Cambridge Journal of Economics 2004, **28,** 347–363
DOI: 10.1093/cje/beh011

Collective invention during the British Industrial Revolution: the case of the Cornish pumping engine

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This paper argues that what Robert Allen has termed *collective invention settings* (that is, settings in which competing firms share technological knowledge) were a crucial source of innovation during the early phases of industrialisation. Until now this has been very little considered in the literature, which has focused on the patent system as the main institutional arrangement driving the rate of innovation. The paper presents one of these collective invention settings, the Cornish mining district, in detail. It studies the specific economic and technical circumstances that led to the emergence of this collective invention setting and analyses its consequences on the rate of technological innovation.

Keywords: Incremental innovation, Patents, Collective invention, Steam engines
JEL classificationss: O31, O34, N53

1. Introduction

According to T. S. Ashton, generations of schoolboys were accustomed to consider the Industrial Revolution as 'a wave of gadgets [that] swept over England' (Ashton, 1948, p. 48). Although admittedly crude, the definition of the Industrial Revolution as a cluster of key technological innovations (steam engine, textile machinery, iron production techniques, etc.) is still held to capture a good deal of historical truth. Traditionally, the history of these inventions has been told in terms of creative leaps of imagination in the technological domain made by individual inventors. Modern scholarship has qualified this view but, in many respects, still regards the early phase of industrialisation as the 'heroic age' of independent inventors.

One of the main qualifications to what one might call the 'heroic' account of the generation of new technologies during the early phases of industrialisation is the acknowledgement of the central importance of incremental improvements. In fact, new technologies first appear in rather rudimentary form and a long process of improvement is necessary before they can manifest their full technical and economic potential. This process of incremental

Manuscript received 29 June 2001; final version received 16 July 2002.
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*Eindhoven Centre for Innovation Studies (ECIS). I am grateful to Nick von Tunzelmann for continuing discussions. The paper has greatly benefited from the detailed comments of Richard Nelson and of an anonymous referee on an earlier draft. Bart Verspagen, Pat Hudson, David Stead, Peter Maskell, Michiel Van Dijk, Geert Verbong and Alison Parkinson have also given helpful suggestions. The usual caveats apply.

improvements, stemming from various learning processes occurring on both the producer's and the user's side is, as shown by Rosenberg (1976), simultaneous with the diffusion of the innovation. It seems quite clear, then, that the dynamics of technological change exhibit both continuities and radical ruptures. Hence, a satisfactory theory of innovation must consider both aspects and the interconnections between them. In this respect, the adoption of evolutionary approaches has been particularly illuminating. Mokyr (1990) has argued that discontinuities in the evolution of a technology are the product of the introduction of 'macroinventions', that is, inventions that open up entirely novel technological domains. After the emergence of a macroinvention, a technology progresses gradually by means of small incremental steps ('microinventions').[1] Many modern empirical studies of innovation also highlight the idea that technologies are developed through a continuous process of interactive learning in which a multitude of agents are involved (Freeman, 1994). According to Mokyr, an appropriate 'technological definition' of the Industrial Revolution is 'a clustering of macroinventions leading to an acceleration in microinventions' (Mokyr, 1993, p. 22).[2]

The significance of streams of incremental improvements during early industrialisation has been stressed in several accounts (see, among others, Landes, 1969; Mathias, 1969; David, 1975). Appropriately, Landes terms this type of innovations 'anonymous' technical change, to emphasise that their nature is markedly different from the most 'visible' individual acts of invention, which have attracted the attention of historians of technology. Landes suggests that 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).

Given the central role that incremental technical change seems to have played during the Industrial Revolution, it is worth reflecting on the sources of this particular 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), and (iv) *collective invention settings*. In collective invention settings, competing firms release information freely to one another on the design and the performance of the technologies they have just introduced. Allen has noticed this type of behaviour in the iron industry of Cleveland (UK) over the period 1850–75. In the Cleveland district, iron producers devoted few resources to the discovery of new technical knowledge; instead, they freely disclosed to their competitors pertinent technical information concerning the construction details and the performance of the blast furnaces they had erected. Additionally, new technical knowledge was normally not protected by patents, so that competing firms could make liberal use of the released information when they had to set up a new plant. As a consequence of the proliferation of these 'voluntary knowledge spillovers', in the period in question, the height of the furnaces and the blast temperature increased steadily by means of a series of small but continuous rises. Increases in furnace height and in

[1] A similar conceptualisation of technical change has been proposed by Dosi (1982, 1988).

[2] O'Brien *et al.* (1996) noticed that in the case of textiles, patent figures suggest the existence of an uncertain and exploratory phase (1733–85) during which macroinventions were attained, followed by a phase (1790–1850) in which technologies evolved gradually and in more predictable ways. Interestingly enough, in the first phase a good number of inventors were employed *outside* the textile industries. Furthermore, the evidence suggests that many inventions in this period were the result of a sort of 'pre-professional' interest (scientific and technological curiosity, fascination for mechanical contrivances, etc.). The second period, characterised by a microinvention profile, is instead dominated by inventors professionally linked with the textile industries.

blast temperature brought about lower fuel consumption and lower production costs. On the basis of his findings, Allen suggests that 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 an institutional arrangement which constitutes one of the most favourable environments for micro-inventive activities.

In this paper, we argue that together with individual inventors, *collective invention settings* were a crucial source of innovation during the early phases of industrialisation. Until now, this has been very little considered in the literature. Furthermore, some recent contributions (Dutton, 1984; Lamoreaux, Sokoloff and Khan in a number of recent papers) have stressed the stimulating impact exerted by the patent system and, relatedly, by the development of a market for (patented) technologies on the rate of technical innovation. We argue that the importance of incremental innovations and of collective invention settings casts some doubt on the general validity of such a proposition. We shall develop our argument by means of a detailed case study of the Cornish mining district. This case is particularly remarkable because it was capable of generating a continuous and sustained flow of improvements in steam technology which, in the end, greatly contributed to raising the thermodynamic efficiency of the steam engine. We study in detail the specific economic and technical circumstances that led to the formation of this particular collective invention setting and we analyse its consequences for the rate of technological innovation. The case study will underline (once more) the historical significance of 'anonymous' incremental technical advances, but it also demonstrates that economic historians cannot rely on the emergence of an intellectual property rights regime to explain the dynamics of technical advance in this historical phase.

2. Patent institutions and individual inventors

Historians of technology have provided detailed accounts of the generation of new technologies during the Industrial Revolution. In many of these accounts, individual inventors are put centre stage (Cardwell, 1994; see especially the section on pp. 496–501 significantly entitled 'In defence of Heroes'). One important reason that has motivated this focus on individual inventors is that historians of technology, such as Cardwell or Musson and Robinson, have been mainly interested in shedding light on the connections between science and technology in this period, and one relatively straightforward way to do so is to study in detail single inventions, trying to appraise how developments in science affected them (see among others Musson and Robinson, 1969; Cardwell, 1971; Musson, 1972, contains an important critical overview of the studies dealing with connection between science and technology during the Industrial Revolution).

Economic historians, however, have paid considerably less attention to the ways in which new technologies were drawn into play. In this respect, they seem to have accepted the view that ascribes the generation of new technologies to the actions of independent individual inventors. What is in need of explanation, then, is why Britain in this period was such a fertile soil for individual inventors, especially when compared to other European countries (Mokyr, 1993, 1994).

From a strictly economic point of view, the most straightforward explanation is that, in Britain, the rewards for inventive activities were high enough to attract a considerable amount of economic resources and human talents into this field. Following this line of reasoning, a number of scholars have turned their attention to the patent system. North

(1981, pp. 164–6) has suggested that the acceleration in the rate of technological innovation in Britain during the eighteenth century should be considered as a *direct* consequence of the progressive development of a fully operational patent system.[1]

Dutton (1984) has explicitly considered the connection between the patent system and inventive activities in Britain. The available evidence, according to Dutton, indicates that the British patent system, although granting imperfect protection and requiring the fulfilment of cumbersome and costly bureaucratic procedures, was nevertheless capable of stimulating inventors' efforts. Many inventors devoted time and resources to inventive activities with a view to appropriating economic returns through patent protection. It is also interesting to note that a fairly large number of patents were taken by 'quasi-professional' inventors, that is to say individuals with several varied patents. Additional evidence shows that technological knowledge protected by patents was the object of a robust 'trade in invention'. Hence, the development of the patent system in Britain led to the emergence of 'an infant invention industry' (Dutton, 1984, p. 104). Moreover, the imperfect protection granted by the patent system allowed for some imitation, and this, in many cases, facilitated a relatively quick diffusion of many innovations. All in all, Dutton's conclusion is that the British patent system had a highly positive effect on the rate of technical change.

Christine MacLeod (1988) has suggested a more nuanced viewpoint. First, one has to take into account that the propensity to patent varied widely across industries and also across regions. Second, a great deal of inventive activities were carried out *outside* the patent system. And third, patents were taken for a variety of reasons, besides the aim of protecting inventions. All this makes it indeed very difficult to reach strong conclusions concerning the overall impact exerted by the British patent system on inventive activities.

We should take into account, however, that the first patent system working by what we might consider truly modern procedures was not the British, but the American one (Khan and Sokoloff, 1998; see MacLeod 1991 for an outline of the emergence of patent institutions in Britain, France and the US). For this reason, one could argue that the validity of North's hypothesis linking the acceleration in the rate of innovation and the emergence of patent institutions ought to be examined primarily in the case of the US.

In a number of recent papers, Sokoloff, Lamoreaux and Khan have tackled exactly this issue, examining the relationship between the patent system and inventive activities in the US in the course of the nineteenth century. Their contributions are based on an extensive quantitative analysis of evidence collected from the patent records. Khan and Sokoloff (1993) examine the issue of the responsiveness of individual inventors to the economic inducements granted by the patent system over the period 1760–1865. They conclude that American inventors sought consistently to secure patent rights for their inventions and that patent protection permitted a quite effective appropriation of economic returns stemming from inventive activities. In related contributions, using data on the licensing behaviour of a large number of patentees, Lamoreax and Sokoloff (1996, 1999A, 1999B) argue that in the US, in the course of the nineteenth century, a solid market for technical innovations structured around the institution of the patent system progressively emerged. Through this well-functioning 'market for technology', individual inventors were able to sell the new technical knowledge they had discovered to firms. The existence of this type of market promoted a fruitful division of labour with 'technologically creative individuals' (Lamoreaux and Sokoloff, 1999B, p. 3) specialising in inventive activities, and firms in the

[1] It is worth remarking that Mokyr's explanation is different. In his view, Britain's main advantages lay in her endowments of mechanical skill and in the favourable attitude of the ruling establishment towards innovation. The latter made sure that episodes of resistance to innovation were actively repressed (Mokyr, 1994).

production and commercialisation phases. The coupled development of the patent system and of the market for technology resulted in a steady acceleration in the rate of innovation.

Lamoreaux and Sokoloff (2000) consider the case of the American glass industry. In this case too, they found evidence of the existence of a solid market for technologies operating through two channels: (i) specialised trade journals disseminating general information and providing detailed descriptions of patent specifications; and (ii) specialised patent agents who were able to act as intermediaries in the sale of patented technologies. In the same study, Lamoreaux and Sokoloff also notice that a number of locations with high patenting activities were characterised by little glass production. In their view, this finding indicates that 'learning by doing' and 'localised knowledge spillovers' (two factors that have been prominently put forward to explain the connection between the localisation of production and innovation) played a relatively minor role in the technological development of the industry. Geographical clusters of patenting in the American glass industry are instead accounted for by the existence of a more developed market for technologies in those areas. Although Lamoreaux and Sokoloff acknowledge that it is hard to make robust generalisations, they contend that, by combining the evidence of the glass industry with their findings for the economy as a whole, the proposition that the development of the patent system produced a tidy and fruitful division of labour between innovation and production appears to be confirmed.

Finally, Khan and Sokoloff (1998) have compared the British patent system with the American one. Undoubtedly, the British patent system before its 1852 reform was far less effective than the American in protecting the intellectual property rights of the patentee. Furthermore, patent fees (and the other connected expenditures necessary to take out a patent) were considerably higher in Britain than in the US, and this considerably restrained access to the system. On the basis of the previous discussion, Khan and Sokoloff suggest that the rate of innovation was probably lower in early industrial Britain than in the US. In addition, high patent fees in Britain may have also induced a specialisation of inventors in highly capital-intensive technologies (where it would have been easier to enforce patent rights and extract higher economic returns). In the end, this should have produced a more biased pattern of technical change in Britain (with more rapid technical change in capital-intensive industries).

As should be clear from this brief summary of their contributions, Lamoreaux, Sokoloff and Khan have elaborated a complex account of technical change in the course of the industrialisation of the US, which is in many respects similar to the one originally proposed for Britain by Dutton. It is worth stressing again that their interpretation, more or less explicitly, downplays the role of learning by doing and of knowledge spillovers in nineteenth-century technical advances.

However, as we have already pointed out, many accounts of the Industrial Revolution have emphasised the crucial role of incremental innovation and learning-by-doing. This leads us to investigate the nature of the connection between processes of incremental innovation and patent institutions in the course of the Industrial Revolution.

3. Boulton and Watt in Cornwall

The Cornish mining district is a particularly interesting case for the purposes of the present discussion. In the first half of the nineteenth century, Cornwall was 'one of the most advanced engineering centres of the world' (Berg, 1994, p. 112). However, as we will see, in Cornwall, inventive activities were mainly undertaken outside the patent system.

In the seventeenth and eighteenth centuries, mining activities were severely hampered by flooding problems. Not surprisingly, some of the first attempts at employing steam power were aimed at finding a workable solution to mine draining problems. In 1712, after a prolonged period of experimentation, Thomas Newcomen developed a steam pumping engine that could be used effectively 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 based on a quite simple working principle. As a consequence, once it was installed, it could work for a long period with almost negligible maintenance costs. Given these merits, it is not surprising that Newcomen types of engines soon became of widespread use in mining activities. 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 the major shortcoming of high fuel consumption, which was determined by the necessity of alternatively heating and cooling the cylinder at every stroke. In coal mining, where large supplies of cheap coal were available, high fuel consumption did not represent a major limitation, but in other mining areas fuel inefficiency did not permit widespread diffusion of the engine (von Tunzelmann, 1978, ch. 4).

Since the early diffusion of the Newcomen engine, fuel consumption was considered as the main 'measure' to be used in the evaluation of the overall performance of a steam engine. The most common measure of fuel efficiency was termed the 'duty' and was calculated as the quantity of water (measured in lb) raised 1 feet high per 1 bushel (84 lb) of coal consumed. From an engineering viewpoint, the duty is a measure of the thermodynamic efficiency of the steam engine. However, 'duty' has also an important economic meaning because it is a measure of the productivity of a steam engine with respect to the largest variable input used in the production process (von Tunzelmann, 1970, pp. 78–9).

In 1769, James Watt conceived an alteration to the basic design of the steam engine (the introduction of the separate condenser) that allowed for a drastic reduction in coal consumption. The Newcomen engine, as improved by John Smeaton in the early 1770s, was capable of a duty between 7 and 10 millions (lb). Watt initially raised the duty to 18 millions and later, when the engine design was fully refined, to 26 millions (Hills, 1989, p. 131). Such an economy of fuel made the use of the steam engine profitable in mines situated in locations where coal was expensive. The first important market for the engine developed by Watt was the Cornish copper and tin mining industry. In Cornwall, coal had to be imported from Wales by sea and was extremely expensive. 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 and Watt stipulated with the Cornish mine entrepreneurs (commonly termed 'adventurers') was that the two partners would provide the drawings and supervise the works of erection of the engine. They would also supply some particularly important components of the engine (such as 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 and Watt). In addition, the mine adventurer had to buy the other components of the engine not directly supplied by the two partners and to build the engine house. These were all elements of the total fixed cost associated with the erection of a Boulton and Watt engine.

The profits for Boulton and 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 out in 1769, which an Act of Parliament 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 with the Newcomen engine. This required a number of quite complicated calculations, aimed at identifying the *hypothetical* coal consumption of a Newcomen engine supplying the same power of that of the Watt engine installed in the mine.

At the beginning, this type of agreement was accepted on very favourable terms by the mine adventurers. However, after some time, the pricing policy of Boulton and Watt was perceived as extremely oppressive. First, the winter months during which most water had to be pumped out (and, consequently, the highest premiums had to be paid) were the ones in which mines were least productive. Second, mine adventurers knew the exact amount of payments they owed to Boulton and Watt only at the end of the month these were actually due. Finally, in the late eighteenth century, several engineers in Cornwall had begun to work on further improvements to the steam engine, but their attempts were frustrated by Boulton and Watt's absolute refusal to license their invention. The most famous case in this respect was that of Jonathan Hornblower who had erected the first compound engine in 1781 and who found the further development of his invention obstructed by the actions of Boulton and Watt (Jenkins, 1931; Torrens, 1994). Watt's patent was very broad in scope (covering all engines making use of the separate condenser *and* all engines using steam as a 'working substance'). In other words, the patent had a very large blocking power. The enforcement of almost absolute control on the evolution of steam technology, using the blocking power of the patent, was indeed a crucial component of Boulton and Watt's business strategy. This strategy was motivated by the peculiar position of the company (as consulting engineers decentralising 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, 1978).

After having considered the idea of submitting a petition to Parliament asking for the repeal of the Act which prolonged the duration of Watt's patent, in the 1790s, Cornish adventurers decided to challenge its validity explicitly by installing a number of 'pirate' engines erected by local engineers.[1] 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 and Watt. The dispute also had other far-reaching consequences. Boulton and Watt, with their legal victory (pursued with relentless determination), completely alienated any residual sympathy towards them in Cornwall. After the expiration of Watt's patent in 1800, steam engine orders to Boulton and Watt from 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.

[1] During the eighteenth century, cooperation among competing firms in order to break down a monopoly was by no means infrequent. Somewhat paradoxically, in the same period, Matthew Boulton was involved in the creation of the Birmingham Brass Company, a joint-stock copper smelting company created to circumvent the monopoly of Swansea and Bristol smelters (Berg, 1991, p. 186).

4. The Cornish engine as a case of collective invention

Following the departure of Boulton and Watt, the maintenance and the improvement of Cornish pumping engines underwent a period of 'slackness', as the mine adventurers were content with the financial relief coming from the cessation of the premia. This situation lasted until 1811, when a group of mine 'captains' (mine managers) decided to begin the publication of a monthly journal reporting the salient technical characteristics, the operating procedures and the performance of each engine. The explicit intention was twofold. First the publication would permit the rapid identification and diffusion of best-practice techniques. Second, it would create 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'. The publication was called *Lean's Engine Reporter*. After his death, the publication of the reports was continued by his sons and lasted until 1904.[1]

Concomitant with the beginning of the publication of *Lean's Engine Reporter*, Richard Trevithick and Arthur Woolf began erecting high-pressure engines in Cornish mines. The layout of the engine designed in 1812 by Richard Trevithick at the Wheal Prosper mine soon became the basic one for Cornish pumping engines. Interestingly enough, Trevithick did not patent this high pressure engine: 'Trevithick only regarded this engine as a small model designed to demonstrate what high-pressure could do. He claimed no patent rights for it; others were free to copy it if they would' (Rowe, 1953, p. 124).

As a result of the publication of the engine reports, the thermodynamic efficiency of Cornish engines improved steadily. On strictly engineering grounds, this amounted to a very effective exploration of the merits of the use of high-pressure steam. Figure 1 displays the evolution over time of the efficiency of Cornish steam engines (based on the collation

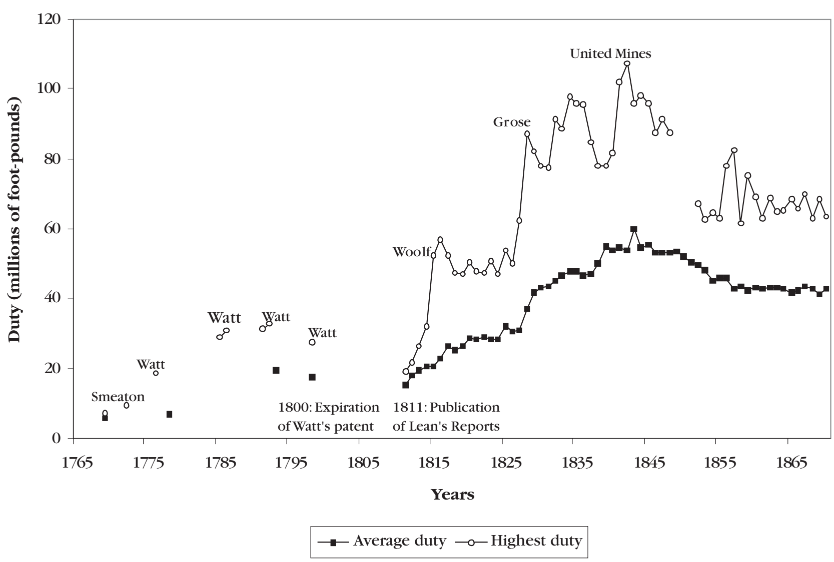

Fig. 1. Duty of Cornish engines.
Sources: Lean (1839), Pole (1844), Dickinson and Jenkins (1927), Barton (1965).

[1] The first three reports were published on the *West Briton*, a local newspaper. From 1812 *Lean's Engine Reporter* appeared as an independent publication.

of several sources). The figure clearly indicates that the practice of information sharing resulted in a marked acceleration in the rate of technical advance. As in the case of the Cleveland iron industry described by Allen, the rate of innovation in Cornish engines appears to be tightly linked with the rate of capital formation. Installation of new productive capacity permitted experimentation with design alterations, facilitating the discovery of new improvements. Hence, the period of high duty growth coincided with the rapid expansion of the Cornish mining industry; conversely, the phase of recession after the 1850s translated itself into a slow decline of the average duty (Barton, 1961, 1965).

The case of the Cornish pumping engine seems to be indeed an 'exemplary' case of collective invention. In his paper, Allen highlights three essential features of collective invention settings: (i) the overall rate of technical change is dominated by incremental innovations; (ii) firms make publicly available pertinent technical information on the relative performance of various designs and operating practices; and (iii) firms employ this common pool of technological knowledge to improve the technology in question further. All these three propositions are amply corroborated in the case of the Cornish engine.

Almost every student of the technological history of the steam engine has pointed to the incremental nature of technical advances in the Cornish pumping engines (see e.g., Cardwell, 1971, pp. 180–1). This is also 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 out 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 . . . and in the exercising 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 made. It must be remarked, however, that although the improvements have been minute, the aggregate result of increased 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. 62–3, italics added)

In analogous terms, Caff remarked:

> So many of the characteristics of the Cornish engine arise from a succession of improvements to details 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. 45–6)

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 cooperative endeavour to raise the standards of all engines everywhere by publishing the details of the performance of each one, so that everybody could see which models were performing best and by how much. (Cardwell, 1971, p. 156)

What were the conditions that determined the emergence of this particular information disclosure regime? In our view, three main factors explained this case of transition from a regime of trade secrets and 'proprietary' technology to collective invention.

The first condition has to do with the nature of the technology. Analogously with the blast furnace case, the design of a steam pumping engine was a rather risky undertaking from an engineering point of view. Technology was much ahead of scientific understanding and complex—the overall performance could be affected by a host of factors (boilers, steam pressure, engine, pitwork, etc.). Engineers could not rely on sound theoretical principles when they had to design a new engine. The best they could do was to extrapolate from the relative performance of existing designs, attempting some small trial-and-error modifications. In such cases, one can expect that information disclosure will enhance the exploration of the space of technological opportunities. By pooling all the accumulated experience, it was possible to focus the search process on the most promising directions.

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

The second condition, instead, is related to the particular organisation of mining activities in Cornwall. Since the first systematic exploitation of copper and tin lodes, the Cornish mining economy was characterised by a peculiar form of industrial organisation, centred around the so-called 'cost book system' (see Rowe, 1953; Barton, 1961). Under such a system, mine entrepreneurs or investors ('adventurers') had first to obtain the grant for working the mine from the owner of the land. This was a normal renting contract (usually for a period of 21 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 owner's dues comprised between 1/18 and 1/15 of the ore excavated. In more profitable mines, this proportion could rise to between 1/12 and 1/10.

Before starting up the mining operations, adventurers met and each of them subscribed shares of the mine venture (normally the mine venture was divided into 64 shares). Shares were annotated in the mine cost book. One of the adventurers was appointed as the administrator of the venture ('purser'). At the same time, one or more mine captains were put in charge of the day-to-day management of the mine. Every two or three months, adventurers met and examined the accounts. If necessary a 'call' was made and the adventurers had to contribute (in proportion to their share) to the coverage of mining costs until the next meeting. Failure to meet the call implied immediate forfeiture of the mine shares. Shares could be easily transferred, the only formality being notification to the purser. When the mine became productive and ore was sold, profits were divided in proportion to shares held. The 'cost book' system had the advantage of allowing mine adventurers limited financial liability (Rowe, 1953).

Adventurers were usually not tied to the fortunes of a single mine but often acquired shares of different mine ventures. Consequently, they tended to be more interested in the overall profitability of the district than in that of individual mines. Improvements in the *average aggregate performance* of the steam engines at work in Cornwall dictated an increase in the overall profitability of the district. Further, improvements in the average aggregate performance of Cornish engines also had the positive effect of increasing the value of the

Cornish ore deposits (a similar mechanism was at work in Cleveland, where improvements in the performance of the blast furnaces were also reflected in increases in the value of Cleveland iron mines). Thus, the particular structure of the Cornish mining industry seems to have permitted (at a sort of second stage) the 'internalisation' of a consistent part of the positive externalities generated by the disclosure of innovations. Note that, in several instances, there were suggestions of implementing a similar system of reports for steam engines at work in textile areas, but nothing happened (Hills, 1989, p. 131).

The third important characteristic of the Cornish mining industry that is worth remarking on is that engineers were recruited by mine captains on a one-off basis (this was also the case in the Cleveland blast furnace industry). Engineers were in charge of the design of the engine, and they supervised the erection works. They also provided directions for the day-to-day operation and maintenance of the engines they were entrusted with. The publication of technical information concerning the design and the performance of the various engines allowed the best engineers to signal their talents, hence improving their career prospects. Christine MacLeod has noted similar behaviour in other branches of civil engineering, where consulting engineers used to release detailed information on their works in order to enhance their reputation. Over time, this practice gave rise to a professional *ethos* favouring the sharing and the publication of previous experiences (MacLeod, 1988, pp. 104–5).

To sum up, the peculiar organisation of the Cornish mining industry made mine entrepreneurs interested in improvements of the *aggregate average performance* of the pumping engines used and, at the same time, engineers in publicly signalling the *above average performance* of the engines they had erected. Thus, *Lean's Engine Reporter* successfully reconciled the tensions between collaboration (among mine adventurers) and competition (among engineers) operating in the Cornish mining district.

Besides these factors, the transition to a collective invention regime in Cornwall was also motivated by the disappointing experience of the Boulton and Watt monopoly period. After the beginning of the publication of *Lean's Engine Reporter*, Cornish engineers followed the example of Trevithick with his Wheal Prosper engine and normally preferred not to take out patents for their inventions. Table 1 reports the geographical distribution (measured using the stated addresses of the patentees) of patents in steam power technology over the period 1698–1852 (see Andrew *et al.*, 2001, for a detailed quantitative analysis of the pattern of steam power patenting over the entire nineteenth century).

The London and Middlesex area holds the predominant position. In this respect the pattern of patenting in steam technology mirrors that for overall patenting outlined by MacLeod (1988, pp. 119–24), and it is likely that this high number is mainly explained both by the growth of the metropolis as a commercial and manufacturing centre and by the proximity to the patent office, which gave would-be patentees the possibility of following closely the administrative procedures related to the granting of the patent. Surrey also has a quite high concentration of steam patents. This case, besides by the proximity to the patent office, may also be accounted for by the presence in the area of a number of engineering firms specialised in the production of capital goods (MacLeod, 1988, p. 124; Hilaire-Perez, 2000, p. 111). Other notable locations with high numbers of steam patents are Warwickshire, Lancashire and Yorkshire, where patents were probably related to the increasing use of steam power by the industries located there. Again, one should take into account that in this case as well, patents were essentially an urban phenomenon (MacLeod, 1988, p. 125) and so they were concentrated in major towns such as Birmingham, Liverpool, Manchester and Leeds. The table also reports the number of patents in major urban centres.

Table 1. *Geographical distribution of British steam engine patents, 1698–1852*

County/location	No. of patents 1698–1852	% 1698–1852	No. of patents 1698–1812	% 1698–1812	No. of patents 1813–1852	% 1813–1852
Cheshire	14	1·23	0	0	14	1·39
Cornwall	17	1·50	8	6·25	9	0·89
Cornwall[a]	21	1·85	12	9·38	9	0·89
Derby	11	0·97	1	0·78	10	0·99
Durham	13	1·15	0	0	13	1·29
Essex	6	0·53	0	0	6	0·60
France	21	1·85	0	0	21	2·09
Gloucester	20	1·76	8	6·25	12	1·19
Bristol	12	1·06	4	3·13	8	0·79
Hampshire	9	0·79	0	0	9	0·89
Ireland	13	1·15	1	0·78	12	1·19
Kent	31	2·73	1	0·78	30	2·98
Lancashire	145	12·78	5	3·91	140	13·90
—Liverpool	35	3·08	1	0·78	34	3·38
—Manchester	58	5·11	2	1·56	56	5·56
London and Middlesex	395	34·80	40	31·25	355	35·25
Northumberland	22	1·94	2	1·56	20	1·99
—Newcastle-upon-Tyne	11	0·97	1	0·78	10	0·99
Nottingham	13	1·15	1	0·78	12	1·19
Scotland	47	4·14	6	4·69	41	4·07
—Edinburgh	9	0·79	0	0	9	0·89
—Glasgow	22	1·94	3	2·34	19	1·89
Shropshire	6	0·53	3	2·34	3	0·30
Somerset	4	0·35	2	1·56	2	0·20
—Bath	2	0·18	1	0·78	1	0·10
Stafford	27	2·38	5	3·91	22	2·18
Suffolk	5	0·44	0	0	5	0·50
Surrey	88	7·75	10	7·81	78	7·75
USA	13	1·15	2	1·56	11	1·09
Wales	12	1·06	1	0·78	11	1·09
Warwick	58	5·11	8	6·25	50	4·97
—Birmingham	55	4·85	6	4·69	49	4·87
Worcester	11	0·97	1	0·78	10	0·99
York	63	5·55	11	8·59	52	5·16
—Bradford	11	0·97	0	0	11	1·09
—Kingston-upon-Hull	9	0·79	2	1·56	7	0.70
—Leeds	17	1·50	3	2·34	14	1·39
—Sheffield	6	0·53	0	0	6	0·60
Others	71	6·26	12	9·38	59	5·86
Total	1135	100	128	100	1007	100

[a] Cornwall including the patents taken by Arthur Woolf.
Source: The list of steam engine patents is taken from *Abridgments of Specifications relative to the Steam Engine*, London, 1871. In order to retrieve the stated residence of the patentees, these patents have been matched with those contained in B. Woodcroft, *Titles of Patents of Invention Chronologically Arranged*, London, 1854.

Over the entire period 1698–1852, the share of Cornwall in total patenting is 1·85%, which does not reflect at all the major contribution of the county to the development of steam power technology. Breaking down the period 1698–1852 into two sub-periods (1698–1812 and 1813–52), in order to take into account the publication of *Lean's Engine Reporter*, is even more revealing. In the first period, Cornwall (including in the count also the patents taken out by Arthur Woolf who, at the time, was working for the Meux and Reid brewery in London) is the county with highest number of patents after the London and

Middlesex area, with a share of 9·38%. In the second period, the share of Cornwall drops to a negligible 0·89%, and this is exactly the period during which the Cornish pumping engine was actually developed. In our view, this finding is indicative of the widely perceived awareness in the county of the benefits stemming from the adoption of a collective invention regime for the rate of innovation. After the unfortunate experience with the Boulton and Watt monopoly, it seems quite clear that in the Cornish engineering community, an *ethos* prescribing the full release of technical innovations into the public domain emerged and became progressively established.

The case of Arthur Woolf is particularly illustrative. Woolf was one of the leading figures in the Cornish engineering community (Jenkins, 1933; Harris, 1966). Born in Cornwall, he had an initial apprenticeship with steam engineering by working with Jonathan Hornblower. In the first decade of nineteenth century, he moved to London, where he was entrusted with the steam engines of the Meux and Reid brewery. In this period, Woolf took out four patents for innovations in steam engines (in particular his famous compound engine patented in 1804). In 1812 he moved back to Cornwall, where he tried to commercialise his compound engine by means of an agreement similar to the one proposed by Boulton and Watt (royalties paid as a proportion of fuel savings). His initiative was unsuccessful. Most mine adventurers awaited the expiration of the patent in 1818 before installing this type of engine (Farey, 1971, pp. 188–9). Later on, in 1823, Woolf invented a new valve for steam engines (the double-beat valve). The adoption of this type of valve greatly facilitated the operation of the engine (Hills, 1989, pp. 109–10). He did not claim any patent right for this invention.

Another example that confirms the negative attitude towards patents existing in the Cornish mining district is the limited diffusion of the two-cylinder compound engine patented by the Cornish engineer, James Sims, in 1841. The first engine of this type erected at the Carn Brea mine performed particularly well in terms of duty (it was the second best engine in the *Reporter* in the early 1840s). However, being a patented design made the engine quite unpopular with other engineers and mine-owners, who, in the end, preferred not to adopt it (Barton, 1965, pp. 110–12).

Passages in the contemporary engineering literature also indicate this bias. For example, John Taylor (a leading mine entrepreneur) wrote in 1830:

> Under such a system [the *Lean's Engine Reporter*] there is every kind of proof that the application of steam has been improved, so as to greatly economise fuel in Cornwall, and also the rate of improvement has been fairly expressed in 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. (Taylor quoted in Farey, 1971, pp. 251–2)

5. Concluding remarks

Recent research in economic history has pointed to the patent system and, relatedly, to the market for technologies, as institutional arrangements that greatly stimulated innovative activities during the nineteenth century. The case study of the Cornish mining district presented in this paper has illustrated the economic and technological significance of incremental and 'anonymous' innovations in the development of one of the key technologies of this period, steam power. Notably, the institutional set-up supporting this stream of incremental innovations was one favouring practices of 'technology sharing' rather than appropriability. In our view, the study presented in this paper also has broader implications. Collective invention processes were probably a common feature of many local production systems during the nineteenth century. Indeed, in analogous terms with what Berg and Hudson (1992, pp. 38–9) and Hudson (1989) have argued concerning patterns of economic and social change, one can suggest that a regional or local perspective on innovation during the Industrial Revolution is likely to be the most fruitful research approach. Aggregate analysis of trends in patents and in patenting behaviours such as those by Sullivan (1989) and the works by Lamoreaux, Sokoloff and Khan previously mentioned, can help us in shedding light on particular aspects of the innovation process, but it is crucial to take into account that the overall pattern is the result of an aggregation of fairly different regional and sectoral experiences. In order to gauge the volume, the intensity and the effectiveness of inventive activities in different contexts, it is necessary to look in detail also at what was undertaken *outside* the patent system (see Sullivan, 1995; O'Brien *et al.*, 1995 for a recent discussion on the merits and drawbacks of using patents as indicators of the volume of inventive activities).

In local production systems where technical advances were the product of collective endeavours as in Cornwall, the organisation of innovative activities was governed by specific institutional arrangements, alternative to the patent system, which made sure that new technical knowledge remained in the public domain. These cases ought not to be considered as curious exceptions. In several instances, they exhibited a much higher degree of technological dynamism than locations which relied extensively on the patent system. Another interesting example is the case of the competition in the silk industry between Lyon and London (Foray and Hilaire Perez, 2000). In London, the organisation of innovative activities was based on patents and secrecy, whereas in Lyon a sophisticated institutional architecture assured rapid dissemination and open use of technical innovations (Cotterau, 1997, pp. 139–43; Hilaire Perez, 2000, pp. 73–82). During the first half of the nineteenth century, the two districts competed fiercely. The ultimate outcome was the complete demise of the London silk industry. Lyon instead proved to be one of the most flourishing industrial districts of the nineteenth century, successfully surviving market crises and other adversities (Sabel and Zeitlin, 1985, pp 156–7). It is worth stressing, however, that it is very difficult to make generalisations. In fact, one can mention other cases of local flexible production systems in which a patent and secrecy regime promoted a high rate of innovation. For example, Maxine Berg has noticed that in Birmingham, one of the leading inventive centres in metal industries, the institutional set-up underpinning innovative activities was based on patents and trade secrets (Berg, 1991, p. 185; 1994, p. 269).

In the US, in a number of industries, processes of 'collective invention' were implemented by means of patent pools. Note that in some cases, these patent pools were created after having experienced phases of slow innovation due to the existence of blocking patents. In the 1870s, producers of Bessemer steel decided to share information on design plants and performances through the Bessemer Association (a patent pool holding control of the essential patents in the production of Bessemer steel). The creation of this patent pool was stimulated by the unsatisfactory innovative performance of the industry under the 'pure' patent system regime. In that phase, the control of essential patents by different firms had resulted in an almost indissoluble technological deadlock (Morison, 1966, pp. 162–205). Similar concerns over patent blockages led firms operating in the railway sector to adopt the same expedient of semi-automatic cross-licences and knowledge sharing (Usselman, 1991, 1999).

Finally, the examples considered in this paper point to the variety of patterns of technological progress across industries. As Merges and Nelson (1994) have contended, the impact of the intellectual property rights regime on the rate of innovation is likely to depend very much on the nature of the technology in question. In the case of 'cumulative systems technologies' (that is, technologies consisting of a number of interconnected components and in which current improvements are tightly related to previous innovations), strong enforcement of intellectual property rights might, in the end, hinder technological progress. In these cases, a better context for innovation is one in which a high degree of pluralism and rivalry in the exploration of technological opportunities is continuously rejuvenated. As we have shown, in Cornwall in the case of steam pumping engines (without doubt a cumulative technology), dissatisfaction over the innovative performance under Watt's monopoly led to the creation of an 'open' collective invention setting that produced a marked acceleration in the rate of technological advance. In other cases, the process of technical change tended to be more discrete and the dynamics of innovation less cumulative. Typically, this happens when technologies are relatively 'simple'. In these situations, an institutional structure facilitating the appropriability and commercialisation of innovations is likely to be conducive to technological progress. The case of the American glass industry presented by Lamoreaux and Sokoloff (2000) seems indeed to fall into this category.

Note that all this does not mean that technologies will more or less automatically trigger transformations in the institutional structure which in the end will spur their own development. On the contrary, the examples discussed in this paper (see again Merges and Nelson, 1994, for additional evidence) indicate that practices of knowledge sharing were based on a set of preconditions that goes well beyond the mere nature of technological advance. Furthermore, the emergence of institutional arrangements underpinning collective technological learning appears to be the outcome of complex historical processes, deserving in most cases detailed study in their own right. For this reason, accounts of technical change in the early phases of industrialisation which rely on simple and general causal mechanisms, such as those based on the emergence of intellectual property rights regimes and of the market for technologies, may be unwarranted. As Nelson (1990) has aptly put it, in capitalist economies, institutional arrangements presiding over the generation and development of technological opportunities exhibit an exceedingly wide degree of variety and of sophistication. Clearly, economic historians interested in discovering 'how Prometheus got unbound' ought to take this consideration into account.

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