DANISH RESEARCH UNIT FOR INDUSTRIAL DYNAMICS

DRUID Working Paper No 01-05

Collective Invention during the British Industrial Revolution: The Case of the Cornish Pumping Engine

by

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May, 2001

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Abstract

In this paper, we argue that together with individual inventors and firms, what Robert C. Allen (1983) has termed as *collective invention settings* (that is settings in which rival firms freely release each other pertinent technical information), were also a crucial 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. 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

Keywords: Collective inventions, information sharing, case study
JEL: O31, D83. L61

(ISBN 87-7873-104-6)

* I am indebted to Bart Verspagen, Nick Von Tunzelmann, Pat Hudson and Geert Verbong for stimulating discussions. A previous version of this paper was presented at the 2001 Druid Winter Conference, I am grateful to Peter Maskell and to the other participants for useful comments.

1 Introduction

According to T. S. Ashton, generations of schoolboys were accustomed to define the industrial revolution as "a wave of gadgets [that] swept over England" (Ashton, 1948, p.48). 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 tend to portray the early phase of the industrialization process in Britain as the "heroic age" of individual inventors.

In this paper, we argue that together with individual inventors and firms, what Robert C. 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 improves on a basic common technological layout), were also a crucial 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. 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

2 Individual Inventors and the British Industrial Revolution

The role of technical change in the British Industrial Revolution is still one of most debated issues in economic history. What might be called the "traditional" view considers the British Industrial Revolution as the result of a marked acceleration in the pace of technological progress (Landes, 1969) in a wide range of industries. In the period 1760-1830, so the traditional view goes, a number of technical inventions completely transformed the structure of British industry, compelling the organization of production in the factory system. The progressive adoption and diffusion of these new technologies had also other far-reaching consequences. It transformed the very structure of the British economy and of British society, representing in the end one of the most important watersheds in the history of mankind.

This view has been recently challenged (see Crafts and Harley, 1992). The "revisionists" do not question the historical importance of the consequences of the process of industrialization. However, the "revisionists" hold that the traditional depiction of the process is unwarranted. The aggregate pace of technical advance(measured in terms of Total Factor Productivity) was much slower that was supposed. Further, productivity increases were not widespread but concentrated in few modernized sectors. The conclusion of the revisionists is that the British Industrial Revolution is more properly explained as a case of highly "unbalanced growth".

The present debate between "traditionalists" and "revisionists" concerns essentially the pace of technological advance and its location (concentrated in few sectors or widespread).
Curiously enough, the fundamental issue of the *sources* of technical advance during the Industrial Revolution has been instead relatively untouched in the most recent discussion.
Economic historians, in this respect, seem to have happily accepted the conclusions emerging from the traditional history of technology, which still ascribes the generation of new technologies to the actions of heroic individual inventors such as Richard Arkwright, Samuel Crompton and James Watt. What is in need of explanation, in this perspective, is why Britain was a much more favourable environment for individual inventors with respect to other European countries (Mokyr,1994)

The most straightforward economic explanation is that in Britain, the rewards from inventive activity were high enough to attract a considerable amount of economic resources and human talents in this field. From these considerations, a number of scholars have turned their attention to the role played by the patent system. The acceleration in the rate of technological innovation is then seen a consequence of the progressive development of a fully operational patent system in the course of the eighteenth century (North, 1981).

Khan and Sokoloff (1993) have investigated the issue of the responsiveness of individual innovators to economic inducements in the United States over the period 1790-1865. In that period, American inventors seemed to have very been keen in securing property rights on their inventions and they were able to use patent protection very effectively to appropriate returns from their innovative activities.
In another related contribution, Lamoreaux and Sokoloff (1999) have argued that, in the United States, during the late nineteenth and the early twentieth centuries, a solid market for technical innovation structured around the institution of the patent system was in effectively in operation. Through this well functioning "market for technology" individual inventors were able to sell the technical knowledge they had discovered to firms. According to Lamoureaux and Sokoloff, the existence of such a market generated a peculiar pattern of division of labour with individual inventors specializing in inventive activities and firms in the production and commercialisation phases.

Finally, Lamoreaux and Sokoloff (1997) investigate the case of the American glass industry. Also in this case, the found evidence of the operation of a market of technical knowledge operating through two channels: i) specialized trade journals disseminating general information and providing detailed descriptions of the patent specifications; ii) specialized patent agents who where able to serve as intermediaries in the sale of patented technologies.
In the same work, Lamoreaux and Sokoloff also notice that in the case of the American glass industry geographical clusters of production differed from geographical clusters of patenting (residence of the patentee). According to them, this finding contradicts the idea of localized knowledge spillovers emerging from the geographical concentration of productive activities (in this case geographical clusters of production and of innovation would coincide)
Geographical clusters of patenting in the American glass industry are instead accounted for by the existence of more developed markets for technologies (existence of specialized intermediaries capable of combining supply and demand) in those regions.
Thus, the works of Sokoloff and his co-authors highlight the role played by individual inventors and the market for technology in the course of American industrialization.
What about the British case ? Without doubt, the British patent system before the 1852 reform was less effective than the American one in protecting the intellectual property rights of the

patentees. Further, the courts used a high degree of discretionary power when they were called to judge on patent infringements (Khan and Sokoloff, 1998).
Nevertheless, according to the study of Dutton (1984), however imperfect, the British patent system was capable of stimulating the efforts of inventors: “[s]o long as patents provided a degree of protection over and above the next best alternative, as in fact appears to have been the case, it paid inventors to continue to use them.” (Dutton, 1984, p.205). Hence, also in Britain a robust “trade in invention” emerged during the industrial revolution (Dutton, 1984, chap. 7).

To sum up, the more recent research in economic history, perhaps in rather tortuous way, seems to have provided new nourishment to the classical accounts of the British Industrial revolution centred on the characters of individual inventors and entrepreneurs. Samuel Smiles’ eulogy of heroic solitary inventors might be, in the end, much less naive than what was supposed to be.

Still, this interpretation of the British industrial revolution neglects important features of the economic and technology history of the period in question. In effect, when carefully scrutinized, these accounts revealed to be based on a rather simplistic depiction of the innovation process. The representation of the innovation process in these studies is pretty much akin to the so called “linear model” of innovation, with a new technology passing through the linear sequence of invention, innovation (first economic application) and diffusion (Kline and Rosenberg, 1986). Once taken this view, it is natural that most of the attention will be devoted to the determinants of individual acts of invention.

The observation from which is convenient to start is that new technologies first appear in a rather rudimentary form and a long process of improvements is necessary before an innovation could fully manifest its technical and economic potential. This process of incremental improvements, resulting from various learning effects occurring both at the producer and at the user side, as Rosenberg (1976) has shown, is simultaneous with the diffusion of the innovation.
The importance of this streams of incremental technical improvements during the British industrial revolution is stressed in Landes’ account. Appropriately, Landes terms this process as “anonymous” technical change, to emphasize the fact it markedly differs from the most “visible” individual acts of invention. All considered, Landes suggests these “small anonymous gains were probably more important in the long run than the major inventions that have been remembered in history books” (Landes, 1969, p.92). Modern empirical studies of innovation also highlight that technologies are developed through a continuous process of interactive learning in which a multitude of agents are involved (Freeman, 1994). This leads support to a more complex conceptualization of innovation in which feedback processes of learning and incremental innovation are constantly at work (Kline and Rosenberg, 1986).

Given the important role that anonymous and incremental technical change seems to have played during the industrial revolution, it is worthwhile to investigate what are the sources of this type of innovation.
According to Allen (1983), in capitalist economies four main sources of invention can be discerned: i) non profit institutions (such as universities and publicly funded research centres), ii) private firms R&D laboratories, iii) individual inventors (such as James Watt and Richard Arkwright), iv) *collective invention settings*. In collective invention settings, private firms freely release each other information about the design and the performance of the new technologies they have adopted. Allen has noticed this type of behaviour in the iron industry

of Cleveland (UK) over the period 1850-1875. In Cleveland, iron producers devoted few resources to the discovery of new technical knowledge, instead they freely disclosed to their competitors pertinent technical knowledge about the construction details and the performance of the blast furnaces they had erected. As a consequence of this practice of information sharing, 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 determined lower fuel consumption and lower production costs. Allen argues, that specific economic and technical circumstances, can bring about the formation of collective invention settings (to repeat, settings where a collection of competitive firms shares information on the relative performance of different technology design and operating procedures). The pattern of technical change emerging from collective invention settings is dominated by incremental innovations. One may indeed say that the main thrust of Allen's contribution is the individuation of the institutional regime that is the main source of Rosenberg's "sequences" of incremental innovations.

In our view, the importance of incremental innovation and the role collective invention settings, raises several doubts on the role that the patent system (and, relatedly, the "market for technology") is supposed to have had in the course of the early phase of industrialization. In the remaining, we will argue that economic historians cannot rely on a simple institutional explanation *a la* North to account for technical change during the British Industrial Revolution. We will we develop our considerations, by means of a detailed case study.
Our research deals with the "Cornish" steam pumping engine, which was, in strictly engineering terms, the highest accomplishment in steam power technology in the early nineteenth century. The case study will point out (once more) the historical significance of "anonymous" incremental technical advances, but it will also strikingly illustrate that the issue of the institutional set-up underlying technical progress during the British Industrial revolution cannot be dealt with by simplistically focusing on the emergence of the intellectual property rights regime.

3 Boulton & Watt in Cornwall

In the seventeenth and eighteenth centuries mining activities were severely limited by flooding problems. Not surprisingly, some of the first attempts of employing steam power were aimed at finding a workable technical solution to mine draining problems. In 1712, after a prolonged period of experimentation, Thomas Newcomen developed a steam pumping engine that could be effectively use for mine drainage. Using steam at only atmospheric pressure, the Newcomen engine was well within the limits of the engineering capabilities of the time. Moreover, the Newcomen engine was robust, reliable and its working principle was quite simple. Hence, once installed, the engine could work for a long period of time with almost negligible maintenance costs. Given these merits, Newcomen engines became soon of quite widespread use for mining activities and waterworks (Cardwell, 1994). Following Von Tunzelmann (1995, p. 106), we can say, that after Newcomen's invention, the steam engine established itself as the relevant technological paradigm in mine draining.

The Newcomen engine had a major shortcoming: the high fuel consumption, which was determined by the necessity of alternatively heating and cooling the cylinder at each operating cycle. In coal mining, where large supplies of "cheap" coal were at disposal, fuel consumption did not represent a limitation. In other mining areas (notably in the copper and tin mines of Cornwall, where coal had to be imported from Wales by sea) fuel inefficiency did not permit a widespread diffusion of the engine (Von Tunzelmann, 1978, chap. 4).

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 (Cardwell, 1994) . 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. 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 consumed. In 1772 Smeaton built a Newcomen engine with a duty of 9,450,000 (lbs), almost doubling the results previously attained (Hills, 1989, p.131).

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" 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. (Dosi, 1982 and 1988, especially pp. 1142-1145)

In 1769 James Watt took a patent for an alteration in the basic design of the engine (introduction of the separate condenser) that allowed for a drastic reduction in coal consumption. 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 (Hills, 1989, p.131). Such an economy of fuel made profitable the use of the steam engine in the mine areas situated in areas where the coal was expensive. The first important market for the engine developed by Watt was the Cornish copper and tin mining industry (where, as we have seen, coal was particularly expensive). Cornish mine "adventurers" (in this way mine entrepreneurs were called) were keenly interested in technological improvements that could curtail their dear fuel bill.

It is not surprising, then, that 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 (Tann, 1996, pp.29-30).

The typical agreement that Boulton & Watt stipulated with the mine 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. (Von Tunzelmann, 1978, pp.51-52)

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, in the late eighteenth century, several engineers in Cornwall had started to work at new improvements to the steam engine, but their attempts were frustrated by Boulton & Watt's refusal to license their invention. The most famous case in this respect was the one of Jonathan Hornblower who had developed the first compound steam engine in 1781 and who found the further perfecting of his invention heavily obstructed by the actions of Boulton & Watt.
Watt's patent resulted fairly broad in scope (covering all the engines making use of the separate condenser *and* all the engines using steam as "working substance" **).** In other words, the patent was endowed with a very large blocking power. Boulton & Watt used the patent in a strategic way, enforcing an almost absolute control on the evolution of the steam technology (on patent strategies see Granstrand, 1999, pp.218-226). This strategy was motivated by the peculiar position of the company (consulting engineers decentralizing the major part of engine production). All in all, it seems quite clear that Watt's patent had a highly detrimental impact on the rate of innovation in steam technology (Kanefsky, 1979).

As time went by, some adventurers responded to the blocking patent by installing a number of "pirate" engines erected by local Cornish engineers. In this way, they challenged 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.

4 The Cornish engine as a case of collective invention.

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 salient technical characteristics, the operating procedures and 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, with favourable effects on the rate of technical progress.

Joel Lean, a highly respected mine captain, 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).

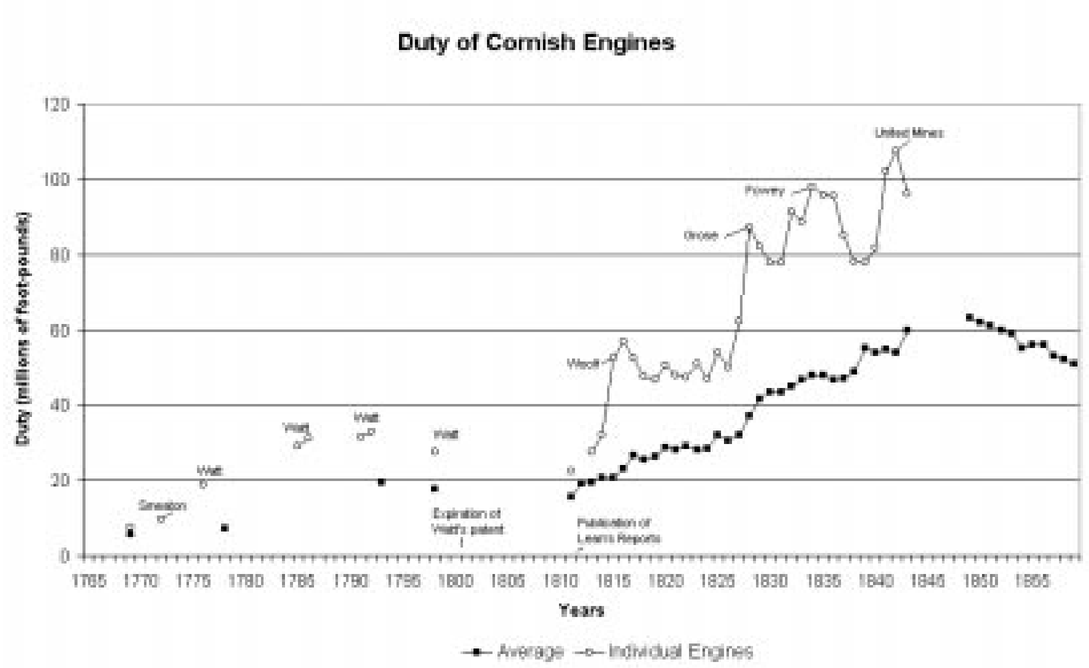
Concomitant with the beginning of the publication of Lean's *Engine Reporter*, Richard Trevithick erected the first high pressure engine of the so-called "Cornish" type.
The Cornish engine was simply a Watt single-acting engine employing high-pressure steam. High-pressure and condensing action were combined in a carefully regulated operating cycle ("Cornish cycle"). The engine had negligible costs of maintenance and it was susceptible of continuous improvements in its efficiency. In the following years the Cornish engine revealed itself as the highest accomplishment in steam technology (Von Tunzelmann, 1978, p. 263). Interestingly enough, Trevithick did not patent his high-pressure pumping engine:

> Trevithick only regarded this engine as small model designed to demonstrate what high-pressure steam could do. He claimed no patent rights for it: others were free to copy it if they would (Rowe, 1953, p.124)

The layout of the engine designed by Trevithick became soon the basic one for Cornish pumping engines.

As a consequence of the publication of the engine reports, the thermodynamic efficiency of 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 1. The figure clearly indicates that the practice of information sharing resulted in a marked acceleration in the rate of technical change.

Figure 1.



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

The case of the Cornish pumping engine seems to be indeed an "exemplar" case of collective invention. In his paper, Allen individuates three essential features of collective invention settings: 1) the overall rate of technical change is dominated by incremental innovations; 2) firms make publicly available pertinent technical information on the relative performance of the various design and operating practices; 3) firms employ this shared information to further improve the technology in question.

All these three propositions are amply corroborated in the case of the Cornish pumping engine. Almost every student of the Cornish engine, has pointed to the incremental nature of technical advances in this field (see e.g. Cardwell, 1971, pp. 180-181). This is apparent when looking at the contemporary engineering literature. For example, William Pole, author of a *Treatise on the Cornish Pumping Engine* noticed:

"The alterations introduced since 1821 may be described as consisting principally in carrying to a further extent the principle of expansion , by using steam of higher pressure , and cutting it off earlier in the stroke ...in a considerable extension of boiler surface in proportion to the quantity of water evaporated; in improvements of minor details of the engine , and of the construction of the working parts, particularly the pump work, whereby the loss of power by pre-judicial resistances has much lessened; and in the exercise of the most scrupulous care in guarding against waste or loss of heat by any means. *All this has been done so gradually, that it becomes difficult to particularize the different improvements with minuteness, or to say precisely when, how , or by whom they have been respectively been made. It must be remarked , however, that although the improvements have been minute, the aggregate result of increase duty produced by them has been most important. They have raised average duty from 28 to above 50 millions , and that of the best engines from 47 to upwards of 100 millions"* (Pole, 1844, pp.62-63, italics added).

In analogous terms, Caff (one of the first historians of the Cornish engine) remarked:

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. (Caff, 1937, pp. 45-46)

The other two propositions are substantiated by the very publication of the *Lean's Engine Reporter* . As 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 co-operative endeavour to raise the standards of all engines everywhere by publishing the details of the performance of each one, so that that everybody could see which models were performing best and how much (Cardwell, 1971, p.156).

After having noticed that technical advances in Cornish steam engine were generated by a collective invention setting, it is necessary to investigate the specific technical and economic conditions that determined the emergence of this information disclosure regime. In our interpretation, three main factors account for the transition from a regime of trade secrets and "proprietary" knowledge to a collective invention setting.

The first condition has to do with the nature of the technology in question. As in the blast furnace case described by Allen, the design of steam engine was a rather risky undertaking form an engineering point of view. Technology was much ahead than scientific understanding and the overall performance of a pumping engine could be affected by a host of factors (boiler, steam pressure, engine, pitwork, etc.). Engineers could not rely on a solid theoretical principles when they had to design a steam engine. The best they could was to extrapolate from the relative performance of existing designs. What happened in Cornwall was mainly a search, by means of small trial and error modifications. In such cases, one can expect that the release of information greatly improved the exploration of the space of technological opportunities. By pooling together the accumulated experience, it was possible to focus the search process in the most promising directions.

It is worth remarking another important feature of the process of technical change in Cornish engines. Over time, a typical design (single cylinder, high pressure, single acting engine, with plunger pump: this was design of the engine erected by Trevithick in 1812) emerged. Interestingly enough, however, alternative designs were never completely ruled out. For example, in different periods, some engineers (Arthur Woolf and James Sims) adopted were in favour of a compound engines. Thus, the design of the Cornish engine remained in what we might call a sort of *fluid* state and this probably facilitated a more thorough exploration of the design space, avoiding the risk of remaining trapped in a local optimum configuration (see Barton, 1965, for a detailed technological history of the Cornish Pumping engine)**.**

The second condition, instead, is related with the particular organisation of mining activities in Cornwall. Since the first systematic exploitation of the copper and tin lodes the Cornish mining economy was characterized by a peculiar form of industrial organization, centred around the so called "cost book" system (see Rowe,1953 and Barton, 1968). 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 usually were comprised between an one eighteenth and one fifteenth of the total ore excavated. In more profitable mines this proportion could rise something between one twelfth and one tenth.

Before the starting of the mining operations, the adventurers met and each of them subscribed shares of the mine venture (usually the mining venture was divided in 64 shares). The shares were annotated in the mine cost book. One of the adventurers was appointed as the administrator of the venture ("purser"). In the same moment, one or more mine captains were put in charge of the day to day of management operations and of the recruitment of the workforce.
Every two or three months, the adventurers met and examined the accounts. If necessary a "call" was made and the adventurers had to contribute (in proportion of their share) to pay for the coverage of mining operations 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 the notification to the purser. When the mine became productive and the ore was sold, profits were divided among the adventurers in proportion of their shares at each meeting. (Rowe, 1953). The "cost book" system had the advantage of allowing to mine adventurers a limited financial liability and it also permitted to spread the risks of the investment. Adventurers were usually not tied to the fortunes of a single mine, but they often acquired shares in different mine ventures. Consequently, they were more interested in the aggregate profitability of the district (and the improvement in the *average aggregate performance* of the steam engines at work in Cornwall was a way of achieving this). Further, improvement in the aggregate performance of Cornish engines had also the positive side 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 rises in the value of the Cleveland iron mines).

In economic terms, we can say that the particular structure of the industry in Cornwall permitted to firms to internalize (in a second stage) a consistent part of the positive externalities that the information disclosure of technological change had generated.

Another characteristic of the Cornish mining industry that is important to remark is that engineers were recruited by the mine captains of the mine on a one-off basis (this was also the case in the Cleveland blast furnace industry). Engineers were in charge of the design and they supervise the erection of the engine that was commissioned to them. They also provided directions for day to day working and the maintenance of the engines they were entrusted with. Thus, the publication of technical information concerning the design and the performance of the different steam engines, permitted to the best engineers to consolidate their reputation and improve their career perspectives. Christine MacLeod has noted a similar behaviour in civil engineering, where consulting engineers used to release technical information in order to consolidate their reputation. Over time, this practice gave rise to a professional ethos favouring sharing and publication of previous experiences (MacLeod, 1988, pp. 104-105)

To sum up, the peculiar organisation of the Cornish mining industry made the mine owners keenly interested in improvements of the *aggregate average performance* of the steam engines used and, at the same time, the engineers in publicly signalling the *above average performance* of the engines they had erected.

However, besides these two factors, the transition to a collective invention regime in Cornwall was also motivated by the disappointing experience of the Boulton & Watt patent monopoly.
After the beginning of the publication of the *Lean's Engine Reporter*, Cornish engineers, followed the example of Trevithick and normally preferred not to take patents for their

inventions. Table 1 reports the patents granted to Cornish engineers over the period 1750-1852.

Cornish steam engine patents		
Number	**Date**	**Patentee**
1298	July 13, 1781	J. Hornblower
2243	June 8, 1798	J. Hornblower
2599	March 24, 1802	R. Trevithick & A. Vivian
2726	July 29, 1803	A. Woolf
2772	June 7, 1804	A. Woolf
2832	March 26, 1805	J. Hornblower
2863	July 2, 1805	A. Woolf
3346	June 9, 1810	A. Woolf
3922	June 6, 1815	R. Trevithick
6082	February 21, 1831	R. Trevithick
6308	September 22, 1832	R. Trevitithick
8942	April 29, 1841	J. Sims
10201	May 23, 1844	J. Taylor
11859	September 9, 1847	J. Sims

Table 1: Cornish Steam Engine Patents (source: Woodcroft (1857))

If we take into account that over the same period, 873 patents for innovations in steam engines were granted (so that the Cornish contribution to the total is less than 2%!) and that Cornwall at that time was, without any doubt, the area with the most vital engineering community, this fact is indeed striking. In our view, this fact should be considered as a very indicative evidence of the widely perceived awareness of the benefits of the adoption of a collective invention regime on the rate of innovation.

In the contemporary engineering literature, it is also possible to find passages that indicate a conscious awareness of the benefits emerging from a context of cooperative rivalry, in which the rate of innovation was not hostage of a supplier monopoly as it was in the Boulton & Watt era. For example, John Taylor (one leading mine entrepreneur), in 1830, wrote:

> Under such a system [the *Lean's Reporter*] there is every kind of proof that the application of steam has been improved, so as to very greatly economise fuel in Cornwall, and also that the rate of improvement has been fairly expressed by the printed reports.....[A]s since the time of Boulton and Watt, no one who has improved our engines has reaped pecuniary reward, it is at least fair, that they should have credit of their skill and exertion. We [adventurers] are not the partisans of any individual engineer or engine maker; we avail ourselves of the assistance of many; and the great scale upon which we have to experiment makes the result most interesting to us. (quoted in Farey, 1971, pp.251-252)

4 Concluding remarks

Recent research in economic history has emphasized the role played by individual inventors in the course of the British Industrial Revolution. The case study presented in this paper has, instead, shown the economic and technological significance of incremental and anonymous innovations in the development of one of the key technologies, steam power. These results are particularly interesting, because, in the early phase of industrialisation, steam engines were one of the most patented fields (MacLeod, 1988, p. 97).

Our conclusion is that recent studies have probably gone too far and their depiction is at risk of obscuring some fundamental aspects of the innovation process. To gain a proper understanding of the role of technical change during the Industrial Revolution, it is , then, necessary to look carefully at innovative activities occurring outside the patent system.
The perfecting of new technologies in this period was, to a major degree, the result of a multitude of learning by doing and learning by using processes. The result of this processes was a series of inconspicuous "incremental" innovations that were surely less visible of most individual acts of invention, but, in many instances, as we have seen in the Cornish engine case, they ended up to be quantitatively more significant.

These learning processes unfolded through a variety of channels involving both competitive and cooperative interactions among a plurality of agents. Our case study has confirmed that, collective invention settings are capable of greatly enhancing this processes with beneficial effects on the rate of innovation.

Current conventional wisdom is that strong and broad patent protection is conducive to rapid technical changes. The case of the Cornish engine casts many doubts on the general validity of such a proposition, confirming the more nuanced viewpoint sustained by Merges and Nelson (1994). The impact of the intellectual property rights regime on the rate of innovation depends very much on the nature of the technology in question (Merges and Nelson use the concept of "topography of technical advances"). In the case of "cumulative systems technologies" (that is technologies constituted by a number of components and where current improvements are tightly related to previous innovations), Merges and Nelson argue that strong and broad patent are likely to delay technical progress. In those cases, a better context for innovation is one where a high degree of pluralism and rivalry in the search process is continuously rejuvenated. In Cornwall in the case of steam pumping engines (without doubt a complex system technology), dissatisfaction for the innovative performance under Watt's patent monopoly led to the creation of an "open" collective invention setting that produced a marked acceleration in the pace of technological change.

To conclude, it seems that a proper approach to innovation policy should be able not only to ensure a sufficient degree of appropriability of investments in new technologies, but, at the same time, to encourage the rapid diffusion of accumulated experience and to keep alive some rivalry and diversity in the search process. The appropriate mix will depend, of course, on the specificities of the technology in question. However, an innovation policy that does not take into account both aspects is likely to be seriously flawed.

References

Allen R.C.1983. Collective Invention, *Journal of Economic Behavior and Organization,* vol. 4,1-24.

Ashton. T. S. 1948. *The Industrial Revolution*. Oxford, Oxford University Press (new. ed. with a preface by P. Hudson, 1996)

Barton D. B. 1965. *The Cornish Beam Engine*, Truro, D.B. Barton.

Barton D.B.1968. *A History of Copper Mining in Cornwall and Devon*, Truro, D.B. Barton.

Caff W. R. M.1937. *The History of the Development of the Steam Engine to the Year 1850 with Special Reference to the Work of West County engineers,* M. Sc. Thesis, London University.

Cardwell D.S.L. 1971. *From Watt to Clausius*, London, Heinemann.

Cardwell D.S.L.1994.*The Fontana History of Technology,* London, Harper and Collins.

Crafts N.R and Harley C. K. 1992, Output Growth and the Industrial Revolution: A Restatement of the Crafts-Harley View, *Economic History Review*, vol. 45, 703-730.

Dickinson H. W and Jenkins R. 1927. *James Watt and the Steam Engine.* Oxford, Clarendon Press.

Dosi G.1982. Technological Paradigms and Technological Trajectories, *Research Policy,* vol. 11, no. 3.,147-162.

Dosi G.1988. Sources, Procedures and Microeconomic Effects of Innovation, *Journal of Economic Literature,* vol. 26, pp.1120-1171.

Dutton H. I. 1984. *The Patent System and Inventive Activity during the Industrial Revolution.* Manchester, Manchester University Press.

Farey J. 1971. *Treatise on the Steam Engine*. Newton Abbot, David & Charles (1.ed., 1827)

Freeman C. 1994. The Economics of Technical Change, *Cambridge Journal of Economics*, vol. 18, 463-514.

Granstrand O. 1999. *The Economics and Management of Intellectual Property*, Cheltenham, Edward Elgar.

Hills R. L. 1989. *Power from Steam. A History of the Stationary Steam Engine*, Cambridge, Cambridge University Press.

Khan Z. B. and Sokoloff K. L. 1993. 'Schemes of Practical Utility': Entrepreneurship and Innovation Among 'Great Inventors' in the United States, 1790-1865, *Journal of Economic History*, vol. 53, no. 2, 289-307.

Khan Z. B. and Sokoloff K. L. 1998. Patent Institutions, Industrial Organization and Early Technological Change: Britain and the United States, 1790-1850, in Berg M. and Bruland K. (eds.), *Technological Revolutions in Europe*, Cheltenham, Edward Elgar.

Kline S. and Rosenberg N. 1986. An Overview of Innovation, in Landau R. and Rosenberg N. (eds.) *The Positive Sum Strategy: Harnessing Technology for Economic Growth*, Washington DC, National Academy Press.

Landes D.S.1969.*The Unbound Prometheus*, Cambridge, Cambridge University Press.

Lamoreaux N.R. and Sokoloff K.L. 1997. Location and Technological Change in the American Glass Industry during the Late Nineteenth and the Early Twentieth Centuries, NBER Working Paper no. 5938.

Lamoreaux N.R. and Sokoloff K.L. 1999. Inventors, Firms, and the Market for Technology in the Late Nineteenth and Early Twentieth Centuries in Lamoreaux N. R., Raff D. M. G. and Temin P. (eds.) *Learning by Doing in Markets, Firms and Countries*, University of Chicago Press, Chicago.

Lean T. (and Lean J.). 1839. *Historical Statement of the Improvements made in the Duty Performed by the Steam Engines in Cornwall*, London.

Lundvall B. A. 1988. Innovation as an Interactive Process: from User-Producer Interaction to the National System of Innovation in Dosi G., Freeman C., Nelson R., Silverberg G. and Soete L. (eds.). *Technical Change and Economic Theory*, London, Pinter.

MacLeod C.1988. *Inventing the Industrial Revolution*, Cambridge, Cambridge University Pres.

Merges R. and Nelson R.R. 1994. On Limiting or Encouraging Rivalry in Technical Progress: the Effect of Patent-Scope Decisions, *Journal of Economic Behavior and Organization*, vol. 25, 1-24

Mokyr J. 1994. Technological Change, 1700-1830 in R. Floud and D. McCloskey (eds.), *The Economic History of Britain since 1700*, Vol I, 2ed, Cambridge, Cambridge University Press.

North D. C. 1981. *Structure and Change in Economic History*, New York, Norton.

Pole W. 1844. *A Treatise on the Cornish Pumping Engine*, London.

Rosenberg N.1976. *Perspectives on Technology*, Cambridge, Cambridge University Press.

Rowe J.1953. *Cornwall in the Age of the Industrial Revolution*, Liverpool, Liverpool University Press.

Tann J.1996.Riches from Copper: the Adoption of the Boulton and Watt Engine by Cornish Mine Adventurers, *Transactions of the Newcomen Society*, vol.67,27-51.

Von Tunzelmann G. N. 1970. Technological diffusion during the Industrial Revolution: the case of the Cornish pumping engine in R.M. Hartwell (ed.), *The Industrial Revolution,*Oxford, Basil Blackwell.

Von Tunzelmann G. N. 1978. *Steam Power and British Industrialization to 1860,* Oxford, Clarendon.

Von Tunzelmann G. N. 1995. *Technology and Industrial Progress,* Aldershoot, Edward Elgar.

Woodcroft B.1857. *Subject-Matter Index of Patents of Invention, 1617-1852.* London

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The theoretical perspective confronts and combines the resource-based view (Penrose, 1959) with recent approaches where the focus is on learning and the dynamic capabilities of the firm (Dosi, Teece and Winter, 1992). The aim of this theoretical work is to develop an analytical understanding of the firm as a learning organisation.

The empirical and policy issues relate to the nexus technology, productivity, organisational change and human resources. More insight in the dynamic interplay between these factors at the level of the firm is crucial to understand international differences in performance at the macro level in terms of economic growth and employment.

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