Collective Invention during the British Industrial Revolution: The Case of the Cornish Pumping Engine.[*]

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Abstract

T. S. Ashton told that one of his students once defined the industrial revolution as "a wave of new gadgets that swept over England". However crude, this definition is still held to capture a good deal of historical truth The industrial revolution, among other things, was a major technological discontinuity. This technological discontinuity manifested itself in a number of critical inventions. The history of these inventions is often told in terms of individual creative leaps of imagination in the technological domain combined with the creation of successful entrepreneurial undertakings. Thus, recent historical research still portrays the early phase of the industrialization process in Britain as an "heroic age" of individual inventors (see Mokyr, 1994). What remains to be explained then, is why England was such a fertile soil for individual inventors compared with other European countries.

In this paper, we argue that together with individual inventors and firms, what Robert Allen (1983) has termed as *collective invention settings* (that is settings in which rival firms freely release each other pertinent technical information and in which each firm incrementally improved on a basic common technological layout), was also an important source of innovation in the industrial revolution period. Until now, this has been very little considered in the literature. This paper focuses on one of these cases: the Cornish mining district. In Cornwall, during the early nineteenth century, a notable collective invention setting, gradually emerged. This case is particularly remarkable because it was capable of generating a continuous and sustained flow of improvements in steam pumping technology which in the end greatly contributed to improve the thermodynamic efficiency of the steam engine (see Von Tunzelmann, 1978). In this paper we study in detail the specific economic circumstances that led to the formation of this collective invention setting and we analyses its consequences for the rate of technological innovation.

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0 Introduction

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In this paper, we argue that together with individual inventors and firms, what Robert Allen (1983) has termed as *collective invention settings* (that is settings in which rival firms freely release each other pertinent technical information and in which each firm incrementally improved on a basic common technological layout), was also an important source of innovation in the industrial revolution period. Until now, this has been very little considered in the literature. This paper focuses on one of these cases: the Cornish mining district. In Cornwall, during the early nineteenth century, a notable collective invention setting, gradually

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1 The development of steam technology

According to Cardwell (1994, p. 121) the "first successful steam engine in the world" was the one developed by Newcomen in 1712.
The structure of the Newcomen engine was the following one (see figure 1).[1] Steam was created in a boiler connected through a vertical pipe, in which a valve was fixed, to a brass cylinder. The working piston was fitted into the brass cylinder. The piston rod was linked with a chain to the arch head of a beam. The other extremity of the working beam was connected by means of another chain to the mine pump rod. The arch heads at the extremities of the working beam assured that the two chains were always in vertical position. In addition to the connection with the boiler, at the bottom of the cylinder there were also two other connections: the first one to another pipe from which a jet of cool water could be sprayed inside the cylinder; the second one to a so-called "eduction pipe", which was used to expel the condensing water from the cylinder.

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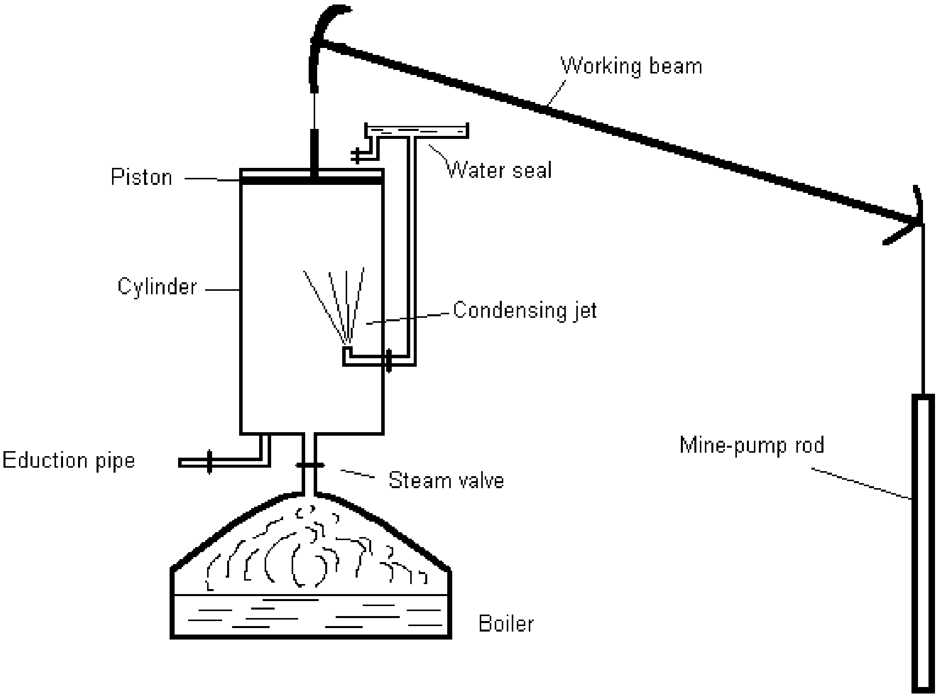
[1] This description of the structure and the working principle of the Newcomen engine draws mainly on Cardwell (1994), p. 122.

At the beginning of each cycle of operations the weight of the pump rod pushed the piston up to the top of the cylinder. In the same time steam (at atmospheric pressure) passed from the boiler to the cylinder. Then the "steam valve" connecting the boiler and the cylinder was closed and a cold jet of water was sprayed into the cylinder. In this way steam condensed and a partial vacuum was created inside the cylinder. The atmospheric pressure pushed the piston down lifting the pump rod by means of the bean. When the piston reached the bottom of the cylinder the condensing jet was turned off. At this point, it was necessary to discharge from the cylinder the condensing water and the condensed steam. This was achieved by letting some steam flow into the cylinder after each stroke. This steam pushed the water and air away from the cylinder through the "eduction" pipe.[2] At this point the cylinder could be filled again with steam and a new operating cycle could start.

It was soon discovered that it was highly uneconomical to condense all the steam inside the cylinder completely, but it was better to work with a warm cylinder making use of only a part of the force of atmospheric pressure.

Figure 1: the Newcomen engine



The opening and closing of the steam and the water valves at the bottom of the cylinder were performed automatically through an ingenious system of lever connected to the beam by means of a plug rod (not represented in the figure). Using steam at only atmospheric pressure the Newcomen was well within the limits of the engineering capabilities of the time. The only problem in this respect was due to the fact that it was impossible for the capacity of the workshops of the time to build a

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[2] Another small outlet pipe (not represented in the figure) was fixed at the bottom of the cylinder through which the air entered in the cylinder because of the imperfect sealing was discharged. At the end of this pipe was fixed a valve called "snifting valve" because of the noise it made.

cylinder so accurately bored to ensure that it fitted the piston tightly enough to prevent the air from entering and ruining the vacuum. However this problem was solved very ingeniously by fixing to the top of the piston a leather disk and further completing the seal by using a layer of water coming from a small tank fixed on the top of the cylinder.

The use of the cylinder and the piston to operate the water-pump made it possible to employ the Newcomen engine for an effective mine drainage (pump rods could be easily extended to reach the necessary depth). Moreover, the Newcomen engine was robust, reliable and its working principle was fairly simple. Hence, once it was installed, it could work effectively for a long period of time with almost negligible maintenance costs.[3]

Following Von Tunzelmann (1995), we can say that after Newcomen's invention, the steam engine established itself as the relevant technological paradigm in mine draining.[4] Moreover by virtue of their reliability, many Newcomen engines remained operative for a long time during the nineteenth century.

The Newcomen engine had a major shortcoming: the high consumption of fuel, determined by the necessity of the alternate heating and cooling of the cylinder during each operating cycle. In coal mining, where large supplies of cheap coal were available, fuel consumption did not represent a serious limitation,[5] but in other mine fields (notably in the copper and tin mines of Cornwall, where coal had to be imported by sea) fuel inefficiency did not permit a widespread diffusion of the engine.

Between Newcomen and Watt there were no dramatic changes in the design of steam engines. Nevertheless, a number of incremental improvements of the steam technology was achieved. Some of them were the result of the progressive perfecting of manufacturing methods of the various components of the engines. Other improvements were the result of a continuous investigation, mainly through a "trial and error" process, on the design of a Newcomen engine. By means of a small model of an engine of which he systematically varied each component in turn, John Smeaton was finally able to individuate the best configuration of the different elements of the Newcomen engine raising significantly its performance.

At this juncture it should be noticed that since the early diffusion of the Newcomen engine, fuel consumption was regarded as the main dimension to be used in the evaluation of the performance of a steam engine.[6] The most common measure of the performance of a steam engine was called the "duty" and it was calculated as the quantity of water (measured in lbs) raised 1 feet high per 1 bushel (84 lbs) of coal

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[3] Von Tunzelmann (1978), p. 79.

[4] Von Tunzelmann (1995), p. 106.

[5] Von Tunzelmann (1995), p.106.

[6] Landes (1969, p. 100) has appraised the direction of innovative activity in this period in these terms: "[T]he leitmotif of steam technology was the effort to increase efficiency, that is, the amount of work done per unit of energy. By comparison the goal of greater power, that is, work performed per unit of time, took second place, although the two objectives were linked and what made for one, permitted or yielded the other". In the same vein, according to Habakkuk (1962, p. 158): "Fuel economy was the purpose of Watt's first improvement to Newcomen's engine (the patent of 1769), and continued to be the motive behind developments in the steam engine from Watt's separate condenser down to the compound engine".

consumed. [7] [8] In 1772 Smeaton built a Newcomen engine with a duty 9,450,000 (lbs), almost doubling the results previously attained (the average performance of Newcomen engines in 1769 was 5,590,000 lbs).[9] From an engineering viewpoint, the duty provides an indication of the thermodynamic efficiency of a steam engine. However this measure has also an important economic meaning because it is a measure of the productivity of an engine with respect to the largest variable input in the "production process" (Von Tunzelmann, 1970, pp.78-79)

The adoption of the "duty" as one of the main parameters for the evaluation of the performance provides a precious indication of the direction taken by innovative efforts. In terms of Dosi's paradigm/trajectory approach, we can say that a set of technological heuristics aimed at focusing the search for innovations in a fuel(coal)-saving direction were progressively established (Von Tunzelmann, 1995, pp. 14-15). According to Dosi, technological trajectories are generated by the interplay between the "autonomous"[10] drift of technology (within the boundaries defined by the prevailing technological paradigm) and a particular set of inducement factors of economic type (relative factor prices). Economic inducement factors are likely to play a role in determining the specific direction of the technological trajectory when the paradigm is its emerging stage. Over time the heuristics get progressively established and technical advances become increasingly localized and irreversible.[11]

For the purposes of this paper, this means that the evolution of the duty can be an appropriate and theoretically grounded metric for measuring the rate of technical change.

Another feature of the steam engine that was necessary to measure was its power. In this case the unit designed by Watt for this purpose, the horsepower (corresponding to 33,000 lbs raised 1 foot in one minute) became soon of common usage.

In 1769 James Watt conceived an alteration in the basic design of the engine that allowed for drastic reduction in coal consumption. For the purposes of the present work, it will be enough to provide a description of the working principle of the Watt pumping engine in its final form, when its design was more or less standardised (see figure 2).

The working cylinder was fixed into a steam case in order to minimise hot losses. The steam case was connected with the separate condenser through a pipe in which a valve (called exhaust valve) was fixed. The separate condenser consisted simply in a vessel immersed in cold water. The condenser was always under vacuum and was connected

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[7] The measure originally used by Smeaton was the *volume* of water the engine could raise consuming 1 bushel of coal. The concept of duty (*weight* of water lifted 1 ft. consuming 1 bushel of coal) was introduced by Watt. As Cardwell puts it : "..the principle will be familiar to most people who, on buying a car, take into account the number of 'miles it can do to a gallon' or 'kilometres to the litre'". (Cardwell, 1994, p.166) .

[8] Note that (for average quality coal) a "duty" of n million lbs corresponds to an overall thermal efficiency of 0.15 *n % and to fuel a consumption of 170/n lbs. per horsepower per hour. See Von Tunzelmann (1978, p. 67).

[9] See Hills (1989), p.131. For other observations on the performance of the atmospheric engines see Von Tunzelmann (1978), pp. 67-70.

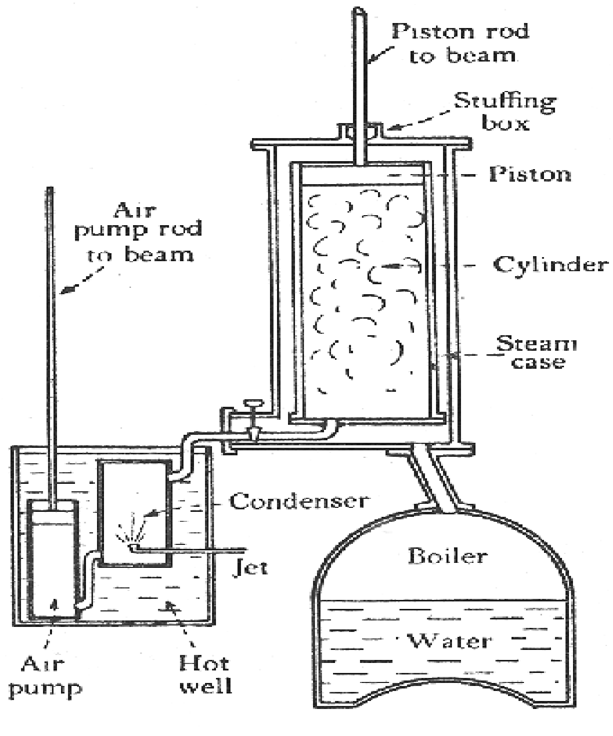
[10] The "autonomous"drift of technology is the product of the "compulsive sequences" of solutions of technical bottlenecks described by Rosenberg (1977)

[11] See Dosi (1988), pp. 1142-1145.

to an air pump that served the purpose of eliminating the condensed steam. Finally, in another pipe connected the top of the cylinder to the bottom. In this pipe a valve called “equilibrium valve” was fixed. The opening of this valve allowed the passage of steam from the top to the bottom of the piston. In the Watt engine the cylinder was completely closed on the top and the piston rod passed through it by means of a stuffing-box.

The operation of the engine was as follows. Steam was admitted, through the steam valve (or inlet valve), into the cylinder above the piston. Steam at a little more than atmospheric pressure drove the piston down. In this respect Watt engine can be considered the first genuine steam engine because its motive agent was steam and not atmospheric pressure. When the piston reached the bottom of the cylinder completing its stroke, the equilibrium pass valve was opened and steam passed from the top to the bottom of the cylinder. At this point under the weight of the pump rod the piston rose. The exhaust valve was then opened and the spent steam under the piston was admitted into the condenser. Simultaneously the inlet valve was also opened and new steam was admitted at the top of the cylinder, starting a new operating cycle.

Figure 2: The Watt Engine



Source: Dickinson (1938), p. 67

The use of the separate condenser greatly reduced the fuel consumption of the steam engine. The Newcomen engine as improved by Smeaton was capable of a duty between 7 and 10 millions. Watt’s pumping engine in a first moment raised the duty to 18 millions and later, when its design was fully established, to 26 millions.[12] Such an economy of fuel made profitable the use of the steam engine in the mine fields situated in areas where the coal was expensive. The first successful application of the Watt engine was in the copper and tin mines of Cornwall where, as we have seen, the high price a coal had previously prevented a widespread penetration of the Newcomen engine.[13]

In a later phase, pushed by the insistence of his business partner Matthew Boulton,[14] Watt conceived a number of modifications to his engine in order to allow the effective transformation of the reciprocating motion in rotary one. This would have permitted a general industrial use of the engine, opening to Boulton & Watt an almost limitless market.

In his 1769 patent Watt suggested the idea of employing the expanding steam before condensation. This was done cutting off the steam when the piston was at the beginning of the stroke and letting the expansion of the steam in the cylinder to complete it. The use of the expansive working of steam would have permitted some additional fuel economy. However at low pressures, the gain in efficiency was quite limited.

Watt was strongly adverse to the use of high-pressure steam. He feared the possible negative consequences in terms of popularity of boiler explosions, supposing that this could have discredited the use of steam power irreparably.[15]

After the expiration of Watt' s key patent in 1800, new operators entered the steam-power field and the high-pressure trajectory began to be explored. The pioneers of this domain were Richard Trevithick in England and Oliver Evans. In the following, I will deal mainly with the contribution of Trevithick, which is the most relevant for our purposes.

To employ high pressure new types of boilers had to be designed. Trevithick built a cylindrical boiler with an internal U shaped tube (taking the gas to the chimney) in it. The boiler could generate a pressure from 50 to 90 p.s.i.[16] The cylinder was fixed inside the boiler in horizontal position. The engine discharged the spent steam in the atmosphere and for this reason it was called "puffer". The main advantage of this type of engine was its compactness and its cheaper cost of installation (due to the elimination of the condenser, the air pump and the beam.). However, high-pressure

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[12] In 1792 two Watt engines in Cornwall were capable of performing respectively the duty of 32 and 35 million. For other data on the duties performed by the different types of steam engines see Hills (1989),p.131. See also Von Tunzelmann (1978), pp. 67-69.

[13] "In Cornwall Boulton and Watt made their names, a great deal of money, and learned all about installing and improving steam engines" (Cardwell, 1994, p. 162.). For a detailed account of the activity of Boulton and Watt in Cornwall see Tann (1996).

[14] In a letter to Watt, Boulton significantly wrote : "There is no other Cornwall to be found and the most likely line for the consumption of our engines is the application of them to mills which is certainly an extensive field" (quoted in Hills (1989), p. 62)

[15] This is the interpretation of Cardwell (1994,pp. 166-167 and pp. 208-209). More prosaically, Hills (1989, p.97) suggests that Watt was also aware that high pressure could have dispensed the use of the separate condenser.

[16] See Hills (1989), p. 127.

engines were less efficient in fuel consumption than Watt engines (they tended to consume circa 25 % more coal). [17]

In 1812 Trevithick built the first steam engine of the so-called “Cornish” type. The Cornish engine was simply a Watt single-acting engine employing high-pressure steam. The working principle of this engine was very similar to the Watt pumping engine described above. High-pressure and condensing action were combined in a carefully regulated operating cycle (“Cornish cycle”). High-pressure steam was admitted at the top of the cylinder from the inlet valve. The inlet valve was closed soon (“early cut-off”) and the steam expanded in the cylinder. At the end of the stroke the equilibrium valve was opened so that the steam could pass below the piston. Note that the exhaust valve was also opened during the working stroke, so that spent steam was discharged into the condenser at the same that live steam was admitted at the top of the cylinder.

In the following years the Cornish engine revealed itself as the highest accomplishment in steam technology.[18] The engine had negligible costs of maintenance and it was susceptible of continuous improvements in its efficiency. [19]
The main rival of Richard Trevithick in Cornwall was Arthur Woolf. In 1804 Woolf had patented an engine incorporating the principle of compounding. In Woolf engine, the steam at high pressure first drove the piston in a small cylinder, then at low pressure it was used for a second larger cylinder. The cylinders were placed side to side and connected at the same point of the beam.

In 1811 Woolf, started to build engines in Cornwall. In a first phase the Woolf engine seemed to outperform its rivals. However, after a period of usage, Woolf engines had troubles in maintaining their initial efficiency.
The “controversy” between the single cylinder engine of Cornish type developed by Trevithick and the Woolf compound engine was resolved in 1824. John Taylor ordered Woolf to build two comparable engines to be used in a test. The Cornish engine achieved a duty of 42 millions, whereas the Woolf engine a duty of 40 millions. Woolf himself reverted to the single cylinder engine and the Cornish engine as designed by Trevithick became the dominant type in Cornwall mines.

Table 1 summarizes the improvement of fuel-efficiency in the development of steam technology.

Table 1: Improvement in the efficiency of “generic” steam engines.

Type of engine	Lbs of coal per horsepower per hour
Savery (Wrigley version)	30
Newcomen (1700-1750)	20-30

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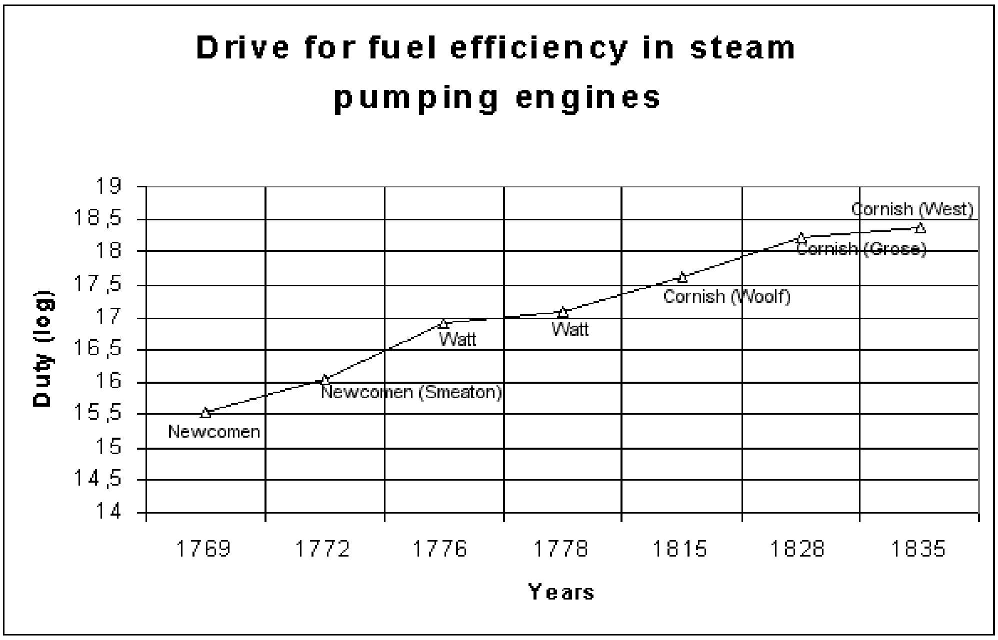
[17] Von Tunzelmann (1978), p. 22. Trevithick high pressure engines were usually preferred to Watt engines at low sizes. The compactness of high pressure engines further extended the number of possible application of steam power.
[18] Von Tunzelmann (1978), p. 263.
[19] As we will see in the next section, a major role in the improvements in the efficiency of the Cornish engine was played by the compilation of Joel Lean ‘s *Monthly Engine Reporter*, which favoured the identification of the best engine designs and operating practices.

Newcomen (Smeaton version)	17
Watt low pressure engine (1800)	10-15
High pressure (1850)	5
High pressure (1850: best Cornish engines)	2.5

Source: Von Tunzelmann (1978), pp. 68-70**.**

Figure 3 reproduces the drive for fuel efficiency (technological trajectory) of best practice steam techniques.

Figure 3



Both table 1 and the figure 3 outline to the crucial role assumed by the Cornish engine in the course of the first half of the XIX century.

2 The Cornish engine as a case of collective invention.

The first important market for the engine developed by Watt was the Cornish copper and tin mining industry. In this area coal had to be imported from Wales, so it was particularly expensive. Hence Cornish mine "adventurers" (in this way mine entrepreneurs were called) were keenly interested in technological improvements that could curtail their dear fuel bill.

For these reasons, it is not surprising that the Boulton and Watt engines became immediately very popular in Cornwall. Between 1777 and 1801, Boulton and Watt erected 49 pumping engines in the mines of Cornwall. Jennifer Tann has described the crucial role of the "Cornish business" for the fortunes of the two partners in these terms:

> Whether the criterion is the number of engines, their size or the contribution to new capital, Cornish engines comprised a large proportion of Boulton & Watt's business during the late 1770s to mid 1780s. From 1777 to 1782, Cornish engines accounted for more than 40% of Boulton & Watt's total business and in some years the figure was significantly higher. In the early 1780s Cornish business was more fluctuating but with the exception of 1784, Cornish engines accounted for between 28% and 80% of Boulton & Watt's business. [20]

The typical agreement that Boulton & Watt stipulated with the mind adventurers of Cornwall was that they would have provided the drawings and supervised the works of erection of the engine. They would have also provided some particularly important parts of the engine (like some of the valves). These expenditures would have been charged to the mine adventurer at their cost (i.e. not including any profit for Boulton & Watt). In addition the mine adventurer had to buy the other components of the engines not directly supplied by the two partners and to build the engine house. All this amounted to the total fixed cost associated with the adoption of a steam engine. [21]

The profits for Boulton & Watt resulted from the royalties they charged for the use of their engine. Watt's invention was protected by the patent for the separate condenser he took in 1769, which an Act of Parliament had prolonged until 1800. The pricing policy of the two partners was to charge an annual premium equal to one-third of the savings of the fuel-costs attained by the Watt engine in comparison to the Newcomen engine. This required a number of quite complicated calculations, amounting at identifying the *hypothetical* coal consumption of a Newcomen engine supplying the same power of that Watt engine installed in the mine.

At the beginning, this type of agreement was accepted in very favourable terms by the mine adventurers. However, after some time, the pricing policy of Boulton & Watt was perceived as extremely oppressive. There were several reasons for this. Firstly the winter months in which most water had to be pumped (and the highest premiums had to paid) were the ones in which the mine was least productive. Secondly, the mine adventurers knew the amount of the payments they owed to Boulton and Watt only after these had matured. Finally, the decision of Boulton and Watt of not giving license to other engineers (in Cornwall at the time there was a vital engineering community) of erecting engines of the Watt type produced additional grudge. As a matter of fact, the enforcement of an almost absolute control on the evolution of the steam technology during the duration of Watt's patent was a crucial component of Boulton and Watt's business strategy.

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[20] Tann (1996), pp. 29-30

[21] Von Tunzelmann (1978), pp.51-52.

As time went by, some adventurers installed "pirate" engines erected by local Cornish engineers challenging explicitly the validity of Watt's patent. A lengthy legal dispute followed. The dispute ended in 1799 with the courts confirming the legal validity of Watt's patent and, in this way, attributing a complete victory to Boulton & Watt. The dispute had also other far-reaching consequences. Boulton and Watt, with their legal victory (pursued by them with relentless determination), alienated completely any sympathy towards them in Cornwall. After the expiration of Watt's patent in 1800, steam engines orders to Boulton and Watt in Cornish mines ceased completely and the two partners had to call their agent in the county back to Birmingham. However, it is also important to mention, that at this stage the market for manufacturing power had become the main focus of the company.
Following the leave of Boulton and Watt, Cornish mining activities underwent a period of "slackness", as the mine adventurers were content with the financial relief coming from the cessation of the premiums and they neglected the maintenance and the improvement of their engines. This situation lasted until 1811, when a group of mine "captains" (the mine managers were termed in this way) decided to begin the publication of a monthly journal reporting the performance of each engine. Their explicit intention was twofold. Firstly, the publication of the reports would have permitted the rapid individuation and diffusion of best-practice techniques. Secondly, it would have been introduced a climate of competition among the engineers entrusted with the different pumping engines.

Captain Joel Lean was appointed as the first "engine reporter". After his death, the publication of the reports was continued by his sons and continued until 1904. In 1839 a synthesis of the first period of reporting, was published under request of the British Association for the Improvement of Science with the title of *Historical Statement of the Improvements Made in the Duty Performed by the Steam Engines in Cornwall* (Lean, 1839). This is the source we will use in the next seection of the paper.[22]

For each engine, the Leans reported the following information: i) the name of the engine and the mine in which it was located, ii) the diameter of the the cylinder (in inches), iii) the load on the pistons (in lbs. per square inch), iii) the length of the stroke in the cylinder (in feet), iv) the number of pump lifts, the depth of each lift (in fathoms), the diameter of each pump (in inches), v) the period during which the engine was in operation, vi) the length of stroke in pumps (in feet), vii) the weight of water raised at each stroke (in lbs.), viii) the consumption of coal (in bushels), ix) the number of strokes effectuated in the period considered, x) the duty of the engine (lbs. of water lifted one foot per bushel of coal consumed), xi) the average number of strokes per minute, xii) the name of the engineer entrusted with the engine and eventual remarks on potentially interesting features of the engine and of its working behaviour.

As we have seen in the previous section, concomitant with the beginning of the publication of Lean's *Engine Reporter*, Richard Trevithick and Arthur Woolf erected high pressure engines in Cornish mines. The layout of the engine designed by Trevithick in1812 became soon the basic one for Cornish pumping engines. As a consequence of the publication of the engine reports, the thermodynamic efficiency of

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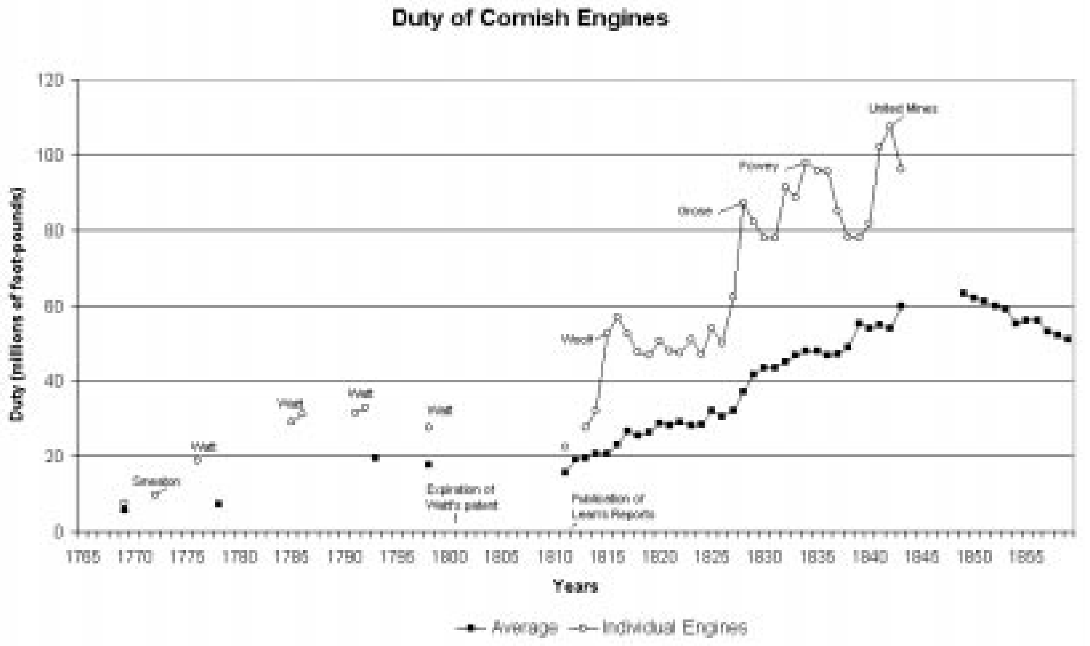
[22] A database containing an almost complete set of the *Lean's Engine Reporter* is currently under construction at the Eindhoven Centre for Innovation Studies (ECIS). For more information about this research project contact the author of this paper.

Cornish engines begun to improve steadily. On strictly engineering grounds, this amounted to a very effective exploration of the merits of the use of high-pressure steam. The improvement over time of the efficiency of the Cornish engines (as resulting by collating several sources) is displayed in figure 4.

Figure 4.



Sources: Lean (1839), Pole (1844), Dickinson and Jenkins (1927), Barton(1965)

The case of the Cornish engine fits nicely in the concept of collective invention introduced by Robert Allen (Allen, 1983). According to Allen, alongside non-profit institutions (like universities and government agencies), firms R&D laboratories and individual inventors (like James Watt), in capitalist economies a fourth inventive institution exists. Allen has termed this fourth institution as “collective invention”. In a collective invention setting, firms freely release each other technical information about the design and the efficiency of new technologies. Allen has noticed this pattern of behaviour in the iron industry of Cleveland (UK) in the period 1850-1875. In Cleveland firms disclosed freely pertinent technical information about the construction details and the performance of the blast furnaces they had erected to their competitors. As a consequence of this release of information, in the period in question, furnace height and blast temperature increased steadily, by means of a series of small but continuous rises. Increases in the height and in the blast temperature of the furnaces resulted in lower fuel consumption and lower costs.

Allen’s notion of collective invention can be fruitfully linked with the incremental and “anonymous” streams of technological improvements described by Rosenberg (1977) as one of the recurring patterns in the dynamics of technical changes. One may indeed consider the main thrust of Allen’s paper is the individuation of the main source of Rosenberg’s “sequences” of incremental technical advances. In this respect, it is worth recalling that, according to Rosenberg, incremental technical change (contrasted to radical technical changes) is the main source of productivity growth.

At this juncture, from our previous discussion, it should be also evident that the Cornish engine represents another particularly important case of collective invention. Almost every student of the Cornish engine has stressed the collective nature and the incremental nature of technical advances in this field. Thus, among others, Caff (1937) noticed that:

> So many of the characteristics of the Cornish engine arise from a succession of improvements to detail that it is impossible to credit them to any single person. Rather they belong to the whole school of Cornish engineers. The mining districts were sufficiently large and yet sufficiently compact for comparison and competition to be effective in a rapid spread of ideas. [23]

3 Measuring technical change in Cornish engines.

The eminently collective nature of the innovative activities in Cornish mining has left us with a rich a data source (the *Engine Reporter)* on the technological development of the steam engine in Cornwall.

This data source can be utilized to build an index of technical change. As we have seen in the previous section, the duty of a steam pumping engine was the main performance characteristic on which the engineers engaged in the search for improvements to the steam pumping engine focused upon. According to Von Tunzelmann (1970, p. 79):

> There is every indication of a qualitative kind that the goal of Cornish engineers (the criterion of their efficiency) was to maximize the duty of the engine they were entrusted with. In some cases managers paid their engineers 'million money' [the duty is measured in millions of lbs of water lifted one foot per bushel of coal consumed] as a bonus for raising duty. The very publication of Lean's *Engine Reporter* was both a symptom of and a stimulus to the competitive spirit prevailing between rival engineers over duty. Accordingly, a body of data is available on precisely the kind of improvement that these engineers most desired to make.

A technological trajectory consists in the improvement over time of the multi-dimensional trade-offs identified by the prevailing technological paradigm. Hence, a technological trajectory unfolds in the multidimensional space of the performance variables that the prevailing paradigm has considered as "relevant". However, technologists have noticed that in a number of cases (especially when dealing with specific application fields of a particular technology) the set of the relevant technological characteristics is dominated by one fundamental performance parameter. (Gordon and Munson, 1981, p. 26). In terms of Dosi's paradigm/trajectory approach, we may say in technologies that can be characterized by a "pacing parameter" the rate of technical change is determined by the speed of movement along the dimension representing this fundamental technological characteristic. .

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[23] Caff (1937), pp.45-46

Our account suggests that the Cornish engine can be considered as a case of a technology characterized by a specific pacing parameter: the duty. [24] Thus, the rate of change of the duty provides a good estimation of the rate of innovation in this specific technological field. The data contained in the Lean's *Engine Reporter* allow us to track the evolution of the duty of the Cornish engines over time. Besides tracking the improvement of the duty of the best-practice engines (the white points in figure 3), this body of data can be used also to estimate the rate of technical progress at the level of the industry. This is done computing the rate of change of the average duty.

The average duty for the industry at the time t is given by:

$$\overline{D}_t = \sum_{i=1}^{n} S_i D_i \qquad (11)$$

where n is the number of engines in operation, D_i is the duty of the i engine, S_i the share of the i engine in the aggregate productive capacity installed.

The *Reporter* does not provide directly information on the capacity of each engine. However from the information contained there, it is possible to compute the number of horsepower "actually" performed by each engine during the period. [25]

So, we can calculate S_i as the share of each engine in the total horsepower in use.

Table 2 reports the evolution of the average industry duty (using the data contained in the *Historical Statement*)

Table 2: Evolution of the average duty of Cornish Engines.

Years	Duty	Horsepower	Number of engines	Annual growth between periods(%)
1814	21784745.36	1445.37	35	-
1821	29305693.72	2344.47	44	4.3
1828	41759567.37	3012.30	60	5.2
1835	57689492.31	2965.70	59	4.7

Now let us consider the time interval $(t, t-1)$ and let us imagine of having ordered the engines in the following way:

Period t :

$\{1,2,3, ..., n_2\}$= engines reported at the time t subdivided in:

$\{1, 2, 3,................ N\}$= "continuing" engines (engines in operation from the beginning to the end of the time interval)

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[24] It is important to stress that this simply mean that the duty appeared to the engineers as the "fundamental" performance parameter. But this does not mean that technical improvement was exclusively restricted to that dimension.

[25] The number of horse-power performed by the engine is obtained by multiplying the duty for the consumption of coal and dividing by 33000 times the number of minutes of working time of the engine. All these information are contained in the *Reporter*.

$\{N+1, N+2, \ldots\ldots\ldots\ldots n_2\}$ = “new” engines (engines not reported at the time $t-1$, but reported at the time t)

Period $t-1$
$\{1,2,3,\ldots\ldots\ldots\ldots,\ n_1\}$= engines reported at the time $t-1$subdivided in:
$\{1,2,3,\ldots\ldots\ldots\ldots,\ N\}$= “continuing” engines
$\{N+1, N+2, \ldots\ldots\ldots\ldots, n_1\}$ = engines scrapped during the time interval

In this way we can sort out the contribution of the different components of technical change (i.e. learning processes consisting mainly in “disembodied technical change”, versus innovations “embodied” in new engines) to the change of the average duty.
This can be done using the following decomposition formula: [26]

$$\frac{\Delta\overline{D}_t}{\overline{D}_{t-1}} = \frac{\sum_{i=1}^{N}(D_{i,t}-D_{i,t-1})S_{i,t-1}}{\overline{D}_{t-1}} + \frac{\sum_{i=1}^{N}(S_{i,t}-S_{i,t-1})(D_{i,t-1}-\overline{D}_{t-1})}{\overline{D}_{t-1}} + \frac{\sum_{i=1}^{N}(S_{i,t}-S_{i,t-1})(D_{i,t}-D_{i,t-1})}{\overline{D}_{t-1}} +$$

$$+ \frac{\sum_{i=N+1}^{n_2}(D_{i,t}-\overline{D}_{t-1})S_{i,t}}{\overline{D}_{t-1}} - \frac{\sum_{i=N+1}^{n_1}(D_{i,t-1}-\overline{D}_{t-1})S_{i,t-1}}{\overline{D}_{t-1}}$$

The first term on the right hand side represents a “within” engine component weighted for the initial share. The term aims at capturing the more efficient operation of the existing capacity (due for example to learning processes, small technical improvements, etc.) and it can be assumed to represent the disembodied component of technical change. This term measures the change of performance of the “continuing” engines. So whenever the physical deterioration of the engines is not counterbalanced by maintenance 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 (also called static shift effect). This term reflects the increase of the average duty due to the reallocation of the installed capacity from the worse to the better engines. Note that the term is expression in deviation from the mean. It can be considered to reflect the degree of efficiency in the management of the existing engine park.

The third term on the right hand side represents what might be called a “dynamic” shift effect and it captures the growth of the average duty due to the reallocation of productive capacity towards more “dynamic” engines, that is engines endowed higher duty growth rates, whereas in the “between” engine component reflected the reallocation towards engines with higher duty levels. Also this term can be deemed to represent a technology management aspect.

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[26] The exercise resembles productivity decompositions at industry level among industrial plants. The formula we used here is the “preferred” decomposition formula in the survey of the literature of Foster, Haltiwanger and Krizan (1998) Of course other decompositions can be envisaged.

The fourth term on the right hand side measures the improvement of the average duty due to the installation of new capacity (introduction of new engines). This term can be assumed to represent the "embodied" component of technical change. Note that the term is expressed in deviation from a mean, so to give a positive contribution a "new" engine should perform a higher duty than the average duty of the industry in the previous period.

Finally, the fifth term represent the effect due to the scrapping of existing capacity. Table 4 reports the results of this kind of exercise using the data contained in the *Historical Statement.*

Table 4: Decomposition of average duty growth

	Duty growth	Percentage of duty growth explained by					
		Within engine effect	Static shift effect	Dynamic shift effect	Entry effect	Exit effect	Total effect
1814-1821	0.35	27.43	1.86	-6.45	74.99	2.17	100
1821-1828	0.42	9.93	-2.65	3.63	82.24	6.86	100
1828-1835	0.38	5.84	4.68	3.27	74.64	11.58	100

The predominant role seemed to have been played by technical change embodied in new engines (entry effect).[27] This is consistent with Allen's observation that, in collective invention settings, the rate of innovation is highly dependent on the rate of capital formation (Allen, 1983, p.13). Phases of high rate of capital formation usually coincide with periods of industrial expansion. Collateral historical research (Barton, 1968) confirms that the period (1815-1840) was a period of particularly rapid growth for the Cornish copper mining industry. In further research we intend to decompose the entry effect between engines of "radical" new design (e.g. the engines introduced by Woolf and Sims) and engines projected along more traditional lines.

Both the static and the dynamic shift component appear (as one might have expected?) to have contributed in a minor way to the improvement of the growth of the average duty. It is worth noticing that the negative impact of the dynamic shift effect in the first sub-period may reflect a phase of experimentation, more than difficulties of the engineers in the allocation of the productive capacity of the engine park.

Finally, it is particularly interesting the fact that the "within engine" component is quite robust in the first sub-period and that it declines in the following two. This can be probably explained by the learning both of the "Cornish cycle" of operation and of the level of steam pressure with which operate most efficiently the engines (both learning processes are likely to have been characteristic of the first sub-period)

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[27] However, it was worth noticing that these results might contain some upper bias in the entry effect, due to the fact that in some cases from the *Historical Statement* it is difficult to understand whether an engine is a really "new" engine or is an engine that was moved from a mine to another.

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