Improvements in the *average aggregate performance* of the steam engines at work in Cornwall dictated an increase of the overall profitability of the district[27]. Further, improvements in the average aggregate performance of Cornish engines also had the positive effect of increasing the value of the Cornish ore deposits (a similar mechanism was at work in Cleveland where improvements in the performance of the blast furnaces were also reflected in increases in the value of Cleveland iron mines). Thus, the particular structure of the Cornish mining industry seems to have permitted (at a sort of second stage) the «internalization» of a consistent part of the positive externalities generated by the free disclosure of innovations. Note that in several instances there were suggestions of implementing a similar system of reports for steam engines at work in textile areas, but nothing followed[28]. A partial exception is the case of the Manchester Steam Users' Association. This association was founded in 1855 and its purpose was to provide its members with accurate reports on the safety and efficiency of the boilers they had in use[29]. In defining the scope of the Association and the procedures for the

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27 Besides the involvement of adventurers in different mining ventures, a long-lasting tradition of cooperation between neighboring mines was well established in the Cornish mining district: «Between the 16th and the 18th centuries a well-developed habit of cooperation had been created between the owners and managers of adjacent mines. Despite the impression of constant antagonism, litigation and even violence… the general rule was for mutual cooperation for mutual profit. […] Examination of the 18th and 19th century cost books for mines in St. Just, St. Agnes and Redruth parishes show that cooperation over something as vital as mine drainage was the norm among mine owners, managers and landlords in Cornwall», BuckleyJ. A., «The great county adit: a model of cooperation», *Journal of the Trevithick society*, 1989, n°16, p.2-3.

28 HillsR. L., *op.cit.* note 4, p.131.

29 The original name of the association was *Association for the prevention of steam boiler explosions and for effecting economy in the raising and use of steam*. Article18 of the rules and regulations of the association stated: «[E]very member [can] have *free access* to the results recorded in the office of the secretary: but in all books and reports open to the inspection of the members each firm shall be designated by a number, and the names of firms shall only be given with their consent», Manchester steam users' Association, *A sketch of the foundation and of the past fifty years' activity of the Manchester Steam Users' Association*, Manchester, Taylor, Garnett & Evans, 1905, p.22. William Fairbairn was one of the promoters of the initiative. In the evidence given on boiler explosion at Stockport in 1851, he declared: «It seems to me that there should be some association [...] by which registers should be kept, not only with reference to the safety of the public, but also to show what duty engines and boilers perform. The best results have arisen from such regulations in Cornwall and it has led there to the greatest possible economy», FairbairnW., *The life of Sir William Fairbairn (edited and completed by William Pole)*, London, Longmans, Green & Co., 1877, p.265.

compilation of the reports, the example of *Lean's engine reporter* was explicitly considered as a model. The initiative had only limited success, being capable of attracting only a small portion of steam engine users[30].

Furthermore, Cornish engineers were recruited by mine captains on a one-off basis. Typically, engineers were in charge of the design of the engine and they supervised the erection works. They also provided directions for the day-to-day operation and maintenance of the engines they were entrusted with. The publication of technical information concerning the design and the performance of the various engines allowed the best engineers to signal their talents, hence improving their career prospects.

The peculiar organization of the Cornish mining industry made mine entrepreneurs interested in improvements of the *aggregate average performance* of the pumping engines used and, at the same time, engineers in publicly signaling the *above average performance* of the engines they had erected. Thus, in the Cornish context, *Lean's engine reporter* was able to reconcile the tensions between collaboration (among mine adventurers) and competition (among engineers) operating in the Cornish mining district, triggering a successful exploration of the space of technological opportunities, which was not attained in other steam using areas of Britain.

To sum-up, the historical evidence presented in this paper, in our interpretation, indicates that (partially) dispersed ownership of mining ventures, combined with the existence of a group of independent consulting engineers led, in the early 1810s, to the emergence of a sustainable collective invention setting in the Cornish mining district. Over time, stimulated by the same process, it is possible to discern the formation in the Cornish engineering community of a rather original «professional culture», characterized by an enduring commitment to advance technology[31].

The study presented in this paper also contains broader implications. In very general terms, current conventional wisdom considers strong and broad intellectual property rights as a key-stimulus to technical progress. Strong intellectual property rights are deemed to constitute an indispensable incentive for motivating an adequate level of private investment in the search for new technologies. At the same time, broad (and well specified) intellectual

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30 Bartrip P.W.J., «The State and the steam boiler in nineteenth century Britain», *International review of social history*, 1980, n°25, p.87.

31 For a discussion of Cornish identity in the nineteenth century, see PaytonP., «Industrial celts? Cornish identity in the age of technological prowess», *Cornish studies*, 2002, n°10. Remarkably, Payton (p.126) notices in the early nineteenth century the progressive consolidation of «an assertive Cornish identity based on industrial prowess».

property rights promote relatively ordered exploration of the space of technological opportunities[32].

The evidence presented in this paper seems however to cast doubts on the general validity of such a proposition. In fact, in industries (such as the cases examined in this paper) where the dynamics of technological change displays a cumulative and incremental character, the protection of «commons» of freely accessible knowledge is likely to yield much higher rates of innovation than the enforcement of strong intellectual property rights. In such instances, even at the level of individual actors, free sharing of technological knowledge may be a much more rewarding strategy than secrecy or individual appropriation and commercialisation.

All this can account for the emergence of particular institutional set-ups (which following Allen might be termed «collective invention regimes») that make sure that new technological knowledge remains freely accessible.

The case presented here is just indicating what seems to us a very promising research agenda. Hopefully, the recent upsurge of interest in intellectual property rights can provide the stimulus for further research in this direction, leading us towards the achievement of a deeper understanding of the factors accounting for the emergence and consolidation of collective invention regimes.

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[32] See MazzoleniR. and NelsonR., «The benefits and costs of strong patent protection: a contribution to the current debate», *Research policy*, 1998, n°27, for a (rather sceptical) overview of the theoretical arguments and the empirical evidence supporting such a proposition.