The Making of Steam Power Technology

A Study of Technical Change during the British Industrial Revolution

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'You see, Tom,' said Mr Deane, at last, throwing himself backward, 'the world goes on at a smarter pace now than it did when I was a young fellow. Why, sir, forty years ago, when I was much such a strapping youngster as you, a man expected to pull between the shafts the best part of his life, before he got the whip in his hand. The looms went slowish, and fashions didn't alter quite so fast – I'd a best suit that lasted me six years. Everything was on a lower scale, sir – in point of expenditure, I mean. It's this steam, you see, that has made the difference – it drives on every wheel double pace and the wheel of Fortune along with' em…….

George Eliot, *The Mill on the Floss*

Preface

This book is the result of a PhD project that I undertook at the Eindhoven Centre for Innovation Studies (ECIS) about four years ago. As it was originally formulated, the research aimed at exploring systematically a small portion of what Sir John Habakkuk called "the debatable borderland between history, technology and economics". For several reasons, the case of steam power technology seemed a particular suitable ground for exploiting the potentialities of cross-fertilization between the three disciplines.

My greatest debt is to my supervisors: Bart Verspagen, Nick von Tunzelmann and Geert Verbong. Bart Verspagen has been an invaluable source of inspiration, first by helping me in the identification of the relevant research challenges and then by providing, at every step, suggestions on how to tackle them. The intellectual debt I owe Nick von Tunzelmann will be, without doubt, apparent to every reader of *Steam Power and British Industrialization to 1860*. Additionally, Nick provided a precious and continuous critical feedback on my research findings. Finally, Geert Verbong, introduced me to the history of steam engine technology, which, before coming to Eindhoven, was completely unknown to me. Furthermore, in various topical moments, Geert drew my attention to the historical importance of issues that, at first sight, looked simply as inconsequential engineering details. Remarkably, in other circumstances, he invited me to broaden the perspective and take into account the wider context in which technological developments had taken place.

In the four years I spent working on the thesis, I was fortunate enough to share my office with colleagues, that soon became invaluable friends: Michiel van Dijk, Andriew Lim and Frank Vercoulen. Besides help and suggestions on parts of the thesis, they are responsible for creating a somewhat chaotic but wonderfully pleasant working environment. It was this atmosphere that greatly helped me to cope with the occasional moments of frustration and temporary set-backs that are typical of every long research project.

Koen Frenken, Carolina Castaldi and Christine MacLeod deserve a very special word of acknowledgment. Koen pushed me to consider the potentialities of complex systems theory for the study of technological change. The results reported in chapter 4 are the outcome of a joint research effort that we undertook in this direction. In addition, Koen made extensive comments on various parts of the thesis. Carolina provided encouragement, suggestions and advice in the concluding phase when I had to weave together the various threads of the research. Finally, I am particularly grateful to Christine for many enjoyable discussions and stimulating electronic correspondence on various aspects of the process of technological change during the British Industrial Revolution.

Special thanks go to John W. Kanefsky for providing me with the updated version of his dataset of eighteenth century British steam engines which has been the basis for the findings reported in chapters 3 and 4.

Along the road, I have enormously benefited from recurring “wide-ranging” discussions with an “invisible college” of friends and colleagues who are also engaged, in various ways, in the “craft” of innovation studies, namely Nicoletta Corrocher, Bart Los, Roberto Fontana, Paola Criscuolo, Fergal Shortall, Stefano Brusoni, Eugenia Cacciatori and Jerry Silverberg. I am deeply grateful to all of them for being an unfailing source of new ideas and enthusiasm for research.

Within ECIS, I could not overlook the support of my colleagues and office neighbours of the “Technology and Policy” department. In particular, I would like to mention Eddy Szirmai, Rudi Bekkers, Ted Clarkson, Jojo Jacob, Onder Nomaler, Effie Kesidou, Cristoph Meister, Orietta Marsili, Andre’ Lorentz, Brian Portelli, Martijn Bakker and Bert Sadowski.

I would like also to thank the members of the “reading committee” Kristine Bruland and Joel Mokyr for thoughtful comments on the first draft of the thesis.

A grant of the European Commission (Marie Curie fellowship) gave me the opportunity to spend a period of six months at SPRU (Science and Technology Policy Research), University of Sussex. The grant was also instrumental for the collection of the data on steam engine patents used in chapter 5. SPRU proved to be another important source of inspiration for my research. I want to thank Aldo Geuna, Vincente Benito Ortiz, Ed Steinmueller, Isabel(la) Freitas, Elisa Giuliani, Andrea Prencipe and Ammon Salter for making my stay at SPRU particularly enjoyable, not only from a “scientific” point of view.

I wish to express my deep gratitude to the staff of the Cornish Studies Library (Cornwall Centre, Redruth), the Royal Institution of Cornwall (Truro), the Science Museum Library (London) and the British Library (London) for their help and guidance. In Eindhoven, Leon Osinski provided constant assistance with library matters.

Two research seminars given at CESPRI (Centro di Studio sui Processi di Innovazione e Internazionalizzazione), Bocconi University, Milan, represented an extremely stimulating sounding board for my preliminary research findings. I am particularly grateful for their constructive criticisms to Franco Malerba, Francesco Lissoni, Anna Canato, Stefano Breschi, Fabio Montobbio, Marco Guerzoni, Lucia Cusmano, Maria Luisa Mancusi, Lorenzo Cassi and Lorenzo Zirulia. In retrospect, I realize that most of the suggestions I received at CESPRI have found their way in the final version of the book.

Chris Hodrien suggested me a number of very helpful references on steam engineering matters. Bridget Howard read and kindly commented in detail an early version of chapter 5. The present version takes into account her remarks, although I am fairly sure that she will still consider some of the conclusions I reach with some degree of scepticism.

Finally, parts of this work were presented at various seminars, conferences, summer schools and workshops in Strasbourg, Dublin, Lisbon, Cargese, Durham, Manchester, Paris, Pisa, Copenhagen, Reading, Groningen, Utrecht, Philadelphia, and Augsburg. I would like to thank the participants at these meetings (especially Richard Nelson, Pat

Hudson, Liliane Hilaire-Perez, Dominique Foray, Laura Magazzini, Ben Gales, Fulvio Castellacci, Marcel P. Timmer, Paul A. David, Alfonso Gambardella, Bart van Ark and Nick Crafts) for their comments and suggestions.

Alessandro Nuvolari
Eindhoven, July 2004

Contents

1. Introduction

1.1. Preliminary considerations

In the Preface to the first edition of *The Making of the English Working Class* Edward P. Thompson revealed that he was not entirely satisfied with the choice of the word "making" for the title of his book. However, he finally decided to stick to it because that word better than others conveys the idea of "an active process which owes as much to agency as to conditioning" (Thompson, 1963, p. 8). The word "making" has been adopted for the title of this study with the same purpose. New technologies do not appear at appointed times, as actors on a play stage. Rather, they are the outcome of complex historical processes in which a variety of agents are involved. Furthermore, agents' actions reflect, in various degrees, the wider historical context in which they are situated. All this makes the study of the process of technological change a difficult task not reducible to simplistic and preordained schemes of interpretation.

The central theme of this book is the process through which steam power first emerged and then grew into a major industrial technology in a period going approximately from the early eighteenth century to the middle of the nineteenth century. As we follow the development of our hero (steam technology) in his arduous journey from infancy to maturity, adopting a literary metaphor, we could say that the "genre" in which this work falls is the *bildungsroman*. The approach adopted is interpretative rather than descriptive. Our account aims at unveiling the fundamental variables shaping the development of steam power technology, instead than providing a comprehensive and detailed technological history of its evolution. As a matter of fact, one could observe that the latter task has been already admirably accomplished by historians of great talent such as Dickinson (1938) and Hills (1989).

Given the particular focus chosen, we will concentrate our attention on a number of selective features of the evolution of steam power technology. In this respect, the choice will obviously privilege "themes" which appear, at least potentially, particularly useful for the explanation of the observed patterns of technical progress.

Our inquiry will, by and large, make use of analytical tools borrowed from the economics of technological change, more specifically (within this body of literature) from what has been referred to as the "post Schumpeterian" or "evolutionary" tradition. Curiously enough, not so long ago, most economists, though recognizing that technical progress was the fundamental driver of modern economic growth, preferred to consider it as essentially "exogenous", or, to say it better, as something that was not amenable of a fully satisfactory explanation using the conventional economist's toolkit. In the words of Joan Robinson, economists regarded technical change as something given to us "by God, scientists and engineers". With a touch of proper modesty, economists decided that understanding the reasons underlying God's behaviour was far outside their reach. Interestingly enough, such a view of technological progress regarded in the same way the behaviours of scientists and engineers. These, when considered from an economic point of view, were seen merely as "carriers" of the autonomous logic of technological progress.

And yet, outside the mainstream of the economics literature, since the early 1950s, a number of contributions began to devote increasing attention to the process of technical change (good surveys of these early studies are contained in Nelson, 1959 and Freeman, 1977). One of the findings of this, rather heterogeneous, body of literature was that a satisfactory economic analysis of technology-related phenomena would have required a deep revision of the basic assumptions of mainstream economic theorizing. The main source of inspiration of these contributions were themes that had featured prominently in Schumpeter's works, namely the emphasis given by Schumpeter to technical change as an endogenous source of dynamism in the development of capitalist economies and his recognition of the "out-of-equilibrium" nature of most economic processes. Therefore, the label "post Schumpeterian" would be, later on, adopted to identify these early inquires in the economics of technical change.

Another noteworthy feature of some of this early post Schumpeterian literature was the "openness" to contributions which had examined technical change from other disciplinary angles, such as those of historians, sociologists, psychologists, etc. In this respect, one of the stated ambitions of the first post Schumpeterian contributions was the construction of an analytical framework for the study of technical change which could fruitfully integrate insights stemming from different disciplinary perspectives (Nelson and Winter, 1977; Nelson and Winter, 1982, pp. 246-272).

Over the last twenty years, a considerable amount of research dealing with particular technologies and industries has adopted this perspective. On reflection, one can probably draw a positive balance of the research efforts undertaken in this direction. A number of generalizations concerning the fundamental features of the process of technical change has been identified, so that, to date, we could say that some light has been thrown into what Rosenberg has called the "black box" of technology. Freeman (1994) contains a detailed survey of the most robust research findings in this area. Certainly, one has to reckon that much ground still remains largely unexplored.

Let us recall here the basic tenets of the post Schumpeterian/evolutionary approach to the study of economic change (see Dosi, 1997 for a thorough discussion):

i) *bounded rationality*: economic agents typically operate in highly uncertain and changing environments. This means that they consistently have a highly imperfect understanding of the environment in which they are situated. As a consequence, most economic decision-making processes cannot be adequately represented by means of well specified maximization problems. In most contexts, agent will follow rule-guided (routinized) behaviours in pursuit of "satisficing" outcomes.

ii) *heterogeneity of agents*: from i) follows that agents will generally differ in their capabilities to perform the various economic activities they are called to carry out.

iii) *continuous generation of novelty*: from i) also follows that agents are constantly engaged in a series of more or less conscious learning processes (aimed at improving their adaptation to the environment). As a consequence, the economic system is characterized by the continuous emergence of novelty.

iv) *collective selection mechanisms*: the collective interaction among heterogeneous agents both within and outside the markets acts as a selection mechanism, rewarding some traits and behaviors and penalizing others.

v) *out-of-equilibrium nature of economic processes*: the interactions among agents will typically take place in a far-from-equilibrium fashion. This is due to the fact that the "traits" of the agents are constantly changing in order to improve their fitness to the environment.

Interestingly enough, this perspective suggests a canon for economic research that is *inherently historical*. In the words of Dosi (1997, p. 1531): "…the explanation of why something exists rests on how it became what it is". In this framework, technical change is essentially conceived as the result of various learning processes undertaken by a multitude of actors (individuals, business firms, other institutions, etc.). Accordingly, technical change displays the features of an evolutionary process taking place in historical time (for a discussion of the possible ways in which an evolutionary view of technical change could be articulated see the essays collected in Ziman (2000)).

The present work is rooted in this line of inquiry. So far, steam engine technology has been studied essentially through the lenses of what may be called the traditional approach to the history of technology, which regards the evolution of technology as the solution of successive technological bottlenecks (what Layton, 1974 has defined as "history of techniques"). The solution of each bottleneck, in turn, creates new technical problems, so that the dynamics of technology is conceived as a self-generating process driven by its internal compulsions and relatively unaffected by other "external" factors. As we will see this perspective has produced a number of valuable insights (see in particular Hills (1989)). The aim of this work is to broaden the focus by giving more latitude to the role played by various actors and the diverse contexts of application. As we have said, the foundation for the broader perspective taken here is represented by the notion of technical change as an evolutionary process.

It is worth remarking from the offset, that we will not deal with the consequences or effects of the diffusion of steam power technology. Concerning the economic impact of steam technology this ground has been covered exhaustively by the work of von Tunzelmann (1978). We will concentrate, instead, in a rather exclusive fashion, on the evolution of the technology itself. Our work is also restricted in its geographical scope. We will mainly deal with technical developments that took place in Britain. *Prima facie*, given the precocious lead of Britain in steam engine technology, our choice could seem to require little justification. However, it must be recognized that, in the early nineteenth century, important developments took place in the United States (this country detained a leading position in steamboat technology, see the comprehensive account by Hunter, 1949) and in France (where significant advances in the understanding of the functioning of steam engine were attained). We will deal with them only tangentially. Therefore, the reader should take into account that our picture of the evolution of steam engine technology limited to the British case is a partial one.

1.2. Steam technology and industrialization

Before beginning our inquiry, it is worthwhile to consider the treatment that steam technology has received in the economic history literature. The aim of this brief historiographic excursus is to help the reader to familiarize with the wider context in which the development of the technology took place.

Writing in 1845 Friedrich Engels (and with him many other informed contemporaries) had few hesitations in identifying the driving forces of the epochal transformation he was witnessing:

> The history of the proletariat in England begins with the second half of the last century, with the invention of the steam engine and of machinery for working cotton. These inventions gave rise, as is well known, to an industrial revolution, a revolution which altered the whole civil society; one, the historical importance of which is only now beginning to be recognized. (Engels, 1993, p. 15).

This view of the early phases of industrialization, ascribing a central role to the steam engine as a driver not only of economic growth, but also of other dramatic changes such as the rise of the factory system, was (and still is) resumed in a major part of the historical studies on the British industrial revolution. Writing about one hundred years after Engels, T.S. Ashton (an author whose ideological standpoint was indeed poles apart from Engels') regarded the steam engine as "the pivot on which industry swung into the modern age" (Ashton, 1948, p. 58). Perhaps the most terse version of this "traditional" account of the British industrial revolution is the one given by Landes (1969). [1] Landes considers the industrial revolution as the outcome of a combination of three interrelated streams of technical advances:

i) "mechanization", that is the substitution in a growing number of production processes of machines ("rapid, regular, precise, tireless") for human skills;
ii) the adoption of new power sources, most importantly the steam engine, which permitted the utilization of an almost boundless energy supply;
iii) the extensive use of new raw materials (in particular the substitution of minerals for animal and vegetable substances, most prominently the substitution of iron for wood).

These innovations revolutionized production processes in a wide array of industries determining a marked acceleration in the rate of productivity growth. Furthermore, they "compelled" the adoption of a new mode of production, the factory system.

In more than one sense, Landes' analysis can still be considered as broadly accurate. However, at least in our judgment, more recent research findings indicate that a number of qualifications ought to be appended to this ("traditional") account of the British industrial revolution.

Firstly, the three streams of technical progress outlined by Landes proceeded at rather different paces, both considering the invention and the diffusion phases. Roughly speaking, one can say that "early mechanization" *preceded* the introduction of steam power.[2] Traditional accounts of the British industrial revolution have instead adopted periodizations which tend to associate the economic significance of steam technology with its early development (in particular with the invention of the Watt engine). These judgments probably reflect the influence of a number of authoritative contemporary sources that, fascinated by the "charm" of the new technology, tended to give exaggerated appraisals of its economic significance.[3] Rostow's account can be considered

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[1] For a comprehensive critical discussion of the enormous corpus of literature devoted to the British industrial revolution, see Mokyr (1999).

[2] The distinction between the expansion of mechanization and the extensive adoption of new power sources was stressed by Marx (1990) in Chapter XV of the first volume of *Capital*.

[3] In particular Ure (1835) and Baines (1835). Rostow (1960) refers to the historical analysis of Baines on pp. 53-54.

as representative of this particular feature of the traditional view of the British industrial revolution (Rostow, 1960, 1975):

Watt's engine – which reduced fuel expenditures to perhaps half of their previous level - is...*an integral part of the first phase of the industrial revolution*….The short-run effects of this radical reduction in the cost of power and its almost complete locational mobility had revolutionary consequences over a wide range of industrial processes. (Rostow, 1975, pp. 164-167, italics added).

Accordingly, Rostow dated the take-off phase in Britain in the years 1783-1802, concomitantly with the commercialization of the Boulton and Watt engine (Rostow, 1960, p. 38). More recent research (Greenberg, 1982) seems to suggest that such a direct and immediate link between steam engine technology and early industrialization is indeed spurious. In fact, as we shall see in more detail later, the diffusion of steam power was a particularly long and protracted process. Consequently, the economic impacts of the technology became significant only in a later stage.

Secondly, the transition to the factory system cannot be considered as an immediate by-product of technological advances (and in particular of the adoption of the steam engine). A number of studies have shown that, although conditioned by technical changes, this organizational innovation (but also the introduction of other novel ways of organizing production that have so far received much less attention) was endowed with its "autonomous" momentum (see Berg 1994, chap. 9 for a discussion).[4] Furthermore, the factory system (and other forms of industrial organization) fed back into technology biasing the emerging technological trajectories in specific directions (Bruland, 1982).

Thirdly, the picture of abrupt economic change which, by and large, emerges from Landes' account of industrialization is in need of some amendment. Revised estimates produced by Crafts and Harley (1992) indicate that in what is conventionally considered as the "classic" period of the British industrial revolution (1760-1830), the rate of economic growth was not characterized by any sharp acceleration. [5] Furthermore, the contribution given by technical progress to overall economic growth measured as total factor productivity in a standard growth accounting framework was remarkably modest.
Given these points, we would maintain - as suggested originally by Cipolla (1962) and later on, in a more articulated way, by Wrigley (1988, 2004) - that rather than regarding the industrial revolution as a unitary process, we should be more appropriately consider it as the combination of two distinct historical phases, partially overlapping in time, but each of them driven, by and large, by distinct sets of forces.

The first phase covering approximately the years 1700-1820, could be labelled - following Maxine Berg (1994), who, in turn, has borrowed the expression from Marx - as "the age of manufactures". This phase was characterized by the early mechanization of a number of production processes (in particular in the textile industries) and by the early rise of the factory system. However, when the historical record is closely examined, the range and scope of innovative activities appears to have covered a remarkably broad front (Bruland, 2004). In particular, industries such as food processing, glass manufactures, "metal trades", etc., witnessed the emergence of significant streams of product innovations (a fact which has received little attention in traditional accounts, also because it does not

[4] In some industries such as silk and metalworking a number of large-scale industrial plants employing some hundreds of workers were actually in operation since the late seventeenth century. However, these must be properly considered as extraordinary cases.
[5] See, however, Landes (1999), for a re-proposition of the traditional view and a rather critical appraisal of the various attempts of estimating the rate of economic growth in this historical phase.

lend itself easily to quantitative measurement). Additionally, beyond the factory system, a wide spectrum of industries experimented novel ways of organizing and coordinating production processes such as advanced forms of "puttying out", "sweated trades", etc. In a number of industries, these organizational innovations proved to be rather successful and continued to represent the predominant mode of production well into the nineteenth century. Furthermore, innovation in marketing techniques, was frequently intertwined with product innovations and was also nothing short of remarkable. As Berg and Hudson (1992) have argued, it is likely that the economic significance of these transformations is severely underestimated by traditional growth accounting exercises such as those carried out by Crafts and Harley (1992). Perhaps the only way to draw an accurate picture of this process is to move beyond national income statistics and examine in detail these transformations at various micro levels (i.e. firms, industries, regions)

A particularly interesting feature of this first spurt of industrialization is that the energy base of the economy, in a qualitative sense, remained unchanged (Wrigley, 1988). In a quantitative sense, the adoption of water power grew remarkably (see Hunter, 1975). The efficiency of water wheels was also raised considerably by a number of technical innovations. At all events, in the "age of manufactures" the traditional mixture of human, animal, wind and water power (although in changing proportions) continued to provide the bulk of power to the economy.

The energy base of the industrializing economies was instead drastically transformed at later stage by the widespread adoption of steam technology. This was a particularly slow and protracted process, spanning more than 150 years since its inception in the early eighteenth century. As Cipolla (1962), has pointed out, in the very long run, this transformation in the energy base of the economy must be considered as the critical determinant of the growth of living standards which has taken place over the last two centuries in industrialized economies. The intensive use of inanimate energy sources drastically changed the energy budget of human societies, opening up the potential for self-reinforcing economic growth. In the very long run the significance of this historical change is fully comparable to the Neolithic revolution (approximately dating around 7000 B.C.) which marked the transformation of human societies from groups of hunters and gatherers into communities practicing agriculture and employing domesticated animals. [6]

Using the data on the comparative diffusion of steam power reported in Landes (1969) and dating back to *Dictionary of Statistics* by Mulhall (1909), we may draw an (admittedly crude!) picture of this second industrialization spurt in which the energy base of western economies shifted to the intensive use of inanimate energy sources. Figure 1.1 shows the existence of a tight connection between national economic performances (measured using levels of GDP per capita) and the comparative diffusion of the steam engine technology in the second half of the nineteenth century. In this sense "the mid nineteenth century was pre-eminently the age of smoke and steam. " (Hobsbawm, 1975, p. 55). Notably, the Netherlands do not fit into the overall pattern, being capable of attaining relatively high levels of GDP per capita without resorting to a particularly intensive adoption of steam power technology.[7]

[6] For a particularly terse appraisal of Cipolla's analysis of the role played by the transition to new energy sources in the dynamics of the industrialization process, see Mathias (2003).

[7] On the peculiarities of the connection between steam power and industrialization in the Dutch case, see Lintsen (1995)

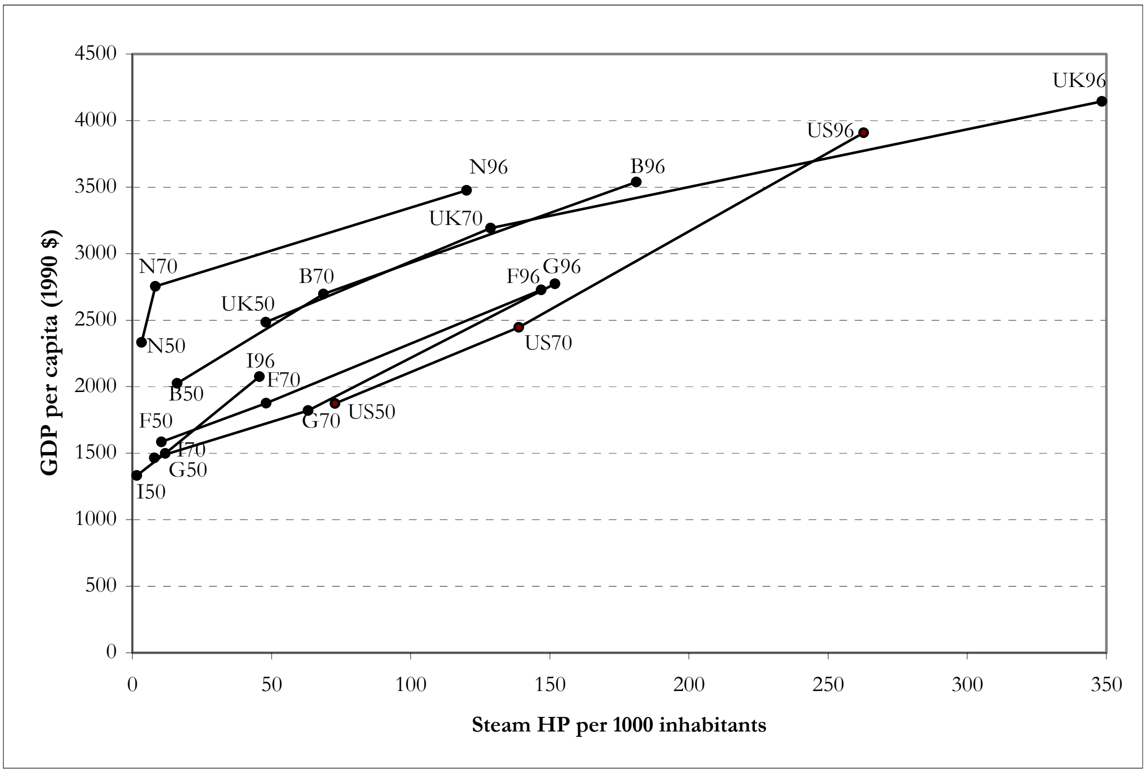

Figure 1.1: Steam power installed (HP per 1000 inhabitants) and per capita GDP levels (1990$), 1850-1896. (United Kingdom(UK), United States (US), Belgium (B), France (F), Germany (G), Italy (I), the Netherlands (N))

Source: for GDP levels and population: Maddison (2001), the figures for 1850 and 1896 have been extrapolated on the basis of the average growth rate respectively over the periods 1820-1870 and 1870-1913; steam HP installed: Landes (1969), p. 221.

Since the development of steam power technology covers the years 1700-1900, in historical terms, it is important not to anticipate the economy wide repercussions induced by the progressive penetration of this technology in the structure of the economy to an earlier historical phase. [8]

Concerning Britain, the available quantitative evidence indicates that the widespread adoption of steam power (and, consequently, the transformation of the energy base of the economy) began to gain momentum from the second quarter of the nineteenth century.

Table 1.1 gives estimates of the extent of steam usage in various years taken from Kanefsky (1979)'s study of the diffusion of steam power technology in the British industry. Kanefsky's data consider total steam HP employed in manufacturing and in mining. It is important to note that these data intend to cover power capacity installed rather than that actual power in use. Although the picture of the diffusion of steam power emerging from table 2 is probably roughly correct, in our judgment, these figures still contain some overestimation of the extension of the use of steam *vis-à-vis* the two other sources of power, especially for the years 1760,1800, and 1830. This is due to the fact that very small productive units (which typically employed wind and water) are likely

[8] On the basis of data from Mulhall (1909), Hobsbawm (1975, p. 55) estimates that *between 1850 and 1870*, total steam power in use in western economies increased of more than four-and-a-half times, growing from 4 million HP to 18.5 million HP.

to have gone unnoticed. Notwithstanding this consideration, the table clearly suggests that the use of steam as a power source became generalized only from the 1840s.[9]

Table 1.1: Sources of Power in Use in HP (mainly mining and manufacturing)

Year	Steam	(%)	Water	(%)	Wind	(%)
1760	5000	5.88	70000	82.35	10000	11.76
1800	35000	20.59	120000	70.59	15000	8.82
1830	160000	47.06	160000	47.06	20000	5.88
1870	2060000	89.57	230000	10.00	10000	0.43
1907	9659000	98.14	178000	1.81	5000	0.05

Source: Kanefsky (1979), p. 338.

Von Tunzelmann (1978) has provided a quantitative assessment of the contribution of steam engine technology to British economic growth. In his study, von Tunzelmann employs two techniques. Firstly, he performs a social saving type of analysis, estimating the cost differential between steam technology and the other technological options which were plausibly available. This exercise reveals that, up to the 1830s, the *direct* impact of cost reductions related with the use of steam technology was a relatively minor one. Secondly, he examines the strength of the backward and forward linkages of steam technology. According to von Tunzelmann, the forward linkages between steam technology and textile industries (which are, of course, particularly critical ones) became consistent only in the 1840s. Overall, von Tunzelmann's results can be seen to provide broad support for the Cipolla-Wrigley view which regards the British industrial revolution as a combination of two distinct industrialization spurts.

In the light of these considerations, it must be remarked that this work is limited to the study of the first phase of the development of steam engine technology (the process that we have called "making"). Our work concludes precisely when the transition between the traditional power system and the new one based on steam is gaining momentum. In this respect, our analysis can be regarded as an examination of the "seeds" of this historically critical turning point.

1.3. Plan of the book

At this juncture, it seems appropriate to give the reader a taste of what is in store in the following chapters. The first part of the book (chapter 2) contains a broad survey of the historical development of steam engine technology over approximately the period 1700-1850. This part is devoted to a narrative history of the main breakthroughs which punctuated the evolution of steam engine technology and it also provides the indispensable technical background for the inquiry that follows. It must be noted that, in this introductory part, the history of steam engine technology is recounted in a rather traditional way, that is to say, from an "internalist" perspective. This means that the focus is on the artifact itself, rather than on the relationships between the artifact and the wider historical context. Accordingly, technical change is viewed as a sequential series of solutions to technological bottlenecks and the influence that non-technical factors exerted on the process of technical change is relatively neglected (Staudenmaier, 1985, pp. 9-11).

[9] For a brief historical overview of the slow progress in the adoption of steam power in Britain in different industries and locations during the first half of the nineteenth century, see Clapham (1926), p. 155 and pp. 441-445.

The second part of the book (chapter 3 and chapter 4) examines the emergence of steam engine technology during the eighteenth century. Both chapters rely on a data-set of British steam engines installed over the period 1700-1800 originally collected by Kanefsky and Robey (1980). Chapter 3 considers the diffusion of steam engine technology during the eighteenth century. The chapter gives a thorough reconstruction of the diffusion process, by providing new estimates for the regional variations in the timing, pace and extent of usage of steam engines. In addition, the chapter attempts to identify the key determinants of the diffusion of steam power in various geographical areas. Chapter 4 investigates the process of progressive adaptation of steam technology to the diverse needs of various ultimate users in the second half of the eighteenth century

The third part of the book (chapter 5, chapter 6 and chapter 7) is devoted to the development of the Cornish pumping engine. The Cornish pumping engine represented the "peak" of steam engineering during the early nineteenth century. This part examines in detail the historical context in which this particular version of steam engine technology grew and matured. Chapter 5 is mainly concerned with the role of the institutional set-up that framed innovative activities in Cornish steam engineering. Chapter 6 is devoted to a reconstruction and interpretation of the main patterns of technical progress. Chapter 7 discusses the role of the "drivers" of technical progress.

Finally, in Part IV, chapter 8 provides a concise summary of the main findings of this inquiry and discusses their broader implications.

PART I. THE BACKGROUND

2. The Development of Steam Power Technology

2.1. Introduction

This chapter contains a condensed overview of the development of steam engine technology over the period 1700-1860. The aim is to provide the indispensable background (in history of technology) relevant to our study. No new findings are presented: we will just limit ourselves to collate and summarize existing materials. For a more extensive and detailed treatment of the issues surveyed here, the reader is referred to Hills (1989) and, for the connections between scientific and technological developments, to the still valuable work by Cardwell (1971). Among contemporary accounts, the *Treatise on the Steam Engine* by John Farey (1827) must be mentioned as one of the most thoroughly written. Furthermore, Farey's book contains an extremely insightful appreciation of many economic aspects of technical change. Thus, in this study, time and again we will make use of Farey's appraisals.[1]

In this chapter we will mainly deal with the evolution of engine designs. However, the reader should take into account that the history of steam power technology is tightly intertwined with the development of machine tools and of related engineering skills in "machine-making" technologies (for a good overview of the development of machine tools in the early phases of industrialisation, see Rolt, 1965). This is a feature of the evolution of steam engine technology that, notwithstanding its critical importance, has received so far very little attention and where further research is definitely necessary.

2.2. Papin and Savery

Historians have frequently described the development of the steam engine as a case of "reverse causation" between science and technology. This means that innovations in steam power technology did not emerge from the application of previously discovered scientific knowledge, rather the casual link run mostly in the opposite direction, with technological innovations in steam engines triggering fundamental developments in science, that, in the course of time, led to the rise of classical thermodynamics. It is important to note that this characterization is a fair description only of the state of affairs of the first half of the nineteenth century. The early development of steam technology, instead, is more properly described as a series of attempts of finding practical application for contemporary advances in science (Kerker, 1961). [2] More precisely, the first attempts to exploit the power of steam to deliver some useful work were palpably influenced by

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[1] Nick von Tunzelmann has made explicitly the case for considering Farey's book as "the finest monograph on technology produced during the Industrial Revolution" (von Tunzelmann, 1978, p. 2). For a brief overview of Farey's life and works, see Woolrich (1997) and for a critical analysis of Farey's *Treatise*, see Woolrich (2000).

[2] Thus, the long term development of the steam engine ought to be characterized in terms of a continuous mutual interaction between scientific and technological advances. For a general critical discussion of the multiple interactive links between science and technology, see Rosenberg (1982), pp.141-159.

the scientific investigations of Torricelli, Pascal, Boyle, and Hooke on the properties of atmospheric pressure. Here, we will neglect what has been called the "pre-history" of the steam engine, which dates back to the "aeolipyle" constructed by Hero of Alexandria around AD 100 and we will begin our account precisely with the "scientific based" artifacts of the late seventeenth century. This is very much in line with most historical accounts, who concord in placing the "date of birth" of the steam engine in the last decade of the seventeenth century with the machines designed by Papin and Savery.

These early developments were instigated by powerful economic stimuli, connected with the expansion of mining activities. The seventeenth century had been a period of rapid growth for the European extractive industries (coal, iron, tin and copper). This prolonged phase of growth put to the fore a number of technical problems related with deep mining operations. One of the most pressing constraints was mine flooding, which prevented the exploitation of deep deposits. In Britain, problems of mine drainage were particularly acute because the country was affected by an extremely severe lag in mine-pumping technology.[3] According to Hollister-Short, in this specific technological field, "England at the end of the seventeenth century was between one hundred and one hundred and fifty years behind the progressive areas of Europe" (Hollister-Short, 1976, p.160). This lag was largely due to the unsuccessful transfer in Britain of the *stangenkunst* technology: a system of hydraulic pumping machines originally developed in Saxony and Slovakia around 1540. After a number of further refinements, by 1600, this technology could be effectively used to drain mines up to depths of about 700/800 feet (Hollister-Short, 1981, p. 112). In Hollister-Short's interpretation, the early development (and rapid diffusion) of the steam engine in Britain in the early eighteenth century is to be related to the closing of this technology gap, via the adoption of an alternative technological solution: steam power (Hollister-Short, 1976). As we will see in the next chapter, the relatively rapid and geographically wide adoption of steam technology for mine drainage in eighteenth century Britain provides some support to Hollister-Short' s argument. It is very plausible that if, in Britain, steam technology had to compete with other viable technological solutions, its adoption in mine draining operations would have been probably more protracted and delayed. A slightly different interpretation is suggested by Harris (1979, p. 178). Harris acknowledges Britain's technological lag in water-powered pumping equipment (although not in the dramatic terms hypothesized by Hollister-Short), however he also stresses that, in many locations, the particular circumstances of mining undertakings (location of the lodes and water sites, layout of the adits, etc.) prevented the effective employment of the continental system of mine drainage. Steam technology, instead, seemed to be, from the very outset, a pumping technology particularly appropriated to the British "coal abundant" context.

With hindsight, the most important of the early efforts of harnessing the power of steam is the apparatus designed by Denis Papin.[4] A description of this machine was published in the *Acta Eruditorum Lipsiae* in 1690. The historical importance of Papin's contrivance is due to the fact that it contains in embryonic form all the basic components of successive

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[3] On the critical influence of mining concerns (in particular of those relating to mine drainage) on scientific and technological developments occurring in Britain in the second half of the seventeeth century, see Merton (1970), pp.137-159.

[4] Denis Papin (1647 – 1712?) was a French Huguenot who first worked as assistant of the Dutch scientist Christian Huygens. In 1666, Huygens had convinced Colbert to support a rather ambitious research programme into the fundamental properties of "vacua, the expansive forces of gunpowder and steam in closed vessels, and the weight of the atmosphere" (Smith, 1978, p. 5). Following the religious persecutions, Papin moved to England were he worked as a laboratory assistant of Robert Boyle and later collaborated with Robert Hooke.

steam engine designs. Papin's apparatus consisted of a vertical tube (cylinder) in which a piston was fitted. The cylinder contained a small quantity of water. The cylinder was heated from the outside and, in this way, steam was generated inside. The formation of steam forced the piston up to the top of the cylinder, where it could be held by means of a catch. When the cylinder cooled down, the steam inside the cylinder condensed creating a vacuum. In that moment, the removal of the catch caused the piston to be driven down by atmospheric pressure. Papin showed that the downward movement of the piston could be effectively used to raise a weight by means of a pulley (see figure 2.1). Although Papin's device was of no practical use because the movement of the piston could not be reciprocated (for this reason it cannot actually be regarded as a true "engine"), it can still be considered the basic model from which further developments took place. Interestingly enough, in Papin's engine the cylinder performed the triple function of boiler, engine-cylinder and condenser. In retrospect, the technological evolution of the steam engine can be seen as a process of progressive attribution of these functions to distinct components of the engine.

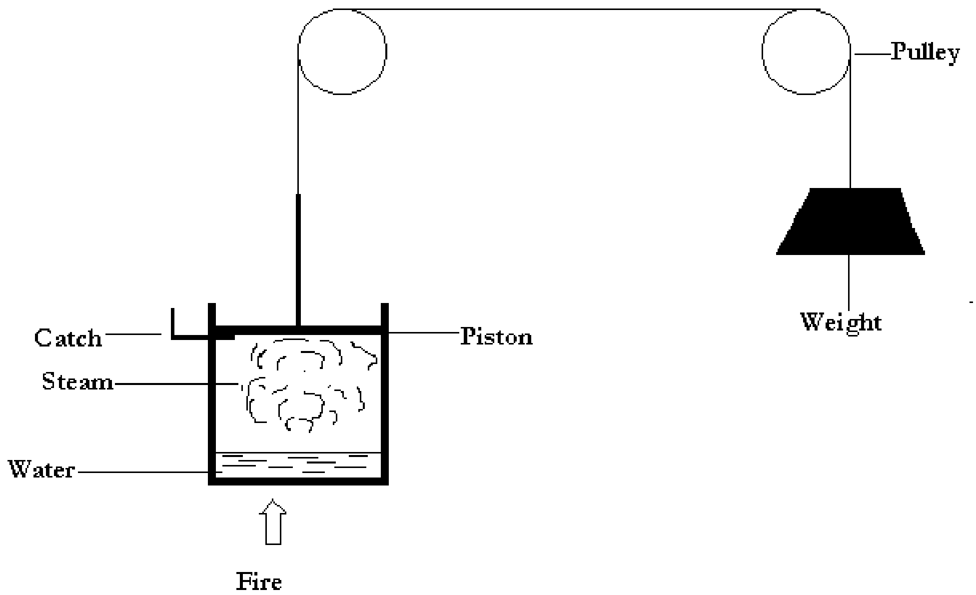

Figure 2.1 : The Papin engine

The Savery engine is usually considered as the first steam engine (although some historians of technology have claimed that it should be more precisely considered as a steam pump) which approached a fully successful industrial application.[5] The engine was developed in the years 1695 – 1702 by Thomas Savery.[6]

[5] Cardwell (1994a, p. 121), given its shortcomings, has regarded the Savery engine as the "precursor of the first unambiguously successful steam engine [namely the Newcomen engine]" . For reasons that will be apparent below, according to Cardwell (1994a, p. 121), the Savery engine should be seen as a "false start", which nevertheless had the important merit of pointing out the potentialities opened by the use of steam power. A more positive evaluation of the Savery engine is given by von Tunzelmann (1978, pp. 15-16).

[6] Thomas Savery (1650 ? – 1715) was granted a patent in 1698. In 1699 he presented a model of his engine to King William III and to a meeting of the Royal Society. A short description of the engine was published in the *Transactions of the Royal Society* in 1699. In 1700, Savery published a short treatise titled *The Miner's Friend* in which he provided a detailed description of his invention. For further biographical details, see Rolt and Allen (1997), pp. 24-30.

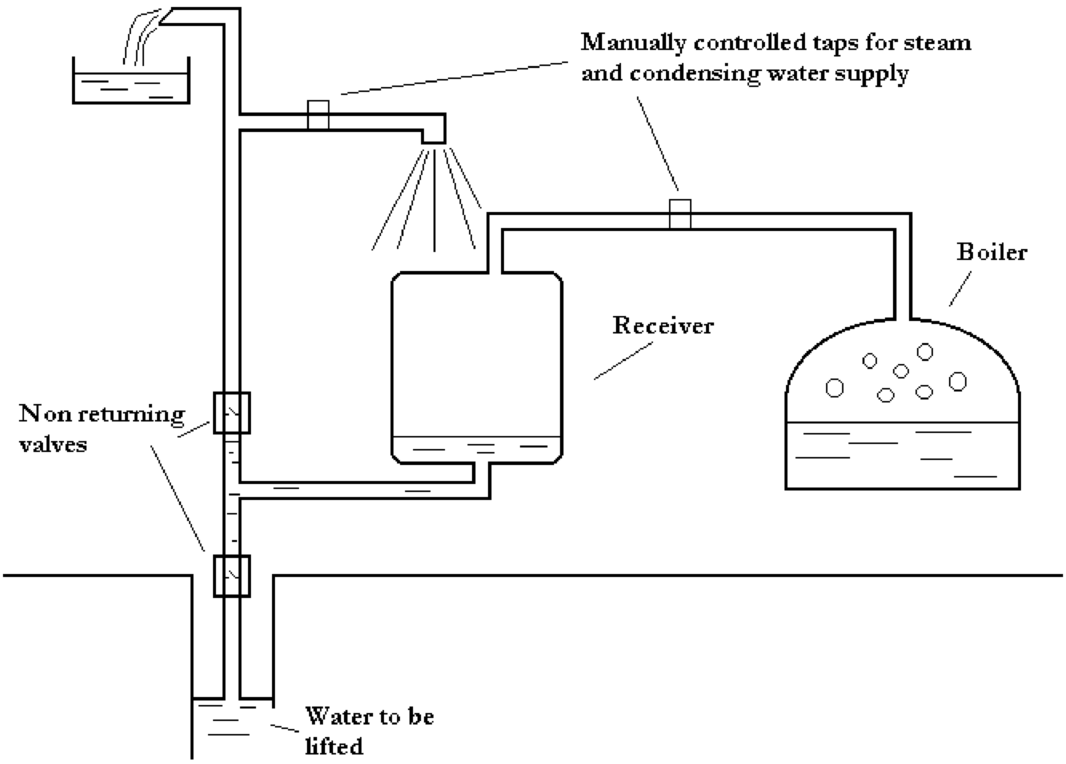

Figure 2.2: The Savery engine

In the Savery engine (see figure 2.2) a pipe, via a manually controlled tap, conducted steam from the boiler to an iron vessel.[7] From the bottom of the vessel (or receiver) another pipe carried steam to a long vertical pipe, whose lower part was immersed in the sump from which water had to be pumped. Above and below the connection between the two pipes there were one-way (non-returning) valves. The working of the apparatus was as follows. At the beginning of each "stroke", the tap on the steam pipe was opened, so that steam was conducted from the boiler into the vessel forcing the water there contained up into the vertical pipe. When the steam blew off from the vertical pipe, the tap was closed and cold water was poured over the outside of the iron vessel, by opening a second tap. In this way steam was condensed and the atmospheric pressure drove water from the sump up into the vessel. When the receiver was full of water, the operative cycle of the machine could be repeated. By opening again the tap on the steam pipe, the steam coming from the boiler was readmitted into the vessel, expelling the water there contained through the vertical pipe.

The Savery engine suffered from a number of major technical shortcomings, which severely limited its practical application. First, it was highly uneconomical: the need of recreating the high pressure steam necessary to expel the water at every stroke was extremely wasteful of fuel. Second, the metallurgical techniques of the time prevented the construction of reasonably safe high-pressure boilers and vessels. Thus, quite often the use of high pressure was either restrained or even completely avoided. Third, in practice, the suction lift could raise water only to a height of 20-30 feet and the forcing lift could push the water higher of more or less the same distance (Dickinson, 1938, p. 26). Hence,

[7] The figure and the description of the engine refer to the engine in its final form, see Farey (1827), p. 106.

notwithstanding the "marketing" efforts of its inventor, the Savery engine found only a very limited use in mine drainage.

Savery engines were instead employed more successfully for low lifts (mostly working only by suction) In these cases they were used to raise water for large buildings and fountains or for water-wheels which in turn powered factory machinery.[8] The latter application of the engine became the most common one and it was enhanced by two improvements that were introduced in the course of the eighteenth century. The first one was the use of a jet of cold water sprayed directly into the receiver to condense the steam. This improvement which, as we shall see, was rather obvious after Newcomen, is to be ascribed to J. Desaguliers around 1717-1718 (Hills, 1989, pp. 33-35). The second modification consisted in rendering the engine fully automatic, by means of contrivances that ensure the self-operation of the two taps. William Blakey in the 1760s was probably one of the first engineers to design Savery engines endowed with self-acting valve gears (Bootsgezel, 1936). He also tried a number of design modifications aimed at reducing the fuel consumption of the engine, but his attempts in this direction were largely unsuccessful (Hills, 1989, pp. 37-40).

Although the Savery engine was the most uneconomic type of steam engine as far as fuel consumption is concerned, at small sizes (when incorporating the two improvements described above) it was very often preferred to the Newcomen engine because of its lower cost of installation.[9] On these grounds, Landes (1969, p. 101) has pointed to the emergence of a spontaneous pattern of specialization with the market for "small" powers covered by the Savery engines, whereas Newcomen engines occupied the market for large prime movers. In this respect, von Tunzelmann has estimated that the "threshold" at which it would have been profitable to switch from a Savery to a Newcomen engine was between 4 to 6 horsepower (von Tunzelmann, 1978, pp. 47-48).[10] Precisely because of their lower cost of installation, the production of Savery engines was revived at the end of the eighteenth century when a number of them was employed in the form of "water returning engines" to power machinery in several factories in Lancashire. The leading producer of this type of engines was Joshua Wrigley, a millwright working in Manchester, who appears to have been able to contrive a fairly effective self-operation mechanism which was acted by the water wheel.[11]

Savery's patent was so loosely specified, that it turned out to cover every use of "the Impellent Force of Fire". In 1699 Parliament prolonged the duration of Savery's patent to 1733 (that is to say, for an extra 21 years beyond the normal 14). The prolongation meant that even the Newcomen engine (that, as we shall see, was based on a quite different working principle) was blocked by Savery's patent. Concerning the patent

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8 In the contemporary engineering literature, steam engines of the Savery or the Newcomen type employed to pump water for a water wheel were commonly called " water returning engines". See von Tunzelmann (1978), p. 142. The first engine of this type was probably erected in 1742 at the Coalbrookdale ironworks (Hills, 1989, p. 37). Some evidence seems to indicate that is possible that one engine based on this design was installed as early as 1731 at the Lloyd's metal works in Birmingham (Kanefsky and Robey, 1980, p.180).

9 Furthermore, at small sizes, Newcomen engines gave rise to a number of technical problems, see Hills (1972).

10 From these considerations, it seems that Cardwell 's appraisal of the technical and economic potentialities of the Savery engines (see footnote 5) is far too severe.

11 Another maker of this type of Savery engines in Manchester area was Joseph Young. On the fierce competition between the producers of Savery engines and Boulton and Watt, see Musson and Robinson (1969, pp. 394-406).

rights, it is not clear what exactly happened after Newcomen' s invention proved to be suitable of being commercially exploited. Some authors argue that Newcomen was forced to form a partnership with Savery because of the wide scope of his patent. Rolt and Allen (1997) instead put forward a rather different interpretation: Newcomen was actually willing to form a partnership with Savery, so that also his invention could enjoy patent protection for a prolonged period (apparently an agreement between Savery and Newcomen was reached as early as 1705, when the latter was still developing his engine, see Rolt and Allen, 1997, pp. 39-40). After Savery's death in 1715, a stock company named "The Proprietors of the invention for raising water by fire" was formed to exploit the patent rights of the (Savery)-Newcomen steam engine until the expiring date.[12]

2.3. The breakthrough: Newcomen

According to Cardwell (1994a, p. 121) the "first successful steam engine in the world" was the one developed by Newcomen in 1712.[13] The engine developed by Newcomen can be seen as a Papin engine in which the boiler is separated from the cylinder. The layout of the engine was as follows.[14] Steam was created in a boiler (see figure 2.3) connected through a vertical pipe, in which a valve was fixed, to a brass cylinder. The working piston was fitted into the brass cylinder. The piston rod was linked with a chain to the arch shaped extremity of a rocking beam. The other extremity of the beam was connected by means of another chain to the mine pump rod. The arch shaped heads at the extremities of the working beam assured that the two chains were always in vertical position. In addition to the connection with the boiler, at the bottom of the cylinder there were also three other openings: the first one led to a pipe from which a jet of cool water could be sprayed inside the cylinder; the second one to a so-called "eduction pipe", which was used to expel the condensing water from the cylinder, the third one to a particular type of valve which permitted the removal of the air from the cylinder.

At the beginning of each cycle of operations the weight of the pump rod pulled the piston up to the top of the cylinder. At the same time steam (at atmospheric pressure) passed from the boiler to the cylinder. When the cylinder was full of steam, the "steam valve" connecting the boiler and the cylinder was closed and a jet of cold water was sprayed into the cylinder. As a result, steam condensed and a partial vacuum was created inside the cylinder. Atmospheric pressure then pushed the piston down lifting the pump rod by means of the beam.[15] When the piston reached the bottom of the cylinder the condensing jet was turned off. At this point, it was necessary to discharge from the cylinder the condensing water and the condensed steam. This was achieved by allowing some steam to flow into the cylinder after each stroke. This steam pushed the water and

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[12] For more details on the relationship between Savery and Newcomen and on the syndicate of the "Proprietors" of the engine patent, see Rolt and Allen (1997). In 1725, one of the licensees of the patent, Stonier Parrot, tried unsuccessfully to convince a group of mine owners to apply to Parliament for the repeal of the patent, arguing that the Savery and Newcomen engines were two completely distinct inventions (MacLeod, 1988, p. 91).

[13] Thomas Newcomen (1663-1729) was an ironmonger in the town of Dartmouth. The engine was developed in partnership with John Calley, a local plumber and glazier. For more biographical details, see Rolt and Allen (1997), pp. 31-43.

[14] This description of the structure and the working principle of the Newcomen engine draws mainly on Cardwell (1994a), p. 122. For a more detailed description of the various parts of the engine, see Rolt and Allen (1997), pp. 89-106.

[15] For this reason, Newcomen engines were also named "atmospheric engines". The power action was performed by the atmospheric pressure, i.e. the steam did not push the piston, but it merely created a pressure differential underneath.

air away from the cylinder through the "eduction" pipe and the "snifting" valve (this valve was called in this way because of the noise it made). At this point the cylinder could be filled again with steam and a new operating cycle could start. It was soon discovered that it was highly uneconomical to condense all the steam inside the cylinder completely, but it was better to work with a warm cylinder making use of only a part of the force of atmospheric pressure.

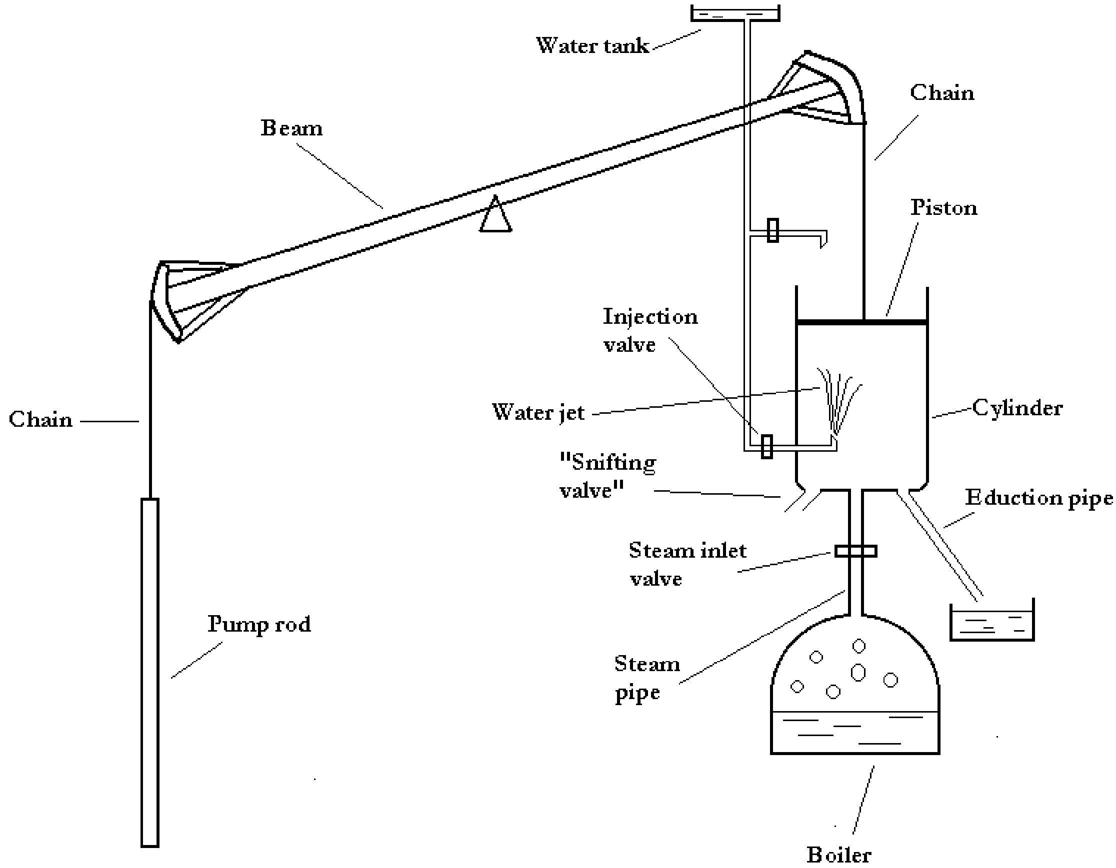

Figure 2.3: The Newcomen engine

The opening and closing of the various valves were performed automatically through an ingenious "working gear" connected to the beam by means of a plug rod (not represented in figure 2.3).[16] Using steam at only atmospheric pressure, the Newcomen engine was well within the limits of the engineering capabilities of the time. The only problem in this respect was due to the fact that it was impossible for the capacity of the workshops of the time to build a cylinder so accurately bored to ensure that it fitted the piston tightly enough to prevent air from entering and ruining the vacuum. However this problem was solved very ingeniously by fixing to the top of the piston a leather disk and further completing the seal by using a layer of water coming from a small tank fixed on the top of the cylinder.

The use of the cylinder and the piston to operate the water-pump made it possible to employ the Newcomen engine for an effective mine drainage as pump rods could be

[16] According to Farey (1827, p.133), the invention of the self-acting valve gear is to be ascribed to Henry Beighton in 1718. Rolt and Allen (1997, p. 90) consider more plausible that the arrangement was introduced by Newcomen himself.

easily extended to reach the necessary depth, overcoming the main limitation of the Savery engine. Moreover, the Newcomen engine was robust and very reliable. Hence, once it was installed, it could work effectively for a long period of time with almost negligible maintenance costs (von Tunzelmann, 1978, p.79).

The technical merits of the Newcomen engine have been aptly summarized by Cardwell:

> It is only fair if we assert some of the outstanding advantages of this remarkable invention seen *in its historical context*, for there is no other way in which we can correctly assess its merits. To begin with, it was, as we have said, the greatest single step forward in the whole history of mechanical power. Its virtues were evident and outstanding: it could be fabricated by local craftsmen without requiring any techniques other than those to which they were well accustomed; only the cylinder and one or two other components might have to come from "specialist" manufacturers – like the famous ironworks at Coalbrookdale - and even the cylinder made little demand on the skills of the time beyond those already acquired for the noble arts of casting and boring cannons. The nature of the beam engine was such that its components did not have to be very accurately aligned. It was simple to operate, no great skill, and certainly no science, being needed by the engineman; and in a country wholly without technical education, this was no small thing. It was wholly reliable: the pressure exerted by the atmosphere never ceases, or even falls enough to impair efficient working. There was little in the engine to wear out. But above all, it was safe, almost completely safe, the safest prime mover ever invented. (Cardwell, 1963, pp. 25-26, italics in the text).

Given these advantages, it is not surprising that Newcomen engines became quite soon of widespread use in mining activities (especially after the expiration of the Savery patent in 1733). In this respect, the diffusion of the engine appears to have been very rapid and geographically wide from the very outset (the overall pattern of diffusion of the Newcomen engine will be examined in detail in the next chapter). Interestingly enough, the "dissemination" of the engine was supported by the early "codification" of a set of rules dictating the proportions of the various parts of the engine. In 1721 Henry Beighton published in *Ladies' Diary* a table reporting the diameter of the pumps and of the cylinder necessary to pump a given quantity of water from a given height. Farey (1827, p. 157) noted that "[a]s..[Beigthon's table]… was arranged in a very convenient form, for the use of persons unaccustomed to calculation, it came into general use".

It must be pointed that the Newcomen engine also had two major limitations. The first one was the high consumption of fuel, which was, like in the Savery engine, determined by the necessity of the alternate heating and cooling of the cylinder during each operating cycle. In coal mining, where large supplies of cheap coal were available, fuel consumption did not represent a serious limitation. In other mine fields (notably in the copper and tin mines of Cornwall, where coal had to be imported by sea) fuel inefficiency hampered a widespread diffusion of the engine. The second was the irregularity of its motion that prevented the use of the engine for applications other than pumping water.[17] In particular the lack of regularity in the motion of the piston made almost impossible the task of producing steady rotary motion from an engine of the Newcomen type. Thus, as in the case of Savery engines, Newcomen engines were used to pump water for powering a waterwheel instead of producing directly rotary motion (Hills, 1989, pp. 32-33). [18]

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[17] The descent movement of the piston was quite irregular: at the beginning of the stroke the movement was slow then it gradually accelerated because of the diminishing resistance encountered. The upward movement was more rapid being achieved with weight of the mine pump rod. See von Tunzelmann (1978), pp. 16-17.

[18] One drawback of "water returning" engines was that the inefficiency of the water-wheel was combined with the inefficiency of the steam engine. See Hills (1989, p. 49).

After the 1720s, technical improvements in the Newcomen engines assumed a predominantly incremental nature. The main direction of improvement was the search for more robust or cheaper materials. Thus, the copper boilers that Savery and Newcomen had originally employed, whose design was based on those used by breweries, began from 1725 to be substituted by much cheaper boilers of hammered wrought iron plates (Dickinson, 1938, pp. 117-118). Similarly, from the early 1720s, in cylinders, cast iron replaced brass. This permitted the construction not only of cheaper, but also of *larger* cylinders. This improvement was due to the new casting techniques introduced by Abraham Darby at the Coalbrookdale company. Thereafter, this company retained a prominent position in the production of cylinders until the 1760s (Kanefsky, 1979, p. 92). By virtue of this innovation, the growing demand for more powerful engines emerging from various mining areas could be positively satisfied. To understand the relationship between power and cylinder size in Newcomen engines, one has to take into account that atmospheric pressure (about 15 psi) constituted the driving agent of the engine. Being atmospheric pressure a constant, the most straightforward way to construct more powerful engines was to increase the size of the area of the cylinder.[19] Figure 2.4 shows the average and the largest diameters of the Newcomen engines erected in Britain during the eighteenth century, calculated over intervals of ten years. The data are taken from an updated version of a comprehensive list of steam engines of all the *known* steam engines erected in Britain in the eighteenth century compiled by Kanefsky and Robey (Kanefsky, 1979; Kanefsky and Robey, 1980). We will discuss the various properties of this dataset in detail in the next chapter.

Between the 1710s and the 1770s, the data exhibit a clear trend towards increasing cylinder diameters.[20] In this period, the limit to the power of the engine "was set by the size of cylinder you could cast, bore and transport" (Cardwell, 1963, p. 27).[21] It is also interesting to note that in the period 1710-1740 the growth in cylinder size took place by means of very small steps. In fact, increases in cylinder size involved a change in proportions of other components of the engine (boilers, valves, pipes, etc.). Over the period 1710-1740, a set of rules of thumbs governing the relative proportions among the various parts of the engine was gradually articulated by means of a slow trial and error process of adaptation of the various components of the engine to variations in cylinder size.

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[19] The power delivered by a steam engine is equal to P x L x A x N, where P is the (mean) pressure of steam in the cylinder, L is the length of the piston stroke, A is the area of the cylinder, N is the number of strokes per minute (Calvert, 1991, p. 43). In the case of the Newcomen engine, because the pressure was constant (at level somewhat lower than the atmosphere due to the imperfect vacuum created inside the cylinder) and, at least before the cataract regulator, the number of strokes was constrained to a rather narrow range of variation (10-12 strokes per minute), the formula could be translated in a very simple empirical rule (which underpinned Beighton's table). Doubling the power of an engine, required to double the area of the cylinder. This means constructing an engine with a radius equal to $\sqrt{2}$ times the radius of the original engine, or, in other words, an increase of the radius of about 40% (Cardwell, 1963, p. 27). Clearly, this calculation does not take into account the loss of power due to friction. According to Farey, Newcomen reckoned the loss of power due to friction and imperfect vacuum to something between 1/3 and 1/4 of atmospheric pressure (Farey, 1827, p. 156). It is interesting to note that from the 1770s cylinders of Newcomen engines were typically made with diameters of 48", 60" and 72" (Farey, 1827, p. 156).

[20] The largest cylinder diameter contained in Beighton's table of 1721 was only 40" (Farey, 1827, p. 157).

[21] The figure of 120" relative to the largest engine for the decade 1780-1790 seems quite suspicious. The information available in the dataset indicates that this engine was erected at Garratt Chorlton in Lancashire, it had a length of the piston of 2 feet and it was used as water returning engine in cotton mill. The maker is unknown.

Figure 2.4: Cylinder diameter of Newcomen engines, 1710-1800

Interestingly enough, Lindqvist contends (1984, pp. 292-293) that one of the reasons at the heart of the unsuccessful transfer of Newcomen engine technology to Sweden in the late 1720s was the decision to install an engine with an almost unprecedented cylinder size (36"). The engine was erected at the Dannemora Mines in 1728 and was designed by Marten Triewald who, by the time, had acquired a rather solid practice in the design and installation of Newcomen engines, having erected several Newcomen engines in the North East of England. Notwithstanding Triewald's experience, the decision to adopt a very large cylinder size proved to be fatal. Although the engine could work, it was prone to continuous breakdowns caused by the defective proportioning of the various components and it was finally dismantled in 1734 discouraging further attempts of using steam power technologies for draining mines in Sweden.

As we will see, from the mid 1770s the introduction of the Watt engine permitted the construction of more powerful engines, without resorting to further increases in the diameters of the cylinders.

The Newcomen engine was brought to its highest state of technical perfection by John Smeaton in the early 1770s.[22] In 1769, Smeaton conducted an extensive inquiry on the performance and the design features of the Newcomen engines at work in the Newcastle district.[23] Subsequently, he built an experimental engine on the premises of his house in Austhorpe. By varying each component of this engine in sequence (and keeping all the others unchanged) Smeaton was able to individuate the best design configuration of the Newcomen engine raising significantly its fuel efficiency. Like Beighton, Smeaton constructed a table indicating the optimal proportions between the various components

[22] For a thorough evaluation of Smeaton's contribution to steam engine technology, see Allen (1981).

[23] In 1779, Smeaton undertook a similar survey on the steam engines at work in Cornwall.. The average duty of this group of Newcomen engines was 7.1 millions (Farey, 1971, p. 92).

of the engine (cylinder diameter, length of stroke, dimension of the pipes, etc.) in correspondence of a given lifting power (Farey, 1827, pp. 183-185).

In his experiments and engine tests, Smeaton adopted two measures of engine performance.[24] Following Desaguliers, he measured the power delivered by the engine (which he termed "great product") as the product of weight and distance in a time unit (i.e. foot-pounds lifted in a minute). For example, according to Smeaton the power delivered by a horse in normal conditions (a common reference at the time) was 23,000 foot-pounds per minute. [25]

Relatedly, the efficiency of the engine (which Smeaton labeled as "effect") was measured in terms of the quantity of water lifted per bushel of coal consumed in an hour. To be more precise, Smeaton measured the *volume* of water raised 1 foot high by consumption of 1 bushel of coal burnt in one hour. Slightly later, Watt devised an analogous measure which he termed "duty" (Farey, 1827, p.337) . This consisted simply in the *weight* of water lifted 1 foot high consuming 1 bushel of coal, or foot-pounds per bushel of coal consumed. Watt's "duty" soon became the most common measure for measuring the fuel efficiency of steam engines. As Cardwell puts it, this notion of efficiency "will be familiar to most people who, on buying a car, take into account the number of 'miles it can do to a gallon' or 'kilometres to the litre'" (Cardwell, 1994a, p.166). Note that bushel is a measure of volume (equal to 2815 cubic inches). Hence, the weight of the coal contained in a bushel varied with the quality of the coal. For example, a bushel of Newcastle coal (which was the one used by Smeaton in his calculations) had a weight of 84 lbs., whereas in Cornwall, where Welsh "high quality" coal was employed, a bushel of coal "weighted" 94 lbs (Farey, 1971, p. 232). From a modern "engineering" viewpoint, duty is a measure of the thermodynamic efficiency of the steam engine.[26] However, duty had also an important economic meaning because it was a measure of the productivity of a steam engine with respect to the item which was in most cases the *largest variable input* used in the production process (von Tunzelmann, 1970, pp. 78-79). The "improved" Newcomen engine erected by Smeaton in 1772 performed a duty 9,450,000 foot-pounds per bushel, almost doubling the results previously attained (the average performance of Newcomen engines in 1769 was 5,590,000 foot-pounds per bushel).[27]

Another defect of the original Newcomen design was the clumsy regulation mechanism. Ideally, one would have wanted the possibility of regulating the number of strokes per minute in relation to the work to be performed by the engine. Smeaton found that Cornish engineers had developed a very effective solution for this drawback, which increased the "flexibility" of an engine of given size. The solution consisted in adding to the engine a small water clock called "cataract" which was used to govern the time interval between two strokes. This cataract operated in such way that, after each stroke was completed, it blocked the piston at the top of the cylinder for the pause required (Farey, 1827, p. 189). Smeaton adopted the cataract in his engines, contributing to make it popular outside Cornwall.

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[24] As Cardwell (1967) and Kroes (1991) have argued, the early elaboration of the "scientific" concepts of power and efficiency was profoundly influenced by these engineering standards. Thus, from the second half of the eighteenth century, one may see that the link between science and technology is beginning to run in a "reverse" direction.

[25] Watt would later devise a similar measure, the "horsepower", which became the accepted standard.

[26] For average quality coals, a duty of n millions of foot-pounds per bushel is approximately equal to a thermal efficiency of 0.15 times n and to a fuel consumption of 170/n per HP-hour (von Tunzelmann, 1978, p. 67).

[27] See Hills (1989), p.131 and von Tunzelmann (1978), pp. 67-70.

Besides these achievements, Smeaton also introduced improvements in the manufacturing processes of the engines. In particular he devised a new type of cylinder boring mill which was first used at the Carron Ironworks in Scotland. The cylinders produced by this machine enabled a further reduction of heat losses and friction, contributing to increase the fuel efficiency of the engine (Rolt and Allen, 1997, p.115).

2.4. James Watt and his rivals

Narratives of Watt's invention of the principle of separate condensation abound and there is probably ground to make the case for considering Watt's invention as one of the most studied "inventive acts" in the history of mankind. Significantly, in laying down his theory of invention, A. P. Usher chose Watt's separate condenser as illustrative example (Usher, 1954, chap. 4). Here, for obvious space limitations, we are forced to be cursory, limiting ourselves to a brief outline of the crucial issues.[28]

As is well known, James Watt became interested in the fuel efficiency of the steam engine while repairing a small model of a Newcomen engine belonging to the University of Glasgow, where he worked as a maker of scientific instruments. Interestingly enough, in his initial experiments, Watt attempted to remedy the fuel diseconomy of the Newcomen engine by means of incremental improvements. He explored the use of alternative materials (he built an engine with the cylinder made of wood), leaving unaltered the overall design of the engine. Watt also fixed the condensing jet in such a way that the quantity of cold water sprayed was exactly sufficient to condense the volume of steam contained in the cylinder. In this way, Watt discovered that attempts of maintaining the cylinder as hot as possible during the operating cycle determined an important loss of power. The reason was that by keeping the cylinder as hot as possible, part of the water sprayed in the cylinder, started to boil (in a vacuum water boils at low temperature)[29]creating additional steam which ruined the vacuum and determined the loss of power.

From his experiments, Watt was able to properly understand the terms of the dilemma he was facing: for maximum economy of fuel the cylinder should have been kept hot, on the other hand, for maximum power it had to be cooled down enough to create a sufficiently "good" vacuum. There was no possibility of escaping this trade-off by means of incremental adjustments in the design of the Newcomen engine. Thus, Watt began the search for a drastically innovative design. His solution (according to the tradition conceived during his usual Sunday walk in May 1765) was to add a second vessel (condenser) where steam condensation could "freely" occur. In historical perspective, one can see the Watt engine as the concluding step in the process of "attribution" of the different functions of the steam engine to distinct components (the boiler, the cylinder and the condenser).[30] For the purposes of the present study, it will be enough to provide

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28 The interested reader is referred to the still valuable book by Dickinson and Jenkins (1927) and to Hills (2002).

29 At that time, the fact that water boils at lower temperatures as the pressure is reduced had already been noted by William Cullen, professor of chemistry at Glasgow University in a paper published in 1756. Watt was aware of this result of Cullen's experiments. However he undertook further experiments in order to get a clear grasp of this phenomenon, see Cardwell (1971), p. 34 and Hills (2002), p. 309.

30 This point was noted originally by Thurston (1939, p. 468) and later by Dickinson : "It is interesting to pause for a moment and reflect upon the differentiation of function of working parts of the steam engine that had taken place. Papin had a piston in a cylinder in which he boiled his water, afterwards condensing the steam slowly in the vessel. Newcomen generated his steam in a vessel separate from the cylinder, but still condensed the steam in the cylinder itself. Watt made use of a boiler and a cylinder like Newcomen,

a description of the working principle of the Watt pumping engine in its final form, when its design was more or less standardised (see figure 2.5).[31]

Watt maintained the rocking beam structure devised by Newcomen. The working cylinder was connected with the separate condenser through a pipe in which a valve (called outlet valve) was fixed. The separate condenser was constituted by a vessel provided with an internal water jet for condensation immersed in a cold water cistern. The condenser was linked to an air pump that served the purpose of eliminating the condensed steam. Finally, another pipe led from the top of the cylinder to the bottom. In this pipe a valve called "equilibrium valve" was fixed. The opening of this valve allowed the passage of steam from the top to the bottom of the piston. In the Watt engine the top of the cylinder was completely closed and the piston rod passed through it by means of a stuffing-box. Thus the piston was pushed down by the steam coming from the boiler into the cylinder and not by atmospheric pressure.

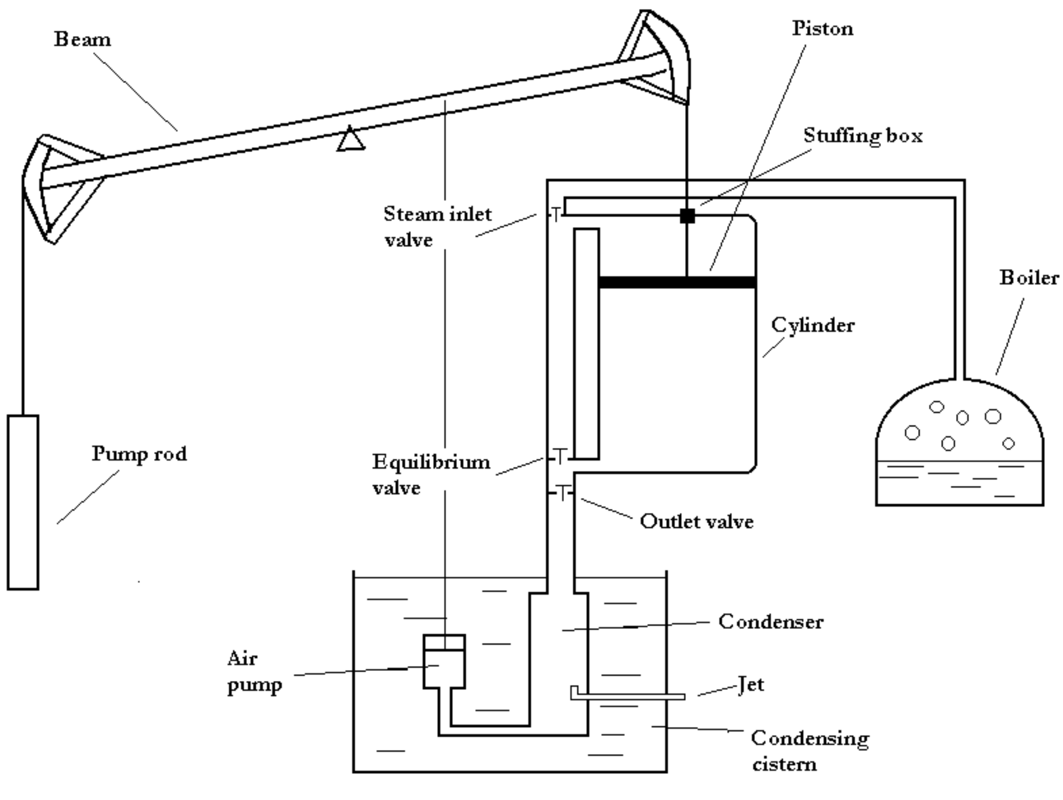

Figure 2.5: The Watt pumping engine

The action of the engine was as follows. Steam (at a pressure slightly higher than atmospheric) was admitted, through the steam inlet valve, into the cylinder where it pushed down the piston. When the piston reached the bottom of the cylinder completing its stroke, the equilibrium valve was opened and steam could pass from the top to the bottom of the piston. At this point, under the weight of the pump rod, the piston rose. The exhaust (or outlet) valve was then opened and the spent steam was admitted into the

but condensed the steam rapidly in an entirely separate vessel. One sees here almost a biological analogy" (Dickinson, 1938, pp. 66-67)

[31] This description of the Watt steam engine draws on Dickinson (1938), pp. 70-71.

condenser. Simultaneously the inlet valve was also opened and new steam was admitted at the top of the cylinder, starting a new operating cycle.

The formulation of the principle of separate condensation gave to Watt the conviction of having identified the "perfect" steam engine design. A perfect steam engine would have employed only one cylinder full of steam (at atmospheric pressure) per stroke and would have condensed the spent steam in a perfect vacuum. As Hills has noted, Watt's elaboration of this concept of a "perfect" steam engine was influenced by eighteenth century ideals of perfection. In particular, Hills suggests that another celebrated contemporary attempt of contriving a "perfect" machine, i.e. a machine capable of reaching the ultimatum in performance, namely John Harrison's "perfect" chronometer that in 1762 lost only 5 seconds after 81 days of sea navigation, might have actually inspired Watt in the ambition of identifying the "perfect" steam engine design (Hills, 2002, pp. 318-319).

The Watt engine required a long period of gestation before the first exemplars of the machine could be successfully installed.[32] This was due to the very compelling requirements on the degree of accuracy of the various components (in particular the valves and the boring of the cylinder) imposed by the Watt engine. From 1774, Watt's invention greatly benefited from the cylinder boring mill developed by John Wilkinson. This new technique allowed the production of cylinders, bored so accurately to assure that only a minimum amount of steam was lost.[33]

In 1769 James Watt was granted a patent for his invention of the separate condenser (more precisely "for a method of lessening the consumption of steam and fuel in fire engines" , Patent 913, 5 January 1769). Following the advice of William Small and Matthew Boulton, who later would become his business partner, Watt wrote the patent specification in terms of "principles of action" without embodying these principles into any specific engine design. As a consequence, the patent resulted extremely broad in its scope, covering all engines using the separate condenser, *but also* all engines using steam, instead of atmospheric pressure as "working substance".[34] Some contemporary engineers, such as Joseph Bramah held that the specification was maliciously kept vague because Watt planned to use the patent strategically, in order to secure himself an unassailable monopoly position in the steam engine market.[35] Although it is absolutely

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32 Watt developed the idea of the separate condenser in 1765. The first full scale engines were built in 1776.

33 On the relationship between the Watt engine and Wilkinson's invention, Scherer has properly noted: "It is frequently stated that Wilkinson's invention was vital to the success of the Watt-Boulton steam engine. This view must be qualified. Surely the engine could have been operated without Wilikinson's cylinders, as the erection of even the few non –Wilkinson engines implies....It is also likely that the Newcomen solution could have been adopted, if Watt had been willing to settle for the additional efficiency provided by his separate condenser and not worry about the loss of heat through the evaporation of sealing water. Thus, it seems more reasonable to conclude that the Wilkinson invention was essential for the level and economic success attained by the Watt-Boulton engine, but that at least moderate success could have been achieved without" (Scherer, 1965, pp. 175-176).

34 During one of the numerous disputes, Watt held that his 1769 patent covered six distinct inventions: i) closed top cylinder, ii) piston pressed down by steam, iii) steam case, iv) separate condenser, v) air pump, vi) piston kept tight by oil (Dickinson and Jenkins, 1927, p. 305). It is easy to see that i) and ii) amount to blocking any engine using steam as driving agent.

35 "Mr. Watt took his patent not for what he had invented, but for what he might invent in future. Thus says he, 'I will lay an indeterminate foundation, which will enable me to lock up the brains and hands of every inventive genius; and if any have the hardihood to stir in the great field of improvement, to make any saving in the expence of fuel….by any means whatever, I will have at them with the hammer of the Law…."(Joseph Bramah, letter to Sir James Eyre, 1797, cited in Robinson and Musson, 1969, p. 207)

true that Watt and his partner Boulton in the last two decades of the eighteenth century made extensive use of the blocking power of the patent, exploiting its wide scope, "it is doubtful if they could have foreseen how all-embracing this patent would be when upheld in the courts" (Hills, 2002, p. 391). More likely, the vagueness of the specification was due to the rather immature stage in which Watt's invention was when the patent was taken.

To develop his invention commercially, Watt initially formed a partnership with John Roebuck. Roebuck paid the debts that Watt had contracted during its experiments and the costs of obtaining the 1769 patent in return of two-thirds of the future profits deriving from the commercialisation of the invention. Roebuck's financial support to the experiments ceased in 1773 when his firm went bankrupt. His partnership with Watt was then taken over by Boulton (at the time one of the leading Birmingham industrialists). The first step taken by Boulton was to make Watt apply to Parliament for an extension of its patent right. The practice of applying to Parliament for the prolongation of a patent was not new (Macleod, 1988, p. 73). In 1775 Parliament promulgated the "Fire Engine Act" which granted to Watt's patent an extension of further 25 years. Thus, since the year in which it was granted (1769), the patent enjoyed a period of protection of 31 years.[36]

The adoption of the separate condenser greatly reduced the fuel consumption of the steam engine. As we have seen, the Newcomen engine as improved by Smeaton was capable of a duty between 7 and 10 millions of foot-pounds per bushel of coal. 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.[37] With such an economy of fuel the use of the steam engine became profitable also in mine fields situated in areas where coal was expensive. The first successful application of the Watt engine was in the copper and tin mines of Cornwall where, as we have seen, the high price a coal had previously prevented a widespread penetration of the Newcomen engine.[38]

In the early 1780s, pushed by the insistence of his business partner Matthew Boulton, Watt conceived a number of modifications to his engine in order to allow the effective transformation of reciprocating into rotary motion. It was abundantly clear to Boulton that the steam engine was about to become a prime mover suitable of being used in a wide range of industrial sectors. In a letter to Watt, Boulton wrote

> There is no other Cornwall to be found and the most likely line for the consumption of our engines is the application of them to mills which is certainly an extensive field (cited in Hills, 1989, p.62)

and in another one dated, June 21, 1781

> [T]he people in London, Manchester and Birmingham are Steam Mill Mad, and therefore let us be wise and take the advantage. I don't mean to hurry you into any determination, but I think in the course of a Month or two we should determine to take out a patent for certain methods of producing Rotative Motions from the vibrating or reciprocating Motion of the Fire Engine….(cited in Robinson and Musson, 1969, p.88).

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[36] The enactment procedure of the 1775 Fire-Engine Act and the related dexterous lobbying actions undertaken by Boulton are well described in Robinson (1964).

[37] In 1792 two Watt engines in Cornwall performed respectively a duty of 32 and 35 millions (Dickinson 1938, p. 87).

[38] "In Cornwall Boulton and Watt made their names, a great deal of money, and learned all about installing and improving steam engines" (Cardwell, 1994a, p. 162.).

Boulton was not alone in envisaging that an effective system for delivering rotary motion would have widened the sphere of application of the engine. [39] An early attempt in this direction was made by Joseph Oxley in 1762 by means of the application of a ratchet and pawl mechanism to a Newcomen engine. The ratchet and pawl was a well known mechanical device for transforming reciprocating in rotary motion. The ratchet was a wheel with slanting teeth, whilst the pawl was a lever perpendicular to the wheel. At every stroke the pawl caught in one of the teeth making the wheel turning. Not surprisingly, the movement was very clumsy and the engine was subjected to continuous breakdowns, so that after a while it was reconverted to a water returning type (Dickinson, 1938, p. 64). In 1779, Matthew Wasbrough constructed another Newcomen rotary engine equipped with a ratchet and pawl mechanism. Wasbrough used a flywheel to regulate the motion of the engine. Just after that, James Pickard replaced the ratchet and pawl with a crank and a connecting rod maintaining Wasbrough's flywheel. He patented this device in 1780. The arrangement was successful and soon after rotative Newcomen engine began to be built in some numbers. In certain circumstances they proved to be capable to resist the competition of the Watt rotary engine. From the 1790s, in applications where a particularly regular motion was needed, Newcomen rotary engines using crank and flywheel were erected on a two cylinders design. This design modification was purported to remedy the very irregular motion of the piston of the standard Newcomen engine. In these engines the two pistons acted in alternation on the beam, somewhat mimicking the double acting motion of Watt rotary engine and providing a more regular movement of the beam. Engines of this type were employed rather successfully in Lancashire where they were introduced by Francis Thompson and Bateman and Sherrat.

Pre-empted by Pickard in the use of the crank, Watt was forced to develop a series of alternative mechanical devices to convert reciprocating in rotary motion, which he patented in 1781. The most effective of these devices was the so-called "sun and planet" gear. The apparatus consisted in a wheel ("planet") rigidly attached to the end of the connecting rod. This wheel rotated round a second wheel ("sun") which was attached to the driving shaft transmitting the stroke of the piston (Dickinson and Jenkins, 1927, pp. 156-158). [40]

The transformation of the reciprocating motion into a steady rotary one was also enhanced by the development of double-action (i.e., the admission of steam on both sides of the piston), which Watt patented in 1782. Double action also permitted to roughly double the power of the engine for a given cylinder size. In this respect, it is significant that the increasing trend in cylinders size was brought to a halt in the 1780s, simultaneously with the diffusion of the Watt engine (Kanefsky and Robey, 1980, pp. 183-184). Double action imposed another modification to the engine layout. The double acting engine needed a rigid connection between the beam and the piston rod. To ensure that the piston rod moved on a straight line, Watt had to contrive an ingenuous mechanical device called "parallel motion".

[39] The 1770s and 1780s were characterized by a sort of explosion of inventive activity in steam technology. Remarkably, in a letter to Boulton dated 13/16 February 1782, Watt wrote "…I don think that we are safe a day to an end in this enterprizing age. One thoughts seem to be stolen before one speaks them. It looks as if Nature had taken up an adversion to Monopolies and put the same things in several people heads at once to prevent them…." (cited in Robinson and Musson, 1969, p. 96).

[40] After the expiration of Pickard 's patent in 1794, Boulton and Watt generally adopted the crank and the flywheel in their rotative engines (Dickinson 1938, p.82)

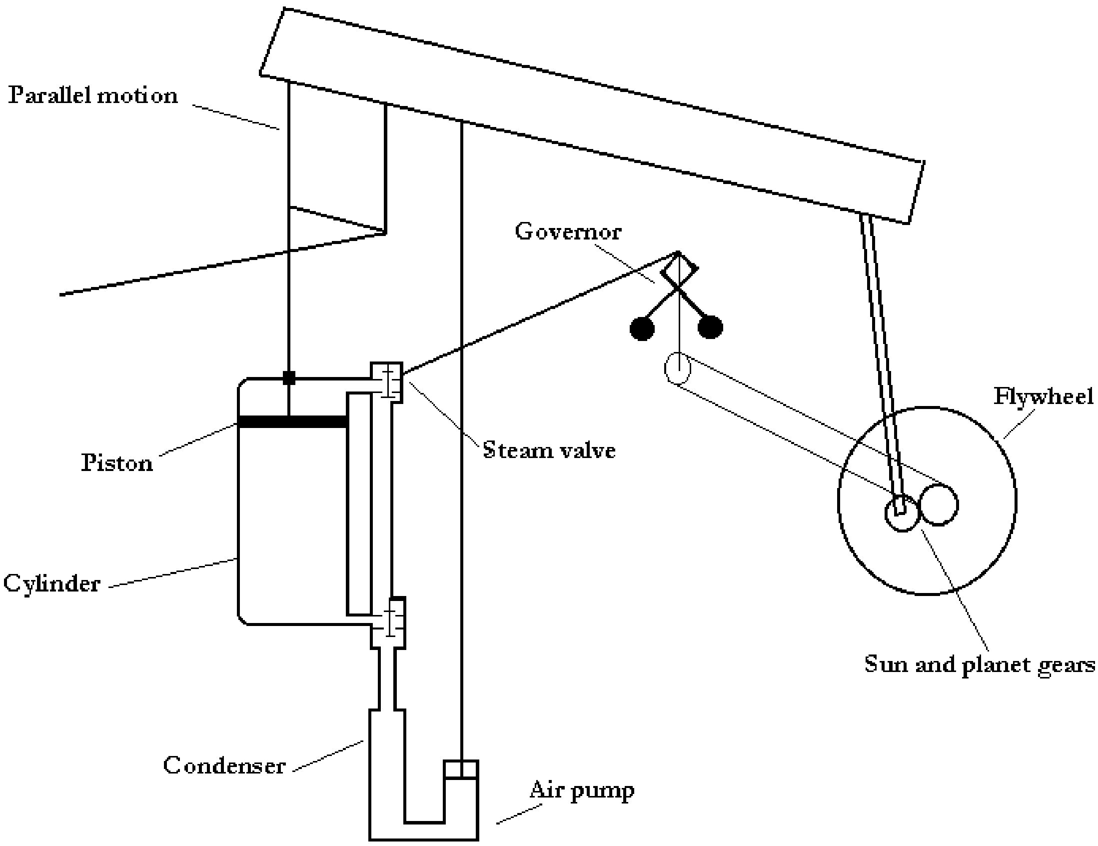

Figure 2.6: The Watt double acting rotary engine

Finally, to achieve an effective regulation of the motion of the engine Watt introduced the fly-ball governor. [41] This consisted in two weights fixed on a rotating spindle driven by the engine: as the two weights moved outwards because of the centrifugal action, they gradually close the steam inlet valve until the engine reached the desired speed.
Figure 2.6 contains a diagram illustrating the layout of the Watt double acting and its constituting components.

Incorporating all these improvements, the Boulton & Watt double acting rotative engine became an effective technical solution for the provision of rotary power. Up to 1800 (date of expiration of the Watt's patent of the seperate condenser) , Boulton & Watt had built 496 engines, of which 38 per cent were pumping and 62 per cent of the rotative type.[42] The rotary engine also proved to be commercially successful, opening new application fields to steam engines and confirming the validity of Boulton' s business intuition.

The rapid growth of the "rotary" segment of their business made it necessary for Boulton and Watt to establish a measure of the power delivered by their steam engines. This was the "horsepower" which Watt fixed at 33,000 foot-pounds per minute. On the basis of this unit some generic rules of thumbs indicating the power requirements of various production processes began to emerge (e.g., in cotton spinning, 1 HP for every

[41] The fly-ball governor was already used in wind mills. In this case, Watt's contribution consisted in the adaptation of the governor to the steam engine.
[42] Hills (1989), p. 70. On the early diffusion of the Boulton & Watt double-acting rotary engine see Hills (1989, chap. 5)

100 spindles) facilitating the penetration of the steam engine in a number of industrial applications (Hills and Pacey, 1972).

Rivalry to Boulton and Watt engine was by no means limited only to rotary engines. In the 1780s, also new type of pumping engines were developed. William Symington, with aim of improving the fuel efficiency of the Newcomen engine without renouncing to its simplicity in construction and maintenance, took a patent in 1787 for an "improved atmospheric" engine where condensation took place at the bottom of the cylinder.[43]

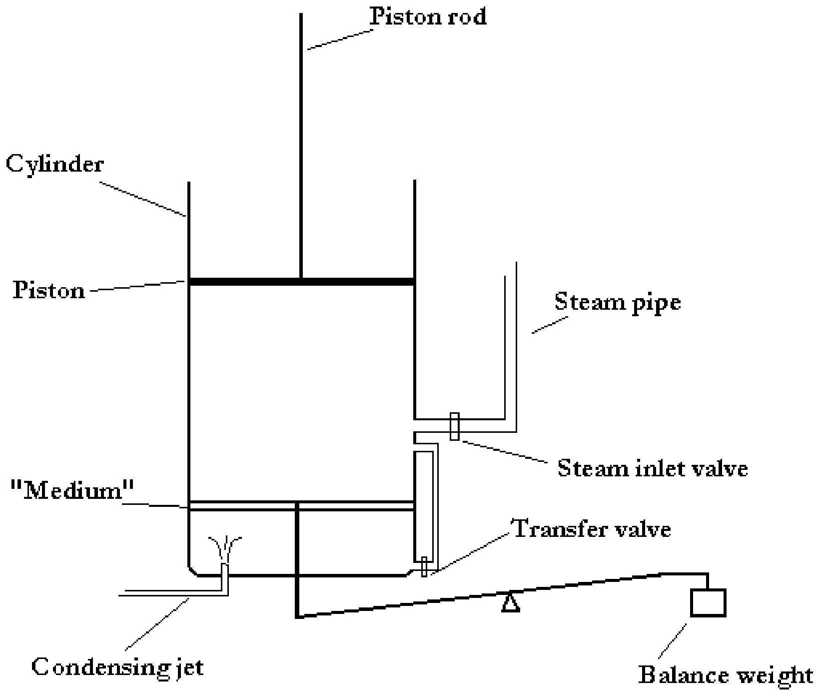

Figure 2.7: The Symington pumping engine

In the Symington engine, the bottom of the cylinder was separated from the upper part (which, in this way, could be kept always warm, avoiding cooling and reheating) by a floating piston (called "medium"), which acted as an air pump expelling the condensate when it was pushed down by the main piston. Steam was admitted in the cylinder between the main piston and the "medium". A system of valves ensured that the steam could pass below the "medium". The top of the cylinder was open and, like in the Newcomen engine, the main piston was pushed down by the atmospheric pressure acting against the vacuum created under the medium (see figure 2.7).

In 1788 Symington converted a 36" Watt engine installed at the Wanlockhead lead mines to his design. After the alteration, the engine delivered the same power with "somewhat less" coal consumed (Harvey and Downs-Rose, 1980, p.30). Following this successful trial, another engine on Symington design was erected in 1790 at the same mine.

43 The following description of the Symington engine is based on Harvey and Downs-Rose (1980 pp 19-33).

In the Boulton and Watt collection in Birmingham, it has been found an unsigned note (probably compiled by a one of Boulton and Watt's agents) reporting some comparative results of the Watt and Symington engines installed at the Wanlockhead mine undertaken in 1791. These results are summarized in table 2.1.

Table 2.1: Comparative trials of Watt and Symington engines

Engine type	Watt	Watt	Symington	Symington
Cylinder diameter	36"	58.5"	36"	44"
Duty (millions of foot-pounds per bushel of coal consumed) performed in the trials.	22.2	20.5	16.6	17.1

Source: Harvey and Downs-Rose (1974, p.29).

Overall, the table shows that the two Watt engines had a superior fuel efficiency. It is important to note, however, that in these trials, Symington engines performed substantially better than the Newcomen engines as improved by Smeaton (capable of duties around 10 millions). If we take into account the greater simplicity in construction and operation of the Symington engine with respect to Watt this is by no means a minor achievement.

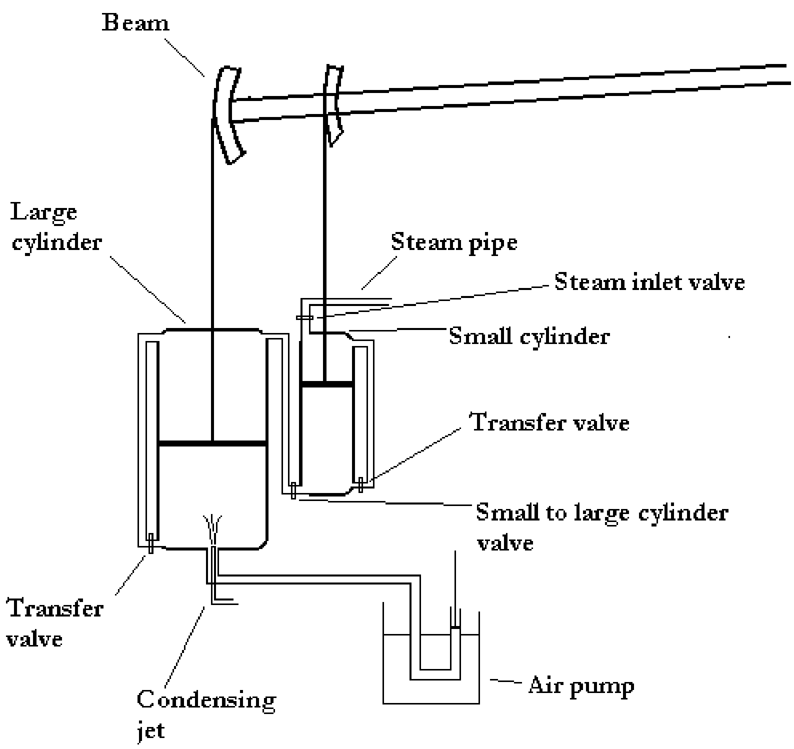

Figure 2.8: The Hornblower compound engine

In retrospect, the most important of Watt's rivals was Jonathan Hornblower, the grandson of Joseph Hornblower who constructed the first Newcomen engine in the Cornish mining district. In 1781 he took a patent for a new pumping steam engine. In Hornblower's engine steam (at atmospheric pressure) was expanded consecutively into two cylinders, one larger than the other (principle of compounding). More precisely, first steam was admitted in the small cylinder where it pushed the piston down. After having completed this stroke, it passed into the larger cylinder where it expanded forcing the second piston down. In the same moment, in the bottom of the larger cylinder the "residual" steam of the previous stroke was condensed by a water jet, further facilitating the descent of the piston (see figure 2.8).

Hornblower's engine is thus to be considered the first compound design. Compound expansion can generate concrete advantages in terms of fuel efficiency for steam pressures above 60 psi. As we will see, this is a trend of development which took off from the 1840s-1850s (Hills, 1989, p.160). The Hornblower engine was clearly working at too low pressures for reaping such gains.

Nevertheless, the Horblower engine was capable of a performance in terms of coal consumption fully comparable with that of the Watt engine.[44] Hornblower found the further development of his invention obstructed by the actions of Boulton and Watt who deemed that the salient features of his invention were a "direct and palpable plagiarism"[45] of Watt's patent. We will deal in more detail with the conflict between Watt and Hornblower in chapter 5.

Another improvement due to Boulton and Watt was the replacement of the wooden beam with the elliptical cast iron beam.[46] Cast iron beams had a number of advantages: they were less expensive than timber, they were more suited to resist tropical climates (the sugar cane industry in the West Indies was an important market for Boulton and Watt) and they responded to growing fireproof concerns in textile mills (Andrew et. al., 1999).

Finally, Watt introduced another mechanical device which was of great importance for the subsequent development of the steam engine technology: the indicator.[47] The indicator was constituted by a small cylinder, in which a small piston was fitted. A pencil was attached to the piston rod. The pencil could draw on a paper sheet that was attached to a board. The small cylinder was in communication with the engine cylinder. In this way, the movement of the pencil could be used to record the pressure inside the cylinder. The board also moved in accordance with the displacement of the engine piston.

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[44] In trials effected in 1791 an Hornblower engine performed duties of 14.8 and 27.2 millions (Farey, 1827, p. 388).

[45] Hornblower's invention was described in these terms in a printed *Short Statement, on the part of Messrs..Boulton and Watt, in opposition to Mr. Jonathan Hornblower's Application to Parliament for an Act to prolong the Term of his Patent,* see Robinson and Musson (1969), p.160.

[46] Cardwell (1994a, p. 208) tributes this invention to the Aydon and Elwell company near Bradford in 1795.

[47] The indicator was actually invented by John Southern, who was one of Watt's assistants. This description of the indicator draws on Dickinson (1938) , pp.85-86.

Table 2.2: Technological progress in steam engines, 1700-1800

"Locus" of innovation	1700-1710	1710- 1720	1720 – 1730	1730-1740	1740- 1750	1750-1760	1760 - 1770	1770 – 1780	1780 –1790	1790 – 1800
Engine design	Savery (1698)	Newcomen (1712); Savery engine with direct injection of water (Desaguliers, 1717);					Improved Savery (Blakey, 1766); Separate condenser (Watt, 1769);	Water returning Savery (Wrigley, 1780)	Hornblower compound (1781); Watt double acting (1785); Symington (1787);	Newcomen double cylinder (Thompson,1790);
Regulation		Self-acting working gear (Newcomen, 1712);					Self acting working gear for Savery engine (Blakey); Cornish cataract;	Boiler water feeder (Watt);	Flyball governor (Watt, 1788); Boiler water feeder (Watt);	Boiler fire regulator (Murray,1799);
Valves and other critical components							Condenser (Watt); Air pump; (Watt); Stuffing Box (Watt);	Counter (Watt, 1775); Drop valve (Watt); Piston packing (Watt);		Indicator (Southern, 1797); Slide valve (Murdoch, 1799);
Materials		Wooden frame; Wooden beam; Brass cylinder; Copper boiler;	Cast iron cylinders (1722); Wrought iron boiler (1725);							Elliptical cast iron beam (Boulton & Watt, 1797); Cast iron bedplate (Murray,1802);
Boilers		Haystack boiler						Waggon boiler (Cornish engineers and Watt); Water-tube boiler (Blakey,1776);		
Power Transmission					Newcomen water returning (Coalbrookdale, 1742);		Ratchet and pawl mechanism (Oxley, 1762);	Flywheel (Wasbrough, 1779);	Crank and flywheel (Pickard 1780); Sun and planet gear (Watt 1782); Parallel motion (Watt,1784);	
Production processes							Cylinder boring mill (Smeaton, 1769);	Cylinder boring mill (Wilkinson, 1774);		Cylinder boring mill (Murray,1795);

In this way, the indicator produced a closed diagram describing changing steam pressures and volumes during the piston stroke. The area of the diagram represented the work done by the engine and it could be used to calculate the (effective) horse-power delivered.[48,49]Although, it was simply a measurement device, the historical importance of the indicator ought not to be underestimated. By providing a detailed account of what was happening in the cylinder at each point of the stroke, the indicator paved a significant part of the way towards the establishment of a scientific understanding of the action of the steam engine (Bryant, 1973, p. 158).

Table 2.2 provides a summary view of the technological evolution of the steam engine over the course of eighteenth century (obviously in many cases, dates are to be regarded as approximate).

2.5. The rise of thermodynamics

At this juncture, it is probably useful to provide the reader with a brief overview of the historical development of the scientific understanding of the functioning of the steam engine. Most of the early scientific contributions in this field were actually stimulated by the differences in performance between high pressure and low pressure engines. Thus, *in a rigorous historical perspective*, it would be appropriate to place this section after the discussion of early nineteenth century evolution of steam power technology. Yet, we have chosen to anticipate the discussion of the early development of thermodynamics, because we believe that the reader may actually benefit from considering nineteenth century technological developments, with the advantage of hindsight (that is, against the background of subsequent scientific developments).

In the early nineteenth century the predominant scientific theory of heat stated that heat was constituted by a material, imponderable and invisible fluid termed “caloric”. This fluid permeated material bodies surrounding all particles of matter. Caloric was a self-repellent fluid so that it tended to separate the atoms of the matter which it surrounded causing bodies or liquids to expand or dilate. On the other hand, caloric was also attracted by other material bodies, so that when it was released it displayed the tendency to penetrate into them (this could account the rise in temperature of a body which was put in contact with another body at a higher temperature). The quantity of caloric contained in a material body was released when this was burnt. Most importantly, caloric was indestructible, so in a given “closed” system the quantity of caloric was constant (Hills, 1989, pp. 164-165).[50]

Interestingly enough, the idea of “conservation of heat” had received some support also by the study of the workings of the steam engine. As we have noted above, Watt

[48] The indicator was extremely helpful in achieving the optimal valve settings of the engine (Hills 1989, pp. 92-93).

[49] The indicator was developed in 1796. The invention was not patented and kept as trade-secret inside the Boulton & Watt company. It became public about 1826 (Cardwell 1994a, p. 215).

[50] A particularly terse appraisal of the merits of the caloric theory of heat has been provided by Cardwell (1971, pp. 95-96): “At the beginning of the nineteenth century the material theory of heat in the form which Lavoisier had formulated it was well established in France and, by virtue of the high prestige of French science, was increasingly accepted elsewhere. The merits of the theory were considerable, for it provided a very convincing explanation of the process of thermal expansion in solids, liquids and gases; it accounted for the latent heats of fusion and vaporisation and it harmonised very well with the phenomenon of compressive heating or expansive cooling of a gas – indeed the picture of material heat being squeezed out of a gas was a particularly persuasive one.....Beyond all these advantages, the caloric theory held out some hope that a major correlation of human knowledge might be achieved if the phenomena of heat, electricity and light could all be shown to be the effects of some ultimate substance.”

performed a number of experiments in which he calculated the total amount of heat (sensible plus latent, the latter consisting in the heat absorbed by a substance when it changes its state without increases of temperature) contained in steam at various pressures. These experiments seems to indicate that the total heat was constant (not dependent on the pressure). A result that in the later scientific literature became known as "Watt's law" (Cardwell, 1971, pp. 52-55).

Implicit in Watt's analysis of the steam engine, there was also the idea that the motive power of the machine was the outcome of heat flowing through the machine from the boiler to the condenser (Cardwell, 1971, p. 89). In this regard, George Lee, an industrialist of Salford near Manchester performed a number of experiments on one of the Boulton and Watt engines installed in his cotton mill. Lee endeavoured to calculate the quantity of heat supplied by the boiler and compared it with the one received by the condenser. His experiments showed that the two quantities were indeed very close,[51] supporting the idea of a constant quantity of heat flowing through the system (Pacey, 1974). In other words, at every stage of its passage in the machine, steam contained the same quantity of heat.

Late eighteenth century and early nineteenth century engineers were, by and large, not particularly conversant with the subtleties of the caloric theory of heat. In this respect, their knowledge was essentially limited to the fundamental properties of heat and of expansion of gases. They had, instead, a much more intimate knowledge of the behaviour of hydraulic machines, in particular water wheels (Cardwell, 1978, pp. 112-113). For this reason, it was rather natural for them to couch their analysis of the mechanical work accomplished by the steam engine, in terms of hydraulic analogies, mostly equating steam pressure to water pressure or weight. Hence, the functioning of the steam engine was often accounted for by means of a water wheel's analogy. The pressure of steam was the counterpart of the "fall" of the water. If the analogy was correct, the same amount of horsepower could have been delivered as efficiently by a large quantity of water flowing from a small height or from a small quantity of water flowing from a great height (Hills, 1989, p.165). Accordingly, up to the 1850s, the steam engine was essentially conceived as a *vapour-pressure* engine (Hills, 1989, p. 162). In this view, it was the elasticity (pressure) of steam to cause the engine to perform mechanical work. The role of heat was subordinate, merely to ensure the transformation of water into an "elastic" fluid capable of accomplishing mechanical work.

As is well known the first formulation of the basic principles of thermodynamics is due to Sadi Carnot in 1824. In his book *Reflexions sur la Puissance Motrice du Feu*, Carnot retained the hydraulic analogy, but he expressed it in terms of steam *temperature* rather than steam *pressure*. In particular, Carnot elaborated, as a reference term, the concept of a perfect engine. This engine can be thought as constituted by a cylinder of non conducting material (excluding the base) in which a piston is fitted.[52] The other components of the engine are a heat source (which delivers heat at the temperature t_1) and a receiver (condenser, which has the temperature $t_0 < t_1$). The cylinder contains

[51] Lee's interpretation of the results of the experiments was misled by the low thermal efficiency of the Watt engine (about 2.5%). In this case, assuming that the same amount of heat was lost in various ways (pipes, etc.), about 95% of the heat would have been received by condenser. Lee's procedures were, of course, too inaccurate to point out systematically the existence of such a difference (Pacey, 1974, pp. 140-141).

[52] The discussion of the Carnot and Rankine cycles presented in this section draws mainly on Ewing (1910).

water that converted into steam will act as driving agent. The operation of the engine is as follows. In the first phase the cylinder is put in contact with the heat source. Water is transformed into steam, expanding its volume (movement AB in figure 2.9). This phase is termed isothermal because the temperature level remains constant. In the second phase, the heat source is removed from the base of the cylinder. Steam will continue to expand its volume adiabatically (this means that in this phase steam expands without any heat transfer to or from its surroundings). In this phase both the pressure and the temperature will progressively decrease (movement BC in figure 2.9). When steam has reached the temperature level t_0, the base of the cylinder is put into contact with the receiver. The steam now is compressed and begins to be condensed. This phase is again isothermal (the temperature remains constant at the level t_0). In this phase, the volume of the steam is reduced and its pressure remains constant (movement CD in figure 2.9). Finally, the receiver is removed from the base of the cylinder. The compression of steam is continued. This phase, which "closes", the cycle is again adiabatic. The cycle is concluded when steam is restored into water at the original temperature t_1.

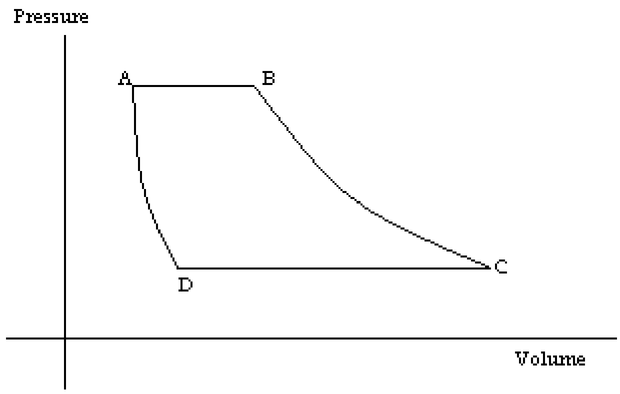

Figure 2.9: Carnot's cycle for a steam engine

It is possible to show that the work accomplished during the cycle is represented by the area ABCD on the pressure volume diagram represented in figure 2.9. Furthermore, it can be proven that no other cyclical process operating between the same temperature limits can be more efficient than the Carnot cycle. The efficiency of an engine working on the Carnot cycle is given by $\frac{t_1 - t_0}{t_0}$ where the temperatures are expressed in absolute (Kelvin) degrees.

On the basis of the cycle of his "ideal" engine, Carnot could set out an analysis of the operation of the steam engine as a *heat* engine. It is worth quoting at length his conclusions:

It is easy to imagine a host of engines suitable for developing the motive power of heat through the use of elastic fluids. But whatever approach is adopted, we must not lose sight of the following principles:

1) The temperature of the fluid must first be raised as high as possible, in order to secure a large fall of caloric and thereby the production of a great amount of motive power.
2) For the same reason, the cooling must be carried out as far as possible
3) We must see that the passage of the elastic fluid from the highest to the lowest temperature is brought about by an increase in volume. In other words, we must see to it that the cooling of the gas is a spontaneous consequence of rarefaction (Carnot, 1824, pp. 102-103)

When he wrote his succinct treatise on the operation of the steam engine, Carnot was a relatively peripheral figure in the French scientific community. In addition, his argument based on the relatively abstract notion of an "ideal" engine, did not result particularly palatable to contemporary steam engineers. For these reasons, his findings passed by almost unnoticed and had no effect on steam engineering practice. Carnot's *Reflexions* were first "rediscovered" in 1834 by Clapeyron, and later on, in 1848, by William Thomson (Lord Kelvin) who finally gave to Carnot's work the credit it deserved. [53]

In the 1840s, James Joule by means of a series of experiments was able to demonstrate the actual conversion of mechanical work into heat. Joule experimental apparatus consisted in a paddlewheel which was employed to stir the water contained in a vessel. The movement of the paddlewheel was delivered by a weight falling under action of gravity. In this way, it was possible to calculate rather easily the amount of mechanical work accomplished by the paddlewheel. The change in heat was measured by the increase in the temperature of the water stirred by the paddlewheel in the vessel.[54]

The results of Joule's experiments on the conversion of heat into work and the Carnot's analysis of the operation of the steam engine were reconciled by Rudolph Clausius in 1850. The reconciliation required the definitive abandonment of the caloric theory of heat. Heat, as shown in Joule's experiment is a form of energy. In the operation of the steam engine, heat is not conserved, but it is converted into mechanical work. In other words, the engine acts as a converter of thermal energy into mechanical energy. The principle of the conservation of heat was replaced by the principle of the conservation of energy. Clausius was able to show that Carnot's analysis of the operation of the heat engine in terms of a closed cycle of operations could be made consistent with Joule's experimental results on the nature of heat.

Clausius, in his works, published in a number of scientific papers in the early 1850s, provided an elegant mathematical formulation of the new theory of heat and of the processes of energy of transformation. However, he did not devote much space to work out the implications of the new theory of heat for practical engineering design. This was done instead by William Rankine, professor of engineering at the University of Glasgow. Rankine in 1859 published a treatise (*Manual of the Steam Engine and Other Prime Movers*) which had the explicit goal of exposing the recent advances in the understanding of the nature of heat in terms accessible to practical engineers. Furthermore, he also outlined a number of practical design implications which were suggested by the new theory.[55] It is important to remark that the contribution that the recently established field of thermodynamics (as "popularized" to engineers by Rankine) provided to steam engineering was to provide a set of *broad* prescriptions for the design of efficient steam engines, namely maximize the range of steam expansion between the working temperatures, avoid useless heat losses, etc. These fairly general prescriptions had to be applied taking into account the design constraints arising from the context of application of the engine, the physical properties of steam expansion and most of all the condensation of steam due to contact with the walls of the cylinder (Bryant, 1973; Hills and Cardwell, 1976). Thus, from the mid nineteenth century when the functioning of the steam engine was finally understood from a thermodynamic point of view, in actual

[53] On the neglect and successive rediscovery of Carnot's *Reflexions*, see Fox (1986).

[54] The experiments were conducted in the period 1845-1850. In 1850 Joule published a paper "On the mechanical equivalent of heat" on *Philosophical Transactions of the Royal Society* summarising the results and the implications of his experiments.

[55] For an appraisal of Rankine's scientific and engineering contributions, see Hutchinson (1981).

design practice it remained necessary to combine the scientific conception of the operation of the steam engine with engineering rules of thumbs based on the extrapolation of previous experiences.[56]

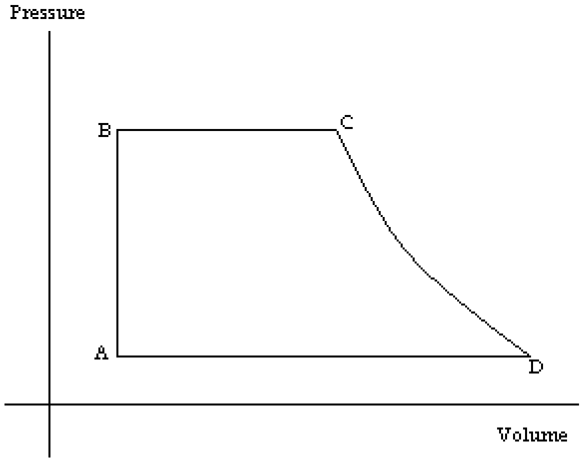

Figure 2.10: Rankine's cycle for a steam engine

Another contribution of Rankine was to devise a cycle of operations of a steam engine which could have been effectively used to evaluate the relative efficiency of different engines. The idea underlying the Rankine's cycle was to provide engineers with a yardstick indicating the maximum efficiency for a "practical" steam engine, working between two given operating temperatures. The cycle (depicted in figure 2.10) begins with the quantity of water in the cylinder at temperature t_0 and at pressure p_0. As in Carnot's cycle a hot body is applied to the base of the cylinder containing water. Consequently, pressure and temperature rise respectively to the levels p_1 and t_1 (movement AB in figure 2.10). At point B, water is transformed into steam. In this phase (isothermal), both temperature and pressure remain constant (movement BC in figure 2.10). At this point the hot body is removed and steam is expanded adiabatically until it reaches the pressure p_0 (movement CD in figure 2.10). Finally, the cold body is put in contact with the cylinder so that steam is condensed and reconverted in water; this transformation is again isothermal (movement DA in figure 2.10). As in figure 2.9, the work performed by the piston is given by the area ABCD. As it is possible to see by comparing figure 2.9 and figure 2.10 the difference between the Carnot and the Rankine cycle is that the latter excludes the final phase of adiabatic compression. In fact, in actual steam engines the separate condenser makes this phase impracticable (Ewing, 1910, p. 100). The efficiency of the Rankine cycle is lower that the one attained by a Carnot cycle working on the same range of temperatures precisely because the absence of adiabatic compression makes it necessary to provide additional heat to the steam to reach the upper working temperature t_1 (Ewing, 1910, pp. 104-105).

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[56] See Cardwell (1994a, pp. 313-318). Hunter (1985, pp. 436-437) remarks: "This emerging body of theory [thermodynamics] was hardly suited to the understanding and needs of practical men, being much too abstract for general understanding and concerned more with the ideal engine of theory than the actual engine in practical use....". In a particularly insightful discussion, Unwin (1895) distinguishes between "rational" theory of the steam engine (describing the working of the steam engine according to scientific thermodynamics) and "experimental" theory of the steam engine (based on the empirical testing of the working of steam engines under different conditions). Unwin's account shows how many prescriptions for engine improvement originated in the "experimental" rather than in the "rational" theory.

Although scientific advances in the theory of heat exerted a restricted impact on design practice, it should also be mentioned that they provided precious suggestions for setting up rigorous procedures for evaluating steam engine performances. In this field, from the second half of the nineteenth century, "scientific" procedures for the assessment of the performance were progressively integrated with engineering criteria. As we have previously mentioned, in the second half of the eighteenth century, Smeaton and Watt had developed "duty" as measure of the efficiency of the steam engine. Duty was a rather straightforward measure for assessing the performance of pumping engines. In case of engines employed in other applications, to calculate duty was necessary to convert the mechanical work performed by the engine in millions of lbs. lifted one foot high.[57] As such, duty was a measure of the performance of the overall machine system, that is boiler – engine - pump (or the other mechanical device powered by the steam engine in question). Duty could not assess the efficiency of the various components of the engine. In 1838 Josiah Parkes proposed another measure aimed at gauging the efficiency exclusively of the engine. Parkes' proposed measure was the amount of lbs. of steam used per HP-hour.[58] The new measure permitted to judge individually the performance of the engine and that of the boiler. After the 1850s, with the establishment of the idea that in the steam engine heat is converted into work, engineers elaborated a number of increasingly more sophisticated accounting procedures ("heat balances") for tracking the heat as it passed from the boiler to the condenser (Bryant, 1973, p. 158).[59] The thermodynamic understanding of the steam engine finally led to measure the efficiency of steam engines in terms of their *thermal efficiency*. The new procedures were definitely codified by Henry Sankey in 1896 in a paper published on *Minutes of Proceedings of the Institution of Civil Engineers*. According to these procedures, the efficiency of a steam engine ought to be expressed as percentage of the thermal efficiency of an engine working on a Rankine cycle between the same temperatures.

2.6. Nineteenth century developments in steam engine technology

In his patent of 1769 Watt had suggested the idea of expanding steam before condensation. The idea behind the adoption of the principle of expansion was that of fuel economy (allowing the "expansive force" of steam to perform some of the overall work). This was done by cutting off the steam when the piston was at the beginning of its course and letting the expansion of the steam inside the cylinder complete the stroke. However, in order to achieve some gain in fuel efficiency using steam expansion, higher pressures than atmospheric ones ought to be employed (at low pressures, the gain in efficiency was bound to be very limited).[60]

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[57] A measure analogous to duty which was commonly used for assessing the performance of non-pumping steam engines was the number of lbs. of coal consumed per HP-hour.

[58] Actually, Parkes' measure was the weight of boiler feed water (which was assumed to correspond to the steam) generated (Cardwell, 1994b, p. 117).

[59] Gustave Adolphe Hirn by means of heat balances confirmed experimentally that the amount of heat consumed by a steam engine corresponds to the mechanical work performed. Hirn was one of the first engineer to propose the adoption of thermal efficiency (heat energy transformed into work divided by total heat energy supplied) as a measure of the performance of the steam engines (Cardwell 1994b, pp. 120-121).

[60] High pressure expansive engines have a higher fuel efficiency than low pressure ones because they operate between a wider range of operating temperatures. In the words of Carnot (1824, p. 104): "The reasons for the superiority of what we call high pressure engines over engines operating at a lower pressure are now evident. Their superiority lies essentially in their ability to utilize a greater fall of caloric. Since steam that is produced at a higher pressure is also at a higher temperature, and since the temperature of condensation always remains much the same, the fall of caloric is obviously greater. But, in order, to derive really advantageous results from high-pressure engines, the fall of caloric must be used in the best possible way. It is not enough that the steam should be formed at a high temperature; it is also essential that,

Watt was strongly adverse to the use of high-pressure steam. He was afraid of the possible negative consequences in terms of "popularity" of boiler explosions, fearing that this could have discredited the use of steam power irreparably.[61] After the expiration of Watt' s key patent in 1800, however, engineers were free to begin the exploration of the high-pressure *cum* expansion trajectory. The pioneers in this domain were Richard Trevithick and Arthur Woolf in England and Oliver Evans in the United States. In the following, we will deal mainly with the contribution of Trevithick and Woolf, which is the most relevant for our purposes.[62][63]

For the generation of high pressure steam, new types of boilers had to be designed. From the late 1770s the "waggon" wrought iron had begun to replace the old "haystack" boiler which had been in use since Newcomen. Broadly speaking, the waggon boiler was a stretched version of the haystack. Its main advantage with respect with its predecessor was that it had a slightly higher ratio of heating surface to capacity, allowing a reduction in coal consumption. However, waggon boilers could not withstand high pressure. So with the first introduction of high pressure engines, engineers had to look for new designs.

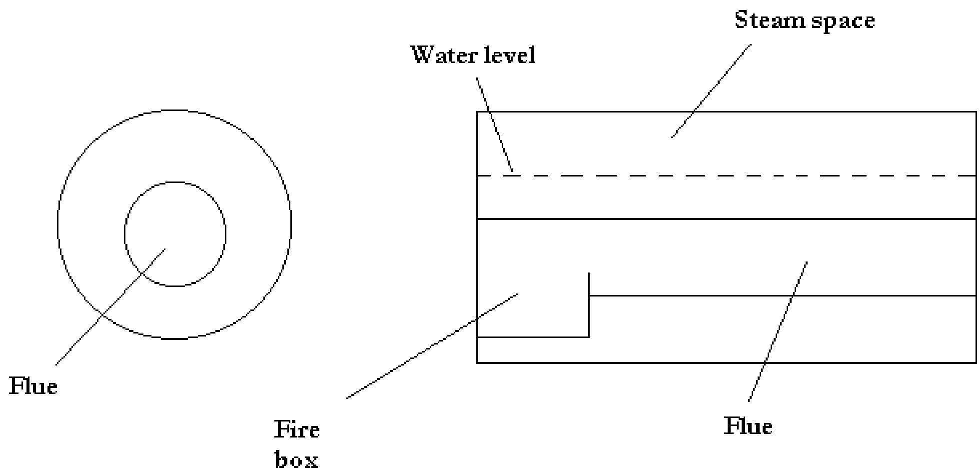

Figure 2.11: Cornish boiler

The most successful of these new designs was the one developed by Trevithick around 1811, which will become later known as "Cornish" boiler. It consisted of a cylinder (made of cast iron plates) with flat ends. Inside the boiler, there was a large cylindrical flue where the firebox was placed. The flue run for the entire length of the boiler just

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through expansion, it should reach a sufficiently low temperature. The mark of a good steam engine, therefore, must be not only that it uses steam at high pressure but also that it uses it a pressures that are not constant but which vary substantially from one moment to the next and progressively decrease". Given their conception of the steam engine as vapour-pressure engine, early nineteenth century engineers found extremely difficult to account for the superior fuel efficiency of the high pressure expansive engine, see Fox (1976).

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

62 For a short account of the steam engines developed by Evans, see Hills (1989), pp. 97-99 and Dickinson (1938), pp. 94-95.

63 For a biographical account of Trevithick's life, see the recent work by Burton (2000). On Arthur Woolf, see Harris (1966).

beneath the water level (see figure 2.11 that represents the Cornish boiler in section). The chief advantage of this boiler lay exactly in the position of the fire where all the heat could be directly radiated to the water. Cornish boilers were able to withstand steam pressure of 40 psi, which was the one used commonly in Cornish engines in the first half of the nineteenth century. However, for pressures around 50 psi, the internal flue displayed a tendency to collapse, sometimes causing explosions (Kanefsky, 1979, p. 133).

Another boiler design of some interest is the one patented by Arthur Woolf in 1803. This was of the so-called water-tube type (the idea was to heat the water in tubes which would be placed in direct contact with the furnace). An early project embodying this idea was patented by William Blakey in 1776 in the Netherlands (Dickinson, 1938, p.125). In Woolf's boiler, multiple water tubes were heated by the furnace gases in a sort of waving way (Hills, 1989, p. 160). Woolf used this boiler in his high pressure engines erected in the early 1810. However, from the late 1810s he reverted to the Cornish boiler, probably because of the excessive complication of his design.

With the trend towards increasing steam pressure gaining momentum, in 1844 Fairbairn and Hetherington took a patent for an improved version of the "Cornish" boiler. In design terms, this can indeed be seen as a minor modification, consisting simply in employing two smaller flues instead of one. Nevertheless, in performance terms, the gains associated with this new design were conspicuous, as the boiler was capable of withstanding steam pressures up to 300 psi (Kanefsky, 1979, p. 133). From the 1850s, this type of boiler (commonly called " Lancashire") dominated the normal engineering practice, especially for in steam engines used in textile factories.

Table 2.3: Heating efficiency of various types of boilers

Boiler type	Ratio
"Old" haystack boiler	1/3.28
Common waggon boiler	1/3.26
Cornish boiler	1/1.65
Woolf boiler	1/1.06
Lancashire boiler	1/1.01

Source: Fairbairn (1851), cited in von Tunzelmann (1974), p. 27.

In 1851, William Fairbairn used the ratio of heating surface to capacity to portray the rate of improvement in boiler efficiency that had taken place since the early 1720s. His results are reported in table 2.3.

Coming back to the development of engine designs, it is probably fair to say that the first successful high pressure steam engine is due to Richard Trevithick. The available evidence seems to indicate that Trevithick had an intuitive grasp of the merits of high pressure steam, although this does not seem to have been articulated in a coherent theory of the operation of the steam engine (see Todd, 1967, pp. 79-101).

Around 1800 Trevithick introduced a fairly simple high pressure engine. This engine discharged the spent steam directly into the atmosphere and for this reason was called "puffer". Trevithick also dispensed the beam, making the engine act directly on the crank. Steam entered into the cylinder at a pressure of about 25 psi, falling, after the expansion was completed, to about 4 psi (von Tunzelmann, 1978, p. 22). The main advantage of this type of engine was its compactness and its cheaper cost of installation (due to the elimination of the condenser, the air pump and the beam.). However, this type of high-pressure engine was less efficient in fuel consumption than Watt engines (they tended to consume circa 25 % more coal).[64] It is worth noting that since 1800 with the increasing adoption of steam engines in manufacturing applications the demand for engines of small sizes was increasing. So besides Trevithick with his high pressure non-condensing engine, other engineers working at low-pressure focussed on compactness and in a number of cases even on portability. In 1805 Matthew Murray introduced a "side-lever" engine where cylinder, beam, frame and flywheel where all fixed to an iron bedplate. [65] Always looking at portability, Henry Maudslay in 1807 took a patent for a "table engine" where the beam was dispensed.

In 1812 Trevithick built the first steam engine of the so-called "Cornish" type (Dickinson, 1938, p.103). The Cornish engine can be simply defined as a Watt single-acting pumping engine (such as the one represented in figure 2.5) employing high-pressure steam. Also, the action of the engine was very similar to the Watt pumping engine described in the previous section. High-pressure and condensing action were combined in a carefully regulated operating cycle ("Cornish cycle"). High-pressure steam (generated by boilers of the Cornish type) was admitted at the top of the cylinder from the inlet valve. The inlet valve was closed soon ("early cut-off") and the steam expanded in the cylinder.[66]At the end of the stroke the equilibrium valve was opened so that the steam could pass below the piston. Note that the exhaust valve was also opened during the working stroke, so that spent steam was discharged into the condenser in the same moment in which new "live" steam was admitted at the top of the cylinder. In Cornwall, Cornish engines were employed to power "plunger pumps", an invention which was introduced at the end of the eighteenth century.[67] Contrary to the most common bucket pumps, plunger pumps lift the water when the pump rod descends. The adoption of this type of pump permitted to operate the engine by means of a highly irregular cycle, in which the "indoor stroke" (the phase in which steam is admitted into the cylinder and pushes down the piston) was relatively rapid, whilst the outdoor stroke (the phase in which the piston is pulled up by the weight of the pumps and pitwork) was characterized by a rather slow pace. This extremely irregular cycle had the advantage of permitting an effective maximisation of the expansion of steam in the cylinder (von Tunzelmann, 1978, pp. 79-83).

In the following years the Cornish engine proved to be the highest peak in steam engineering of the first half of the nineteenth century (von Tunzelmann, 1978, p. 263). The engine had negligible costs of maintenance and it was susceptible of continuous improvements in its efficiency.

The main rival of Richard Trevithick in Cornwall was Arthur Woolf. In 1804 Woolf (who had served as an apprentice with Jonathan Hornblower) patented an engine incorporating the principle of compounding. In fact, Woolf's initial conception of the principle of expansion (which he probably inherited from Hornblower) was to let exhaust steam perform additional useful work before being condensed. Thus, in the

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[64] See von Tunzelmann (1978), p. 22. Trevithick high pressure engines were usually preferred to Watt engines at low sizes. The compactness of high pressure engines further extended the number of possible application of steam power. See Dickinson (1938), p. 92.

[65] Soon afterwards, Murray's side lever became the favourite design in marine-engine practice (Dickinson, 1938, p. 108).

[66] The valve was closed as early as after one-tenth of the stroke, the remaining part being done by the expansive working of steam.

[67] The plunger pump was adopted more or less concomitantly by William Murdock (Boulton and Watt engineer in Cornwall), Richard Trevithick and Joel Lean, see Michell (1980).

Woolf engine, steam was first expanded in a small high-pressure cylinder and subsequently in a large low-pressure one. The cylinders were placed side to side and connected at the same point of the beam. In 1811, Woolf started to build compound engines in the Cornish mining district. In a first phase the Woolf engine seemed to outperform its rivals. However, after a period of usage, Woolf engines had troubles in maintaining their initial efficiency. This was by and large due to the fact that the rather complex two cylinder engines required continuous and careful maintenance, especially when working conditions changed. For instance, after a period of operation it was difficult to keep both cylinders steam tight. Furthermore, Woolf's cast iron boilers displayed some susceptibility to cracking, so that, after a period of usage, steam pressures had to be reduced in order to operate safely the engine (Hills, 1989, p. 108).

The "controversy" between the single cylinder engine of the Cornish type developed by Trevithivk and the Woolf compound engine was resolved in 1825. In that year a sort of ultimate test between the two competing designs was carried out by installing two new engines (of comparable size) at Wheal Alfred mine. The engines performed the same duty (about 42 millions). This led to the abandonment of the Woolf design on grounds of his higher erection and maintenance costs (Hills, 1989, p. 109). Woolf himself reverted to the single cylinder engine and the Cornish engine as designed by Trevithick became the dominant type in Cornwall mines (Barton, 1969, p. 44). In fact, it is worth remarking that compound engines enjoy an important advantage over the single cylinder from the point of view of fuel efficiency. Compound engines permit to limit the range of temperatures between which steam expansion is carried out. When steam is expanded in a single cylinder, this will cool down during the stroke as a result of the temperature fall of expanding steam. This implies heat transfer from the steam to the cylinder wall, constituting inefficient use of heat. Furthermore, during the expansion, some of the steam, being in contact with the cylinder walls, will condense. As pressure keeps falling, some of this condensed steam will re-evaporate absorbing "uselessly" some of the heat. In a compound engine, these problems are less pressing, because *within* each cylinder the temperature differential between the start and the end of the stroke is reduced.[68] However, this insight is based on an understanding of the steam engine as a *heat* engine. Given their conception of the steam engine as a *vapour-pressure* engine, at the time, it was out of reach of the Cornish engineers.

One can imagine, nevertheless, that Cornish engineers could succeed in exploiting the heat transfer advantages of compounding by trial and error. As we have already mentioned discussing the Hornblower engine, fuel-saving advantages of compounding can be exploited only with steam pressures over 60-70 p.s.i. (Hills, 1989, p.160; Ewing, 1910, p. 206). The highest steam pressure reported by the Leans was exactly 60 p.s.i, namely the Deer Park 40" engine in 1853 (Barton, 1969, p. 63). Thus, the available evidence seems to suggest that Cornish steam engines were never operated at pressures

[68] In the words of Ewing (1910, pp. 205-206): "If the vessels were perfect non-conductors it would be, from a thermodynamic point of view, a matter of indifference whether expansion was completed in a single vessel or divided between two or more, provided the passage of steam from one to the other was performed without introducing unresisted expansion. In practice, the transfer of steam from one cylinder to the another during its expansion cannot be accomplished without some more or less wasteful drop in pressure. But the loss which this entails is more than counterbalanced by the gain that results from the reduced influence of the cylinder walls....Experience shows that it is only by resorting to compound expansion that the economical advantages of high-pressure steam are to be secured . When steam is used in a non-compound engine the waste due to the initial condensation is excessive because of the great range of temperature through which the metallic surface fluctuate at every stroke".

so high as to make compounding advantageous from the point of view of fuel efficiency. We will deal in more detail with technical developments in Cornwall in chapter 5,6 and 7.

The general adoption of the high pressure engine outside Cornwall was particularly slow, due to a number of factors which will be examined in some detail in chapter 6. In industrial applications, the initial use of high-pressure steam expansively can probably be dated to the mid 1840s when John McNaught revived once again the compound design, by adding to traditional beam low pressure engines a small high pressure cylinder. Contrary to Woolf and Hornblower, the small cylinder was placed at the other end of the beam with the respect to the low pressure cylinder (more precisely between the trunnions and the crank). This solution permitted a quite effective upgrading (called "McNaughting") of existing low-pressure engines, increasing significantly their power. At the same time the arrangement resulted in some fuel economies, although steam pressures were mostly lower than 60-70 psi.(Hills, 1989, p. 157).

The "correct" application of the principles of compounding in view of the actual reaping of fuel economies, could begin only after the basic principles of thermodynamics had been laid down, and hence the advantages of high-pressure steam were also understood correctly from a scientific point of view. From the 1850s, in marine engineering, contrary to the case of the Cornish engine, compounding became the norm, and quite soon the average engine would expand the steam in three steps using as many cylinders (Hills and Cardwell, 1976, pp. 10-11).

The introduction of compounding for steam ships is to be ascribed to John Elder (who was a close associate of Rankine) in the early 1850s.[69] Notably, Elder was probably the first to notice that compound engines were more efficient than single-cylinder engines at steam pressures exceeding those normally in vogue. Elder's compound design became soon the favourite one for marine use (Griffiths, 1997, p. 46). A notable improvement to the compound design was attained in 1857 when E. A. Cowper added to the engine a steam-jacketed receiver where steam could be stored during the passage between the high to low pressure cylinder while minimizing heat losses (Hills, 1989, p. 147).

In retrospect, from the 1840s most inventive efforts in steam engine technology were aimed at minimizing the problem of cylinder condensation. Broadly speaking, there were four main directions for tackling this issue (Cardwell, 1994a, pp. 316-318). The first one was to "steam jacket" the cylinder, as it was done originally by Watt. This involved the construction of a cylinder cover. A steam "layer" was admitted from the boiler into the empty space between the cylinder and the cylinder cover raising the temperature of the cylinder and reducing condensation. The steam jacket was quite frequently adopted in engines of Cornish design. The second solution consisted in superheating the steam, that is using steam at higher temperatures than those corresponding to the saturation level (i.e., the temperature level at which steam and water are in equilibrium). Superheating the steam before its admission in the cylinder reduced the moisture of steam and therefore initial condensation and the loss of temperature due to re-evaporation (Ewing, 1910, p. 200). This was typically done by further heating the steam after it had left the boiler, by making it passed through a series of heated pipes (superheater). The third solution, as

[69] The first application of a compound engine to power a steamboat is actually due to the Dutch engineer Gerald Maurits Roentgen. In 1829, at the Fijnoord Engineering Works, Roentgen (who had visited Cornwall in the early 1820s) designed a compound engine on the Woolf layout for river boats. The engine was employed with some success in steamboats built for service on the river Rhine (Jenkins, 1943, pp. 25-26)

already mentioned, was to make use of compound expansion. Finally, the fourth method was to improve the valve system in order to avoid the "wire drawing" of steam (i.e. drop of steam pressure due to the resistance of ports and passages).

Table 2.4: Technological progress in steam engines, 1800-1860

"Locus" of innovation	1800- 1810	1810-1820	1820-1830	1830-1840	1840-1850	1850-1860
Engine design	"Puffer" (Trevithick, 1802); Side-lever (Murray, 1805); Compound (Woolf, 1804); Table-engine (Maudslay, 1807); High-pressure (Evans,1804); Grasshoper (Evans, 1804)	Cornish (Trevithick, 1812)	Horizontal (Taylor & Martineau,1824)	Compound (Sims, 1839);	Compound (McNaught,1845) Corliss (Corliss, 1849)	Compound (Elder, 1852); Compound (Cowper, 1857)
Regulation	Boiler plug (Trevithick,1803)					
Valves and other critical components			Double-beat drop valve (Woolf, 1823)	Surface condenser (Hall, 1837)	Economizer (Green, 1845); Automatic cutoff (Corliss, 1849); Superheater (Detmold, 1845)	
Materials		Wrought iron shafting				
Boilers	Water tube (Woolf, 1803)	Cornish (Trevithick, 1811) "Egg-ended' (1814)			Lancashire (Fairbairn, 1844); Babcock & Wilcox (1856)	
Power transmission		Line-shafting (Fairbairn, 1815)				
Production processes				Riveting machine (Fairbairn, 1837)		

A particular effective valve system, the automatic variable cutoff valve, was invented by the American George Corliss and patented in 1849. Corliss' improvement consisted essentially in a valve system in which the cutoff point could be precisely regulated by the governor. This new design feature permitted a much better use of the expansion of steam, avoiding "wire drawing". In turn, this resulted in considerable gains in fuel efficiency. Furthermore, the Corliss valve arrangement had also another major merit: the speed could be regulated very precisely, so that, the engine was capable of delivering an extremely uniform motion for a wide range of possible loads (Hills, 1989, pp. 178-188).

Note that these four solutions (compounding, steam jacketing, superheating and improved valves) were not exclusive but could be adopted in combination.
Finally, it is worth stressing that the relative merits of these solutions had to be ascertained by means of long and painstaking trial-and-error processes. As we have

already noted, the phenomenon of cylinder condensation prevented a straightforward application of scientific thermodynamics to steam engineering design activities. As John Ewing (1910, pp. 35-36) observed:

The influence which the walls of the cylinder exert is in fact immense, by the alternate give and take of heat between them and the steam. The exchanges of heat are so complex that there seems little prospect of submitting them to any comprehensive theoretical development, and we must look for help in the future development of engines to the scientific analysis of experiments made upon actual machines. Many such experiments have been made and their value is now fully realised, by no persons more than by designers of the best modern engines. Questions relating to the influence on thermal economy of speed, of pressure, of ratio of expansion, of jacketing, of compound expansion, or of superheating, must in the main be settled by an appeal to experiment.

Table 2.4 summarizes the development of the steam engine over the period 1800-1860. As in table 2.2 dates are to be regarded as approximate.

2.7. Conclusions

Following Thurston (1939), one can identify two major development trends in the long term evolution of steam engine technology. The first one, characterizing engine design, took place from the beginnings up to the Watt epoch and consisted in a progressive differentiation of engine components:

The process of improvement has been, primarily, one of "differentiation"; the number of parts has been continually increased; while the work of each part has been simplified, a separate organ being appropriate to each process in the cycle of operation. (Thurston, 1939, p. 470)

This process may be seen to have come to a conclusion with Watt's invention of the separate condenser; although, it is interesting to notice that Thurston considered compounding as a prolongation of this particular line of development:

A kind of secondary process of differentiation has, to some extent, followed the completion of the primary one, in which secondary process one operation is conducted partly in one and partly in another portion of the machine. This is illustrated by the two cylinders of the compound engine.....(Thurston, 1938, pp. 470-471).

The second development trend, which seems to characterize the entire history of the steam engine is the search for improvements in the fuel efficiency of the machine. This latter feature of the historical progress of steam engine technology was noted not only in the engineering literature (Thurston, 1939, p. 471), but also, by scholars interested in the economic effects of the diffusion of steam power technology. Thus, in *The Coal Question*, Jevons stated rather explicitly:

And with the exception of contrivances, such as the crank, the governor and the minor mechanism of an engine, necessary for regulating, transmitting, or modifying its power, it may be said that *the whole history of the steam engine is one of economy.* (Jevons, 1865, p. 144, italics in the text)

More recently, David Landes has appraised the direction of innovation in steam technology in these terms:

[T]he leitmotif of steam technology was the effort to increase efficiency, that is, the amount of work done per unit of energy. By comparison the goal of greater power, that is, work performed per unit of time, took second place, although the two objectives were linked and what made for one, permitted or yielded the other. (Landes, 1969, p. 100). [70]

In the same vein, according to Habakkuk:

Fuel economy was the purpose of Watt's first improvement to Newcomen's engine (the patent of 1769), and continued to be the motive behind developments in the steam engine from Watt's separate condenser down to the compound engine (Habakkuk, 1962, p. 158).

As we have mentioned, from the early nineteenth century, gains in fuel efficiency were reaped by means of adopting higher steam pressures (which permitted to operate the engines between wider temperature ranges) and of an increasing use of steam expansion (Thurston, 1939, p. 471).

The aim of this chapter was to familiarize the reader with the various types of engine designs and other relevant technical details. Accordingly, we have provided an introductory overview of the development of steam engine technology by adopting an essentially "internalist" perspective. In the next chapters, we will broaden our focus examining more closely the interaction between the evolution of the technology and the wider historical context.

[70] Landes' statement is correct, although, as we have seen, there existed a trade-off between fuel efficiency and increasing power in the first decade of the nineteenth century with the introduction of Trevithick high-pressure non condensing steam engines which had normally a higher coal consumption than low pressure engines.

PART II. THE EMERGENCE OF STEAM ENGINE TECNOLOGY IN THE EIGHTEENTH CENTURY

3. The Diffusion of the Steam Engine in Eighteenth Century Britain[1]

3.1. Introduction

Whilst economic historians have long discussed the nature and the determinants of technical change in the early phases of industrialization (see Habakkuk, 1962; Landes, 1969; Mathias, 1969; just to mention a few "classical" contributions), comparatively less attention has instead been devoted to the *diffusion* of new technologies in this historical period. Reviewing the state of the art more than thirty years ago, Nathan Rosenberg noted:

> ...[I]f we focus upon the most critical events of the industrial revolution, such as the introduction of new techniques of power generation and the climactic events in metallurgy, our ignorance of the rate at which new techniques were adopted, and the factors accounting for these rates is, if not total, certainly no cause for professional self-congratulation…..Our knowledge of the sequence of events at the purely technical level remains far greater than our knowledge of the translation of technical events into events of economic significance. (Rosenberg, 1976, pp. 189-190, note that the original paper was published in 1972).

Interestingly enough for the purposes of the present study, Rosenberg proceeds by mentioning Dickinson's account of the evolution of the steam engine (Dickinson, 1938) as a typical example of a historical study focussed in a rather exclusive fashion on the generation of inventions and in which the analysis of diffusion is limited to some sporadic notations (Rosenberg, 1976, p. 190). At the time, Rosenberg was undoubtedly right in indicating the existence of a fundamental and largely unexplored research issue. Since then, some considerable progress has been made, so that today we have a number of studies which portray with some accuracy the patterns of diffusion for a number of key technologies of the industrial revolution. To name just a few major contributions, Hyde (1977) has analysed the diffusion of iron production techniques, David (1975, chs. 4, 5) has studied the diffusion of the reaper in the US and in Britain, and most relevantly for the purposes of the present study, von Tunzelmann (1978) and Kanefsky (1979) have examined the diffusion of power technologies.

These studies have also ventured some way toward interpreting the factors driving the process of diffusion (sometimes igniting interesting controversies such as in the case of Alan Olmstead's (1975) critique of David's study of the reaping machine). Furthermore, in certain cases, the analysis of the diffusion process has also induced some overall reassessment of the role played by specific technologies in the process of economic growth.

This chapter serves a twofold purpose. The first is to provide a thorough reconstruction of the early diffusion of steam power technology (in the form of Watt and Newcomen engines) by providing estimates for the timing, the pace and the geographical extent of steam engine usage during the eighteenth century. The second goal is to assess the factors influencing the adoption of steam engine technology in this period. In particular,

[1] This chapter draws partially on Nuvolari, Verspagen and von Tunzelmann (2004).

this chapter will pay attention to the process of *spatial spread* of steam engine technology during the eighteenth century. The focus on the geographical aspects of the diffusion process is motivated by the fact that a growing number of contributions have argued (in our view rather compellingly) that a proper understanding of the processes of economic change occurring during the British industrial revolution needs to be based on a regional perspective (Pollard, 1981; Langton, 1984; Hudson, 1989; Berg and Hudson, 1992). These authors claim that industries exhibiting fast rates of output growth and extensive technical and organizational changes displayed a strong tendency towards regional concentrations. From these considerations, it is clear that, when accounting for the diffusion of a technology in this period, due attention must be paid to spatial aspects.

3.2. Diffusion patterns in early steam power technology

Kanefsky and Robey (1980) compiled a survey of all the steam engines erected in Great Britain in the course of the eighteenth century.[2] For each (known) steam engine erected during the period 1700-1800, Kanefsky and Robey recorded the year of construction, the type or design of the engine (i.e. Newcomen, Watt, Hornblower, etc.), the county, and the sector of application.[3] It is worth remarking that this dataset intends to cover *engine construction* and not engine utilization. This means that besides the year of erection there is no other information on the time period over which the engine was actually used, and there is no information on the date at which the engine was scrapped or replaced.

As the authors would admit, the data collected by Kanefsky and Robey are probably affected by some biases in both upward and downward directions. The principal source of overestimation is the double counting of engines that were moved from one place to another, whereas underestimation is mainly due to small engines that have left no trace in the records. Notwithstanding these problems (which might result in some revisions in the future), the survey constitutes the most accurate attempt to trace the growth of steam power in Britain over the eighteenth century. In this work, we employ an up-to-date version of this dataset compiled by Kanefsky.[4]

On the basis of the historical outline presented in the previous chapter, the development of steam power technology in the eighteenth century can be divided rather naturally into three distinct "epochs". The first epoch (1700-1733) goes from the invention of the Savery engine to the expiration of the Savery-Newcomen patent. This phase represents the early introduction of the new technology. The second epoch covers the period 1734-1774. The final period goes from 1775 (the year of the first successful erection of a Watt engine) to 1800 (the year in which Watt's patent for the separate condenser expired).

The maps presented in figure 3.1 provide a preliminary "impressionistic" view of the geographical (county) distribution of the engines erected in these three periods. Darker (lighter) areas indicate a higher (lower) number of engines. White areas indicate that no engines were erected in that particular county. In addition, map 5 represents the

[2] See Kanefsky (1979) for a detailed account of the construction of the database.

[3] Other information available for some of the engines are the maker, the cylinder size and the horsepower.

[4] The list originally compiled by Kanefsky and Robey contained a total of 2191 steam engines, the new updated dataset contains 2279 engines. The updated version of the list has been kindly provided to us by John Kanefsky. Concerning Watt engines, the updated list by Kanefsky contains 479 engines. Tann (1988) on the basis of a careful examination of the Boulton and Watt papers considers this total too high. Her estimation of the engines constructed by Boulton and Watt by 1800 is 449. In this work, mainly for sake of convenience, we have utilised Kanefsky' s list without attempting corrections.

geographical distribution of water wheels (the "predominant" power technology of the period) and map 6 illustrates the prevailing level of coal prices in the various counties in (*circa*) 1800 (again, darker areas indicate higher prices, lighter areas represent lower prices and in this case white areas correspond to missing values).[5]

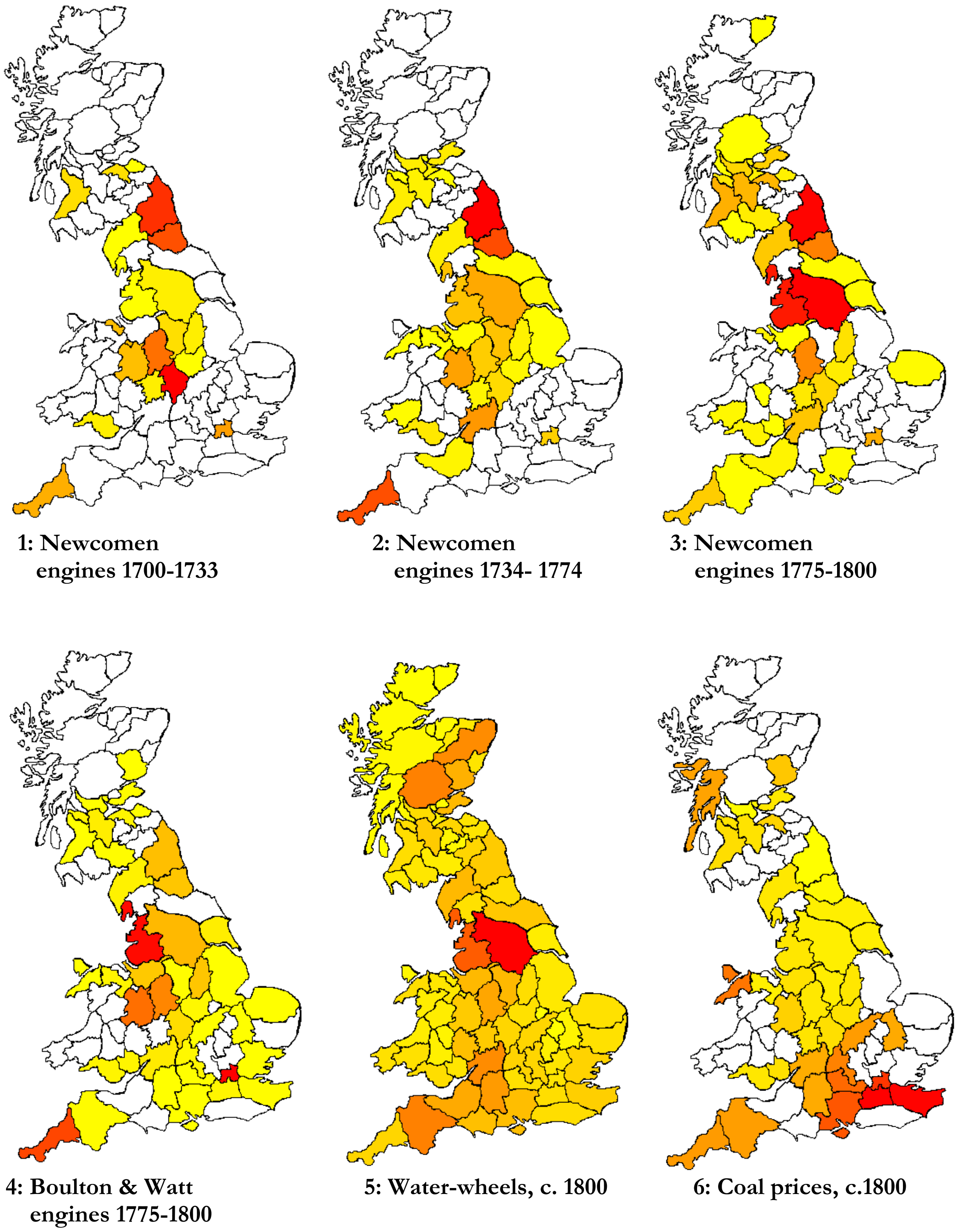

Figure 3.1: Geographical diffusion of steam technology during the eighteenth century

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[5] The source for the number of water wheels is Kanefsky (1979, pp. 215-216) and for coal prices von Tunzelmann (1978, p. 148). For more details on the sources of the data used in this chapter, see Appendix 3.2.

The spread of steam power technology appears to have been, from the very outset, remarkably wide.[6] There is some evidence that indicates that is highly likely that the first Newcomen engine was erected in Cornwall at the Wheal Vor tin mine in 1710. However, because of the high price of coal, Cornwall did not represent the most fertile soil for the diffusion of the new technology. The erection of the Wheal Vor engine remained a sporadic event and the introduction of Newcomen engines in Cornish mines actually took place only from the 1720s (Rolt and Allen, 1997, p. 45).

Coal mining areas represented of course a much more receptive environment for the new technology, since there coal would be relatively cheap. The Midlands coalfields (Stafford and Warwickshire) were the first location where Newcomen engines could take firm root. The commercialisation of the engine was at first controlled by the Newcomen-Savery partnership. As mentioned in the previous chapter, after Savery's death in 1715, a syndicate for the exploitation of the patent rights, the "Committee of Proprietors of the Invention for Raising Water by Fire" was constituted. The Committee, under the direction of its secretary John Meres, promoted rather successfully the use of the engines for drainage in various mining areas by means of a network of agents and licensees.[7] Apart from the Midlands, as the map of figure 1 indicates, by 1733, Newcomen engines, had been adopted in some numbers in Cornwall and in the coalfields in the North East (Northumberland and Durham).

Overall, during the period of the monopoly of the "Proprietors" about one hundred Newcomen engines were constructed. As Smith (1978, p. 12) has aptly remarked, for the time, this must be considered "by any standards a colossal business achievement". On the other hand, it should also be noted that historians (see for example, Flinn, 1984, p.117) have generally contended that the high level of royalties claimed by the "Proprietors" (up to £ 350 a year) hampered the diffusion process in this initial phase.[8] Be this as it may, one has to acknowledge that, under the "Proprietors", a group of skilled engine-builders emerged. As we have mentioned in the previous chapter, one of the main merits of Newcomen's invention was its relative easiness of construction and maintenance. Nevertheless, in this initial phase, the engine still represented a rather sophisticated piece of equipment and its erection probably called for more than ordinary engineering skills. Thus, the formation and consolidation of this base of engine-building skills presumably represented a critical factor for the successful adoption of the engine in various locations. Among these engineers we may mention Henry Beighton, who worked for the Parrot-Sparrow partnership and, as noted in the previous chapter, compiled a table containing some rules of thumb for the proportions of the various components of the engine; Joseph Hornblower, who supervised the erection of various engines first in

[6] Note that maps 1,2 and 3 show the distribution of Newcomen *and* Savery engines considered together. As a consequence, a more precise definition would be "atmospheric engines". Given the relatively small number of Savery engines installed, the results of our study are not affected by ignoring this distinction.

[7] The most active licensee of the "Proprietors" was the partnership formed by Stonier Parrot and George Sparrow who were engaged in the erection of more than fifteen Newcomen engines. According to Flinn (1984, p. 120), the high number of engines erected in Warwick and Stafford (far in excess of the two counties' share in British coal production) is to be accounted for by the fact this was the "home stronghold" of the Parrot-Sparrow partnership. For an account of the activities of Stonier Parrot, see Rowlands (1969).

[8] Kanefsky's data provide some quantitative support for this view. From 1710 to 1733, 95 Savery-Newcomen engines were constructed. This is approximately equal to 4 engines erected per year. In the period 1734-1774, instead, 442 engines were built, corresponding to 11 engines per year.

the Midlands and then in Cornwall;[9] Samuel Calley, the son of John Calley (the partner of Thomas Newcomen in the invention of the engine); and Marten Triewald, a Swedish engineer who installed various Newcomen engines in the North East and who would erect a (not very successful) Newcomen engine in Sweden at the Dannemora mine.

In the period 1734-1774 Newcomen engines continued to be built in mining areas. However, as we can we see from map 2, in this phase, steam power also penetrated new locations. This wider spread of the engine was mainly due to its adoption by the iron sector (Shropshire) where it was used to assist water wheels in blowing coke blast furnaces during drought periods (Hyde, 1977, pp. 69-75). Newcomen engines also began to be constructed in some numbers in Scotland in the counties of the Clyde Valley.[10]

In this second phase, the "Proprietors" had completely ceased to control the market and Newcomen engines were typically erected by local craftsmen, leaving the cylinder, the cylinder bottom and a small number of other critical components to be manufactured by "specialist" firms and then shipped to the location of the engine. In this respect, it is worth noting that, up to the early 1780s, in Britain there existed only four ironworks that could supply cast iron cylinders for steam engines namely Coalbrookdale and New Willey (in Shropshire), Bersham (in Denbigh) and Carron (Stirling).

The period 1775-1800 is characterized by the competition between Watt and Newcomen engines. In this phase, typically textile counties such as Lancashire and Renfrew (cotton) and West Riding (wool) began to resort to some use of steam to power machinery. The main difference in the spread of the two types of engines is that Watt engines appeared capable of achieving some penetration (although in low numbers) in the counties of the South East, an area which appears, by and large, to exclude Newcomen engines.

Table 3.1 reports Moran I statistics for the three periods we are considering. Moran I statistic measures whether a variable displays a tendency to be systematically clustered in space, or, on the contrary, it is randomly spread. Higher values of Moran I statistic indicate a stronger degree of spatial autocorrelation. In other words, higher values of the statistic mean that counties with relatively high number of engines tend to be neighbouring (see Appendix 3.1, for more details on the calculation of Moran I statistic).

Table 3.1: Spatial autocorrelation between engines

Type of engine	Period	Number of engines	Moran I statistic	Significance (Normal)	Significance (Randomized)
Newcomen	1700-1733	97	0.167	**	***
Newcomen	1734-1774	442	0.124	*	**
Newcomen	1775-1800	616	0.192	***	***
Boulton & Watt	1775-1800	479	0.074		

Notes: *,**,*** indicate significance levels of 10%, 5% and 1% respectively.

Table 3.1 shows that Moran I statistic is higher for Newcomen engines than for Watt engines. Notably, in the case of Newcomen engines the coefficient appears to be significantly different from zero both when the original variable is assumed to be

[9] Joseph Hornblower would decide to settle definitely in Cornwall. He was the grandfather of Jonathan, the inventor of the compound engine.
[10] For an account of these cases of early installation of Newcomen engines in Scotland, see Hills (2002), p. 297.

characterized by a normal distribution and when it is supposed to be generated by an unspecified one (randomized).

On the contrary, the Moran I statistic for Boulton and Watt engines does not turn out to be significant. This seems to indicate that the adoption of Boulton and Watt engines was less susceptible of being conditioned by specific local conditions. This finding may be accounted for by two possible sets of factors acting respectively on the demand and the supply side. On the demand side, given its superior fuel efficiency, it is likely that the adoption of Watt engines was less conditioned by the proximity to cheap coal (this is indeed consistent with the penetration of the Watt engine in the South East of England).

Concerning the possible existence of spatial constraints from the supply side, it is worth noting that apart, from the early period of the "Proprietors", the installation of Newcomen engines was typically in the hands of local millwrights and for this reason, the geographical adoption of the engine could have been limited to areas endowed with the necessary amount of engineering skills. On the contrary, as we shall see, Boulton and Watt instead adopted immediately a much wider horizon in their marketing of steam engines, aiming to serve the entire national market for power.

To compare the speed of the diffusion between counties, we have fitted logistic curves to our data.[11] In particular, we have fixed the saturation level at 100% (which amounts to assuming that all the potential adopters at the end of the diffusion process will have adopted the technology). This allows us to make use of the following log-linear transformation, which can then be easily estimated using ordinary least squares.

$$\log_e\left(\frac{P_t}{1-P_t}\right) = a + b \cdot t \qquad (1)$$

In the equation, P_t is equal to the percentage of adopters that, at time (year) t, have erected a steam engine, a is the intercept that defines the position of the logistic curve and the slope parameter b indicates the rate of diffusion (higher values of b indicate a faster diffusion process).

We have calculated values for P_t from the last observation (cumulative number of engines erected) in our possession (1800), assuming that this final observation corresponds to levels of saturation going from 5 to 99% , adopting steps of 1%. Within this set of estimations we have chosen the one with the best fit (higher R^2). Tables 3.2 and 3.3 give the results, respectively for Newcomen and Watt engines (note that we have performed this exercise only for counties with more than 4 engines). The tables also report the growth time (Δt) in terms of the time interval necessary for moving from 10% to 90% of the final saturation level and the estimated midpoint of the logistic curve. Finally, we have also calculated average compound growth rates for the number of engines constructed in each county (which represents the "limit" case of a growth rate invariant over time).

[11] Note that here we are not interested primarily in the relative virtues of the various types of S curves for the estimation of diffusion process (as one would be when engaged in a forecasting type of exercise). Following Griliches (1957), we estimate logistic trends as "summary devices" for comparing the rate of diffusion across counties. In other words, we are more than willing to accept some loss of fit in order to get results that are easily comparable.

Table 3.2: Rates of diffusion of Newcomen engines

County	Number of engines	First erected	Growth rate	Saturation point reached in 1800 (%)	R^2	Intercept (a)	Rate of adoption (b)	Growth time (Δt)	Midpoint
Cornwall	75	1710	0.048	91	0.968	-4.150 (0.1589)	0.0761 (0.0033)	57.7	1765
Cumberland	23	1717	0.038	5	0.965	-5.946 (0.1975)	0.0367 (0.0028)	119.8	1879
Derby	62	1717	0.050	68	0.989	-4.078 (0.1133)	0.0564 (0.0018)	78.0	1789
Durham	103	1717	0.056	88	0.953	-3.437 (0.1568)	0.0606 (0.0033)	72.5	1774
Gloucester	49	1735	0.060	96	0.977	-3.297 (0.1434)	0.1008 (0.0035)	43.6	1768
Lancashire	85	1719	0.055	5	0.993	-7.725 (0.0977)	0.0579 (0.0015)	76.0	1853
Leicester	10	1724	0.030	78	0.996	-2.601 (0.0917)	0.0510 (0.0015)	86.1	1775
Middlesex	44	1698	0.037	48	0.975	-3.936 (0.1178)	0.0373 (0.0015)	117.7	1803
Northumberland	163	1718	0.063	83	0.965	-3.745 (0.1240)	0.0605 (0.0027)	72.7	1780
Nottingham	16	1728	0.038	41	0.942	-3.262 (0.2261)	0.0390 (0.0041)	112.7	1812
Shropshire	74	1715	0.051	79	0.976	-3.963 (0.1068)	0.0563 (0.0018)	78.1	1785
Somerset	8	1745	0.037	70	0.983	-1.582 (0.0908)	0.0427 (0.0018)	102.8	1782
Stafford	59	1706	0.043	72	0.952	-3.615 (0.1648)	0.0452 (0.0023)	97.2	1786
Warwick	39	1714	0.043	96	0.834	-1.877 (0.3225)	0.0468 (0.0054)	93.9	1754
Worcester	13	1725	0.034	66	0.892	-2.338 (0.2310)	0.0340 (0.0048)	129.1	1794
West Riding	100	1715	0.054	26	0.986	-5.852 (0.0949)	0.0550 (0.0014)	80.0	1821
North Riding	4	1754	0.029	85	0.894	-1.034 (0.4393)	0.0846 (0.0198)	51.9	1766
Carmarthen	5	1750	0.031	5	0.931	-4.580 (0.0946)	0.0292 (0.0050)	150.7	1907
Flint	19	1715	0.034	96	0.916	-2.079 (0.2237)	0.0554 (0.0051)	79.4	1753
Glamorgan	13	1717	0.031	83	0.939	-2.961 (0.2020)	0.0575 (0.0034)	76.4	1769
Ayr	32	1720	0.043	5	0.937	-6.002 (0.2022)	0.0361 (0.0030)	121.8	1886
Clackmannan	5	1764	0.043	5	0.968	-4.573 (0.1154)	0.0416 (0.0039)	105.7	1874
Dumfries	6	1787	0.127	99	0.993	-1.811 (0.1672)	0.4645 (0.0237)	9.5	1791
East Lothian	6	1720	0.022	5	0.702	-4.845 (07303)	0.0171 (0.0105)	257.0	2003
Fife	21	1764	0.083	74	0.850	-2.616 (0.3205)	0.0959 (0.0146)	45.8	1791
Lanark	26	1760	0.081	24	0.976	-4.467 (0.1438)	0.0883 (0.0048)	49.8	1811
Midlothian	26	1720	0.041	5	0.858	-6.004 (0.2566)	0.0329 (0.0039)	133.4	1902
Renfrew	8	1767	0.061	5	0.969	-5.179 (0.2966)	0.0669 (0.0107)	65.6	1844
Stirling	18	1760	0.071	78	0.926	-2.517 (0.2366)	0.0896 (0.0080)	49.1	1788
West Lothian	9	1764	0.060	7	0.949	-3.693 (0.0792)	0.0274 (0.0027)	160.5	1899

Notes: The growth rate is the average compound growth rate. The logistic trend is estimated using the formula $\log_e [P_t/(1-P_t)] = a + b \cdot t$. Standard errors are reported in brackets. Growth time (Δt= $\ln 81/b$) is the time interval (in years) for moving from 10% to 90% of the diffusion path. Midpoint = $-(a/b)$ + year in which the first engine was installed in the county.

Table 3.2 reveals some interesting aspects of the spread of Newcomen engines. Looking at the midpoint values there appears to exist a relatively ordered sequence in the penetration of the engine in various locations. The technology is first adopted in the coal mining areas of the Midlands (Stafford and Warwick), of the North East (Northumberland, Durham) and in Cornwall (copper and tin mining). In a second phase, Newcomen engines are adopted in ironworks (Shropshire). Finally, we have the penetration in typically "textile" counties, such as West Riding (wool) and Lancashire, where the adoption appears to be characterized by slower diffusion rates. It is interesting to note that Scottish counties (Lanark, Fife and Stirling) display the highest rates of diffusion. This is probably to be explained by the initially delayed penetration of the engine in these counties. Presumably, the establishment of the Carron ironworks (which made use of the cylinder boring machine designed by John Smeaton) in Stirling in 1760 spurred the rapid adoption of steam power in Scottish counties from the early 1760s, triggering a "catching-up" type of process.[12] Figure 3.2 charts the estimated diffusion paths for a number counties that were particularly intensive users of Newcomen engines.

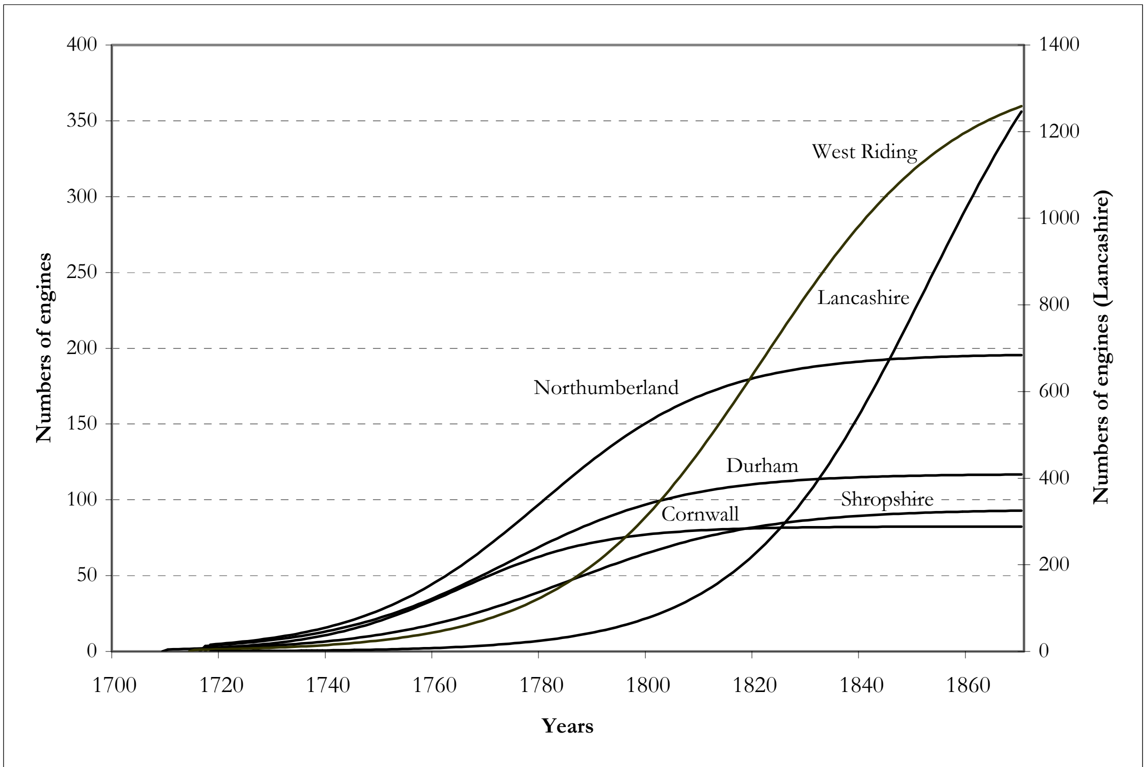

Figure 3.2: Estimated diffusion paths for Newcomen engines

If we compare table 3.2 with table 3.3, the much higher values of the rates of diffusion for Boulton and Watt engines are immediately evident. The average rate of diffusion (b) for Newcomen engines is equal to 0.07, whereas for Watt engines it is equal to 0.26, indicating that the diffusion process of the latter was indeed much faster.[13]

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[12] In the late 1760s and 1770s, Watt himself was involved in the installation of several Newcomen engines in Scotland. The erection of these engines provided Watt, who was until then acquainted only with experimental models, with a good deal of practical experience with the problems related with the installation and operation of full scale engines (Hills, 2002, p. 358).

[13] As a term of comparison the rate of diffusion of the high pressure expansive engine in Cornwall estimated by von Tunzelmann (1978, p. 258) in the early nineteenth century is equal to 0.25. Von Tunzelmann considers this as a case of a relatively fast diffusion process.

Considering midpoint values, as in the case of Newcomen engines, the adoption of the Watt engine in various locations also seems to have been characterized by a sequential order. First we have Cornwall and Shropshire (where steam engines were mainly used in ironworks), followed by the textile districts of Nottingham and later on of Lancashire and West Riding. The table also indicates a comparatively slow rate of diffusion of the Watt engine in Northumberland (coal mining), where the cheap price of coal presumably gave some advantage to Newcomen engines with respect to Watt. The estimated diffusion curves for Watt engines are displayed in Figure 3.3.

Table 3.3: Rates of diffusion of Boulton and Watt engines

County	Number of engines	First erected	Growth rate	Saturation point reached in 1800 (%)	R^2	Intercept (a)	Rate of adoption (b)	Growth time (Δt)	Midpoint
Cheshire	17	1778	0.125	49	0.983	-3.875 (0.1756)	0.1699 (0.0096)	25.9	1801
Cornwall	56	1777	0.175	99	0.907	-2.798 (0.3673)	0.2848 (0.0285)	15.4	1787
Cumberland	5	1789	0.132	81	0.985	-0.890 (0.1257)	0.2299 (0.0161)	19.1	1793
Durham	18	1791	0.301	91	0.959	-4.088 (0.6223)	0.6387 (0.0776)	6.9	1797
Gloucester	7	1787	0.139	87	0.972	-2.399 (0.1495)	0.3323 (0.0137)	13.2	1794
Lancashire	74	1777	0.188	5	0.984	-7.749 (0.1534)	0.1967 (0.0088)	22.3	1816
Middlesex	77	1776	0.182	85	0.975	-3.930 (0.1106)	0.2125 (0.0067)	20.7	1794
Northumberland	20	1778	0.133	5	0.950	-6.446 (0.3905)	0.1468 (0.0203)	29.9	1822
Nottingham	18	1786	0.198	99	0.940	-1.958 (0.3065)	0.4402 (0.0373)	10.0	1790
Shropshire	44	1776	0.157	99	0.966	-3.196 (0.2332)	0.2999 (0.0168)	14.7	1787
Stafford	38	1775	0.144	95	0.975	-3.123 (0.2104)	0.2146 (0.0116)	20.5	1790
Warwick	11	1777	0.101	8	0.965	-4.866 (0.1694)	0.1026 (0.0093)	42.8	1824
West Riding	22	1782	0.167	27	0.968	-4.283 (0.1929)	0.1851 (0.0141)	23.7	1805
East Riding	6	1779	0.081	81	0.957	-1.933 (0.1530)	0.1784 (0.0192)	24.6	1790

Notes: See Table 3.2.

The rank correlation coefficient between the total number of Newcomen and Watt engines erected in each county (Spearman's rho) is equal to 0.7, whereas that between the rates of diffusion is equal to 0.53. They are both significant at the 1% level. This finding can be interpreted as indicating that the rates of diffusion and the extent of usage of the two types of engines were affected by a number of common factors.

This exploration of the patterns of diffusion reveals that steam engine technology was, from a very early stage, integrated rather successfully into the different regional production systems which comprised the British economy during the eighteenth century (see Pollard, 1981 for an overview of the distinguishing features of each regional economy). Of course the regional patterns of usage of steam technology were uneven. However, the spread of the technology suggests that by the end of the eighteenth century the steam engine had already become source of power capable of being used in a wide variety of production processes and in different local contexts.

As mentioned in the previous chapter, the distinctive feature of the Boulton and Watt engine was its superior fuel economy with respect to the Newcomen. Watt engines, however were normally more expensive, because of their additional components (separate condenser, air pump, etc) and because their erection required higher engineering standards.

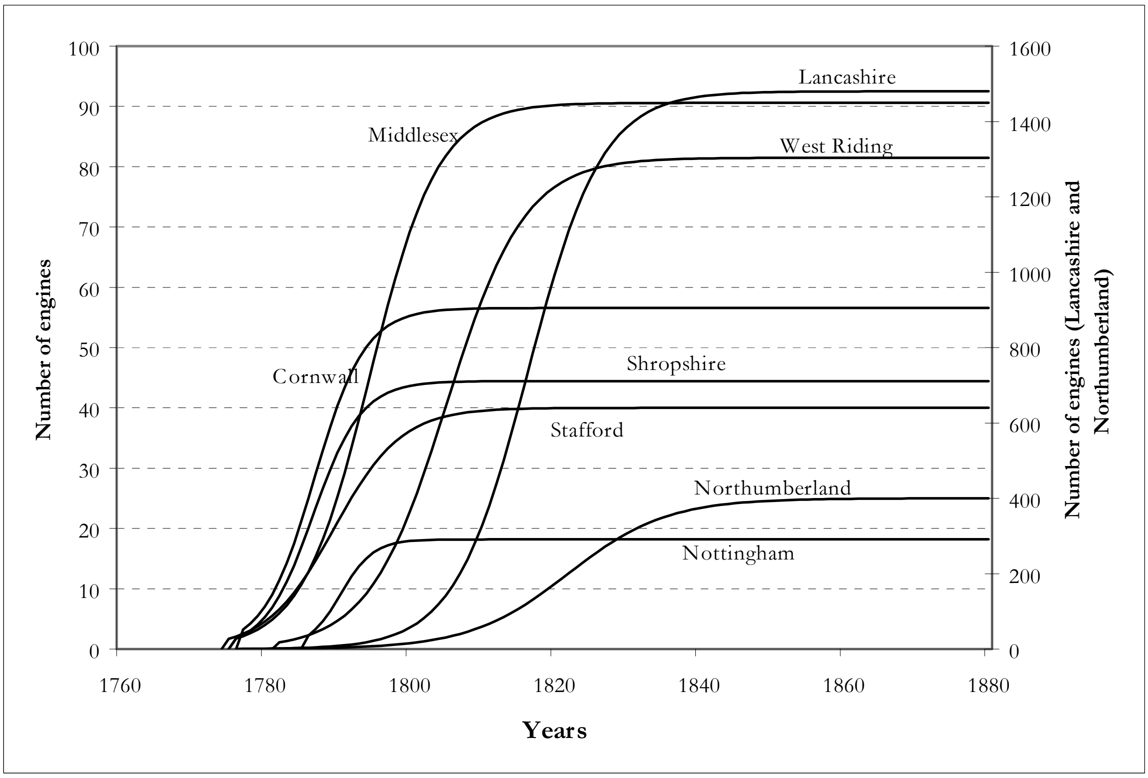

Figure 3.3: Estimated diffusion paths for Watt engines.

On the basis of the available data on the fuel consumption of the two types of engines and of their capital costs, von Tunzelmann (1978, ch. 4) calculated the threshold levels of the price of coal at which it would have been convenient for a "perfectly rational" entrepreneur to adopt a Boulton and Watt engine. Figures 3.4 and 3.5 contain scatter diagrams showing the relation between price of coal and the share of Watt engines in the total number of engines erected in the county during the period 1775-1800. [14] We have also plotted by means of vertical lines the threshold levels as calculated by von Tunzelmann (1978). Note that there are two threshold levels in each diagram: the first (and lower) one (I) indicates the threshold for a new engine, the second one (II), the threshold for the replacement of an existing Newcomen engine with a new Boulton and Watt one.[15] Figure 3.4 considers the case of reciprocating engines (where the gap in fuel efficiency between Newcomen and Watt engine was larger), whereas figure 3.5 displays the scatter diagram for rotary engines. It is important to remark that these threshold levels are computed for best-practice techniques.

[14] Coal prices in various counties are taken from von Tunzelmann (1978, p. 148), whereas the share of the Watt engine is computed using the updated version of Kanefsky's dataset.

[15] The threshold prices calculated by von Tunzelmann are in case of rotary engines 7s. 10d. for installation of a new engine and 14 s. for replacement, in case of reciprocating engines 5s. 10d. for installation and 11s. 3 d. for replacement, see von Tunzelmann (1978, pp. 76-77).

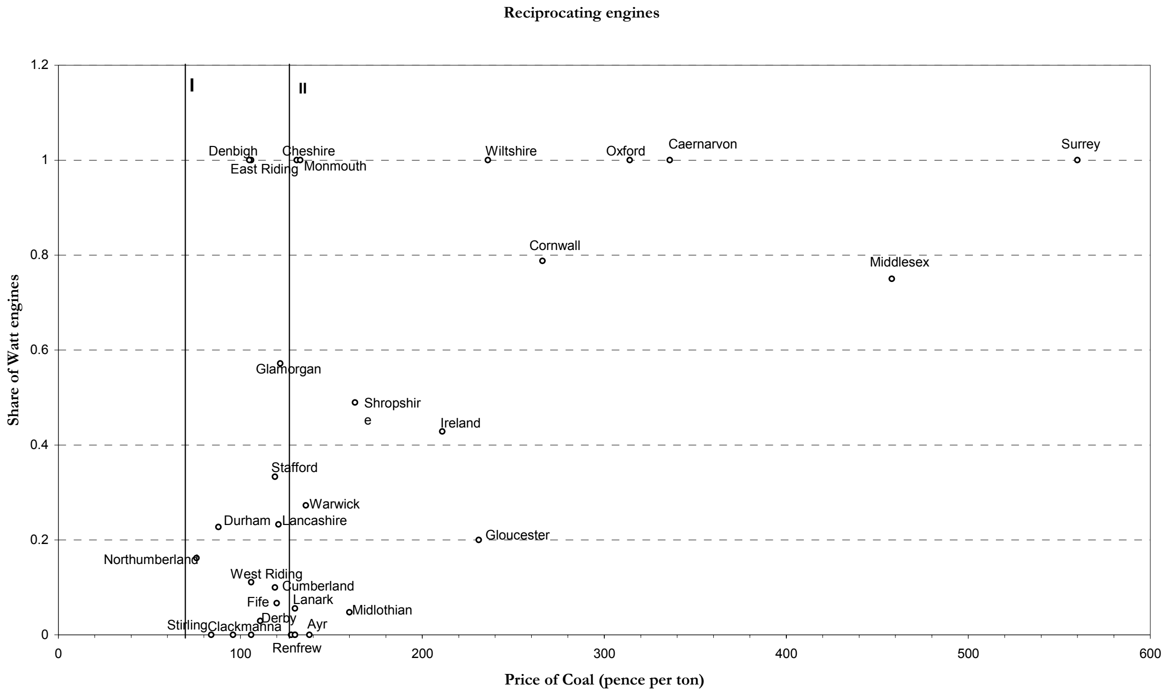

Figure 3.4: Price of coal and share of Watt reciprocating engines.

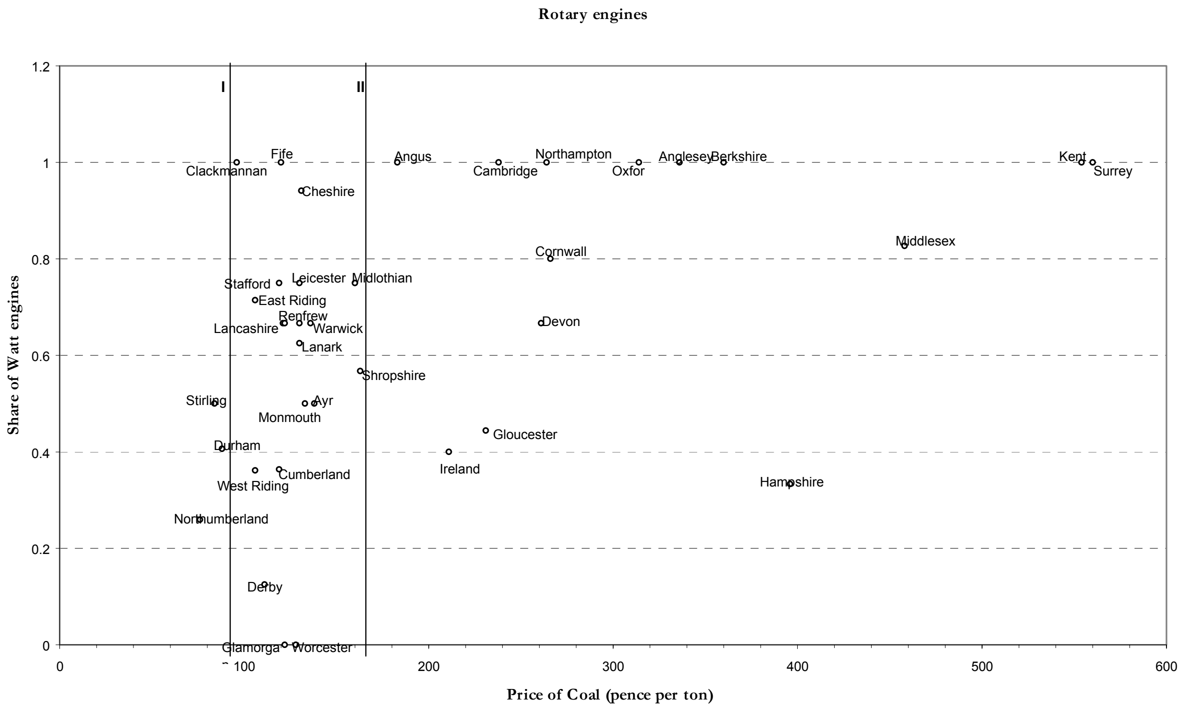

Figure 3.5: Price of coal and share of Watt rotary engines

Figures 3.4 and 3.5 suggest that the price of coal was indeed one of the major determinants (acting on the demand side) dictating the adoption of a Watt *vis-a-vis* a Newcomen engine. In other words, an interpretation of the patterns of adoption of steam engine in terms of the threshold model is surely consistent with some broad features of the diffusion process. However, considering that most counties are situated in what seems to be a "transitional" state, it is clear that non-economic factors, possibly in combination with information delays and "entrepreneurial failures", also affected the geographical spread of steam power technology.[16] In this respect, it must be recognized that the adoption of a new technology involves much more than the assessment of the costs and benefits between different pieces of equipment as it is assumed in the "threshold view" of the diffusion process. In fact, it must be recognized that a wider range of factors beyond the straightforward profitability calculation based on current factor prices, such as the availability of skills in operating the new technology, the expectations concerning possible future technological developments and the overall fit of the new technology with complementary pieces of equipment and other contingent production activities affect the choice-of-technique context, making the individual adoption the outcome of a particularly complex decision process (Gold, 1980).

3.3. An econometric model of engine adoption

In order to shed some additional light on the factors driving the spread of steam power technology we estimate "adoption" equations for eighteenth century steam engines. We focus on the late eighteenth century (1775-1800) and estimate two distinct models for Newcomen and Watt engines. Clearly, the aim is to check whether there were noteworthy differences in the factors driving the diffusion processes of the two type of engines. Our dependent variable is the number of steam engines (Newcomen or Watt) erected in each county in the period 1775-1800. In both cases, the distribution of the variables is skewed, with a non-negligible number of counties having no (i.e., zero) engines. Accordingly, we will make use of negative binomial regressions for estimating the two models (Greene, 2000, pp. 880-893; for a thorough treatment of the regression analysis of count data, see Cameron and Trivedi, 1998). Our explanatory variables are:

i) the price of coal prevailing in the county;
ii) a dummy indicating the level of coal prices in a dichotomous way (i.e. low/high, with low being approximately less than 14 s.). This characterization of the price of coal variable permits us to use the estimation of the regression equation all the counties and not just the 41 for which coal prices are directly available. Furthermore, one could argue that the dummy specification is a more appropriate representation of "threshold" behaviour. The dummy variable has been constructed considering the studies of the coal mining industry of Flinn (1984), von Tunzelmann (1986) and Turnbull (1987);
iii) the number of water-wheels, which can be considered as a proxy for the demand for power (note that in some applications such as ironworks and textiles, steam engines were initially used the operation of water-wheels during drought periods);
iv) the number of steam engines erected in the previous period (i.e., 1734-1774) which captures, admittedly in a rough way, both the familiarity of potential users with steam technology and the (possibly related) level of "mechanical skills" in the county in question;
v) the number of blast furnaces in operation existing in the county c. 1800;
vi) the number of cotton mills existing in the county c. 1800;
vii) the number of wool mills existing in the county c. 1800.

The last three variables provide a measure of the size of industries (ironworks and textiles) that were among the most intensive users of steam power and are included in order to assess the influence of the production structure of the county on the patterns of

[16] This was also the speculative conclusion reached by von Tunzelmann (1978, ch. 4)

engine adoption. A complete description of the sources and the construction of the variables used is given in Appendix 3.2.

Admittedly, our set of explanatory variables is far from covering all the potential factors affecting the diffusion of steam technology in the period in question. In particular, our variables consider mainly factors acting on the demand side. Coal prices reflect the cost of a unit of power for the adopter of a steam engine. However the coefficient can also reflect the use of the steam engine in coal mines (as in coal mining areas coal was cheap). Similarly, the number of water wheels is a proxy for the overall demand of power existing in the county but, at the same time, the variable can also capture some "substitution" or "complementarity" effects between steam and water power.[17]

The sectoral variables (number of blast furnaces, number of cotton mills, number of woollen mills), indicating the size of different branches of economic activities in various counties, control for the different (steam) power requirements of application sectors. Note that our coverage of application sectors cannot by any means considered as exhaustive. Lack of suitable data has prevented us from estimating for a sufficient number of counties the size of sectors which were very intensive users of steam power, such as mining, food and drink (breweries) and waterworks and canals. As already mentioned, the variable "engines erected in the previous period (1734-1774)" aims at capturing the degree of familiarity (of both adopters and suppliers) with steam technology extant in each county. In this sense the variable controls for a mix of effects operating both on the supply and on the demand side.

It is fair to say that our model neglects the possible "proactive" role played by the suppliers of the technology on the diffusion process. As we have already mentioned, the high rates of diffusion for Watt engines estimated in table 3.3 were plausibly not only determined by the superior fuel efficiency of the Watt engines, but also by the effectiveness of Boulton and Watt's organisation of steam engine production and marketing techniques. Since the very outset, Boulton and Watt wanted to establish themselves as a leading "national" producer of steam engines.[18] Instead, the construction

[17] One would expect that abundance of cheap water power in one county had a dilatory effect on steam engine diffusion. However, in many areas steam engines were used in combination of water wheels. In addition, a county characterized by intensive use of water power was likely to be endowed with a strong base of millwrighting skills that could have exerted a beneficial effect in the diffusion of steam power technology.

[18] In a famous letter to Watt (February 7, 1769), Boulton declining the offer of Watt and Roebuck (the first partner of Watt) of becoming the licensee of the Watt engine in three counties, wrote : "…I was excited by two motives to offer you my assistance which were love for you and love of a money-getting ingenious project. I presumed that your engine would require money, very accurate workmanship and extensive correspondence to make it turn to best advantage and that the best means of keeping up the reputation and doing the invention justice would be to keep the executive part out of the hands of the multitude of empirical engineers, who from ignorance, want of experience and want of necessary convenience would be very liable to produce bad and inaccurate workmanship; all of which would affect the reputation of the invention. To remedy which and produce the most profit, my idea was to settle a manufactory near to my own by the side of our canal where I would erect all the conveniences necessary for the completion of engines and from which manufactory we would serve all the world with engines of all sizes. By these means and your assistance we could engage and instruct some excellent workmen (with more excellent tools that would be worth any man's while to procure for one single engine) could execute the invention 20 per cent cheaper than it would be otherwise executed, and with a great difference of accuracy as there is between the blacksmith and the mathematical instrument maker. *It would not be worth my while to make for three counties only, but I find it very well worth to make for all the world*" (quoted in Dickinson and Jenkins, 1927, pp. 30-31, italics added).

of Newcomen engines was mainly undertaken by local manufactures with rather narrower and less ambitious business horizons.[19]

In this respect, Roll (1930) and Dickinson (1936) stressed the fundamental role played by Boulton's entrepreneurial and marketing abilities for the success of the partnership.[20] Boulton's efforts ensured that Watt engines were quickly adopted in a wide range of industrial applications, which before had not made much use of steam power (breweries, textiles, etc.). For example, the erection of the famous Albion Mills in London is frequently pointed out as an example of a successful marketing strategy which succeeded in triggering the interest in steam power of many industrialists (in particular, breweries) in the London area.[21] Another initiative of Boulton and Watt aimed at broadening the use of steam technology was the publication of small technical booklets (of course only reserved for their customers) providing detailed descriptions of the procedures for erecting and operating their engines. In this way, "distant" customers could hopefully cope with minor technical difficulties without the assistance of Boulton and Watt's men.

Furthermore, as recalled in the previous chapter, Boulton and Watt successfully established standard units of measure for both the fuel efficiency (duty) and the power (horsepower) of steam engines. Note that the establishment of a standardized unit of power was an event not only of technically, *but especially of economic* significance (perhaps one of the main determinants of the successful adoption of the engine in various manufacturing applications). The horsepower unit permitted industrialists to have a rather reliable assessment of their power requirements and it also permitted a rough, but rather effective, cost-benefit analysis of the adoption of various power sources. Rules of thumb soon came into common usage for expressing the power requirements of a number of industrial processes (e.g. in cotton spinning 1 horsepower was typically supposed to drive 100 spindles).

From these considerations it is clear that our econometric exercise can hope to provide just a partial appraisal of the determinants of the usage of steam technology in the late eighteenth century. Hence, the results ought to be regarded with care, taking into account not only the possible influence of factors not included in our set of explanatory variables, but also that the interpretation of the coefficients of the variables included in the econometric model is by no means straightforward.

Table 3.4 and 3.5 give the results of the estimates for Newcomen engines. Table 3.4 includes all the specifications with the coal dummy variable (these regressions include all

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[19] For an account of the activities of local producers of atmospheric engines in Lancashire in the second half of the eighteenth century, see Musson and Robinson (1969, pp. 393-426).

[20] In his *Memoir* of Matthew Boulton written in 1809, Watt stressed the role played by Boulton's entrepreneurial abilities (and by his extensive network of acquaintances) for the successful development of the engine partnership: "Boulton....possessed in a high degree the faculty of rendering any new invention of his own or others useful to the publick, by organizing and arranging the processes by which it could be carried on, as well as promoting the sale by his own exertions and by his numerous friends and correspondents" (cited in Dickinson, 1936, pp. 195-196).

[21] The engines constructed for the Albion Mills were among the first rotary double acting engines constructed by Boulton and Watt. The choice of a plant of the almost unprecedented size of the Albion Mills was meant to attract the maximum of attention towards the new engine. From a strictly economic point of view the undertaking was not successful, however, according to many contemporaries, following the purely "mechanical" success of the mill, double-acting rotary engines were adopted in a variety of industrial mills where direct rotary motion was needed (Westworth, 1933). The engine erected at the Albion Mill also convinced some textile manufacturers in the North to install Boulton and Watt engines for powering their mills, see Hills (1970, p. 156).

the observations in our sample), whereas table 3.5 covers the specifications employing the price of coal variable (these regressions refers to a more restricted sample of 41 counties). We have estimated the coefficients considering two different forms of the negative binomial density function. In the first case we have assumed that the negative binomial density function has mean equal to μ and variance equal to $\mu(1+\alpha\mu)$. Cameron and Trivedi (1998, p. 62) refer to this model as "NB 2". In the second case we have assumed a density function with mean equal to μ and variance equal to $\mu(1+\delta)$. This case is termed "NB 1" by Cameron and Trivedi (1998, p. 62). It is possible to test for the actual existence of "overdispersion" (i.e., that the variance is larger than the mean) by verifying that α or δ are different from zero. In our case this was done by means of a likelihood ratio test (Cameron and Trivedi, 1998, pp. 77-78).

Table 3.4: "Adoption" equations for Newcomen engines, 1775-1800

Model	(I)		(II)		(III)		(IV)	
Type	NB 2	NB 1	NB 2	NB 1	NB 2	NB 1	NB 2	NB 1
Number of counties	84	84	84	84	84	84	84	84
Constant	1.122***	1.328***	0.270	0.633**	1.497***	1.855***	1.390***	1.647***
	(0.334)	(0.261)	(0.363)	(0.273)	(0.463)	(0.273)	(0.285)	(0.218)
Dummy Coal	-1.919***	-1.740***			-2.021***	-1.901***	-1.900***	-1.613***
	(0.359)	(0.333)			(0.436)	(0.346)	(0.369)	(0.335)
Waterwheels	0.003	0.004**	0.003	0.002	0.008**	0.004**		
	(0.002)	(0.002)	(0.003)	(0.002)	(0.003)	(0.002)		
Engines	0.079***	0.035***	0.078***	0.046***			0.087***	0.037***
	(0.021)	(0.004)	(0.028)	(0.005)			(0.022)	(0.004)
Blast furnaces	-0.005	0.032*	0.063	0.068***	0.008	0.035	0.011	0.045***
	(0.043)	(0.016)	(0.059)	(0.017)	(0.046)	(0.023)	(0.045)	(0.015)
Cotton Mills	0.003	0.004*	0.015	0.010***	-0.002	0.005	0.008	0.009***
	(0.008)	(0.003)	(0.014)	(0.003)	(0.010)	(0.003)	(0.008)	(0.002
Wool Mills	-0.008	-0.015*	-0.014	-0.008	-0.018	-0.011	-0.001	0.002
	(0.012)	(0.009)	(0.013)	(0.009)	(0.015)	(0.009	(0.011)	(0.004)
α	1.474***		2.586***		2.795***		1.572***	
	(0.391)		(0.603)		(0.630)		(0.403)	
δ		6.268***		9.828***		13.744***		7.331***
		(1.8)		(2.748)		(3.946)		(2.051)
Log likelihood	-172.122	-159.629	-184.825	-173.546	-186.199	-173.969	-173.160	-162.241
Pseudo R^2	0.154	0.215	0.091	0.147	0.084	0.144	0.148	0.202

Notes: Negative binomial estimations. Standard errors in brackets. *,**,*** indicate significance levels of 10,5, and 1%. The α and δ statistic verify the existence of "overdispersion" (χ^2 test).

In all specifications, α and δ are significantly different from zero, confirming the existence of overdispersion and supporting our choice of negative binomial estimations. In this respect, one can note that the existence of overdispersion points to the fact that the data exhibit a higher degree of cross sectional heterogeneity (i.e. clustering in counties with "high" or "low" number of engines), than the case of a spatially homogeneous Poisson process.[22] In other words, the existence of overdispersion points to a pattern of spatial clustering among counties in terms of their extent of steam usage that goes beyond what can be accounted for by our set of explanatory variables. One could actually suggest that this cross-sectional heterogeneity reveals the existence of *county-specific absorptive capabilities* affecting the spread of steam technology.

The coefficient for the coal dummy variable is significant with a negative sign in all the specifications in which it is included. Similarly, the price of coal (whose inclusion restricts

[22] Silverberg and Verspagen (2003) have originally proposed this intuitive interpretation of the overdispersion test in the context of the temporal clustering of "major" innovations.

the sample to 41 counties) is also negative and significant. These results confirm rather clearly that the high coal prices deterred the adoption of Newcomen engines.

The coefficient for the variable "engines erected in the previous period" is positive and significant in all specifications, showing the positive influence of a certain degree of "previous" familiarity with steam technology.

The coefficient for water wheels is significant (with a positive sign), only in the NB 1 type of model. Similarly, also the sectoral variables turn out to be significant only in NB1 type of models. In this respect, one may note that NB1 model seem to display consistently a better "fit" to the data, at least, so far as this is reflected in the "pseudo R^2".

Table 3.5: "Adoption" equations for Newcomen engines, 1775-1800

Model	**(I)**		**(II)**		**(III)**	
Type	NB 2	NB 1	NB 2	NB 1	NB 2	NB 1
Number of counties	41	41	41	41	41	41
Constant	1.817***	2.442***	1.962***	2.509***	2.933***	3.423
	(0.463)	(0.427)	(0.405)	(0.422)	(0.455)	(0.464)
Coal price	-0.003**	-0.007***	-0.003**	-0.006***	-0.004**	-0.008***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)
Water wheels	0.002	0.003*				
	(0.003)	(0.002)				
Engines	0.047***	0.028***	0.049***	0.031***		
	(0.016)	(0.005)	(0.016)	(0.005)		
Blast furnaces	0.047	0.039**	0.059	0.050***	0.065	0.049**
	(0.042)	(0.017	(0.040)	(0.015)	(0.048)	(0.020)
Cotton Mills	0.010	0.006**	0.012*	0.010***	0.011	0.010**
	(0.008)	(0.003)	(0.007)	(0.002)	(0.008)	(0.002)
Wool Mills	-0.015	-0.013	-0.011	-0.001	-0.009	-0.001
	(0.011)	(0.008)	(0.009)	(0.004)	(0.013)	(0.006)
Log likelihood	-126.331	-113.44	-126.515	-115.116	-134.141	-125.594
α	1.190***		1.214***		2.019***	
	(0.359)		(0.362)		(0.520)	
δ		6.970***		8.124***		17.812***
		(2.301)		(2.626)		(5.853)
Pseudo R^2	0.096	0.188	0.095	0.176	0.040	0.101

Notes: see Table 3.4

The coefficient for the blast furnaces appears to be higher than the one for cotton mills, indicating a stronger relationship between iron manufacturing and the adoption of Newcomen engines. These results probably reflect the different degree of familiarity that these user sectors had with the Newcomen engine. Newcomen engines were successfully adopted in ironworks from the early 1740. Instead they had begun to be used to drive cotton machinery only from the 1780s. In general, the motion they delivered was rather unsteady and it was not particular suited for powering textile machinery (Hills, 1970, pp. 141-143). Some ingenious technical solutions that could mitigate this problem were introduced in the early 1790s by Francis Thompson and Bateman and Sherrat for Newcomen engines installed in cotton mills in Lancashire and Nottinghamshire (Hills, 1970, pp. 147-148). Finally, it is worth noting that the adoption of Newcomen engines in ironworks and in cotton mills in the period we are considering was limited by the competition of Watt engines. Unfortunately, lack of suitable data has prevented us from assessing the impact of the main sector of application of the Newcomen engine, coal mining.

The coefficient of the wool mills variable is not significant (with the only exception of regression I (NB1) in table 3.4 where it has a negative sign). This can be accounted for by the fact that the transition to steam power mechanization in the wool textile industry (which was concentrated in Yorkshire (West Riding) and in the West of England) was much slower than in cotton. Furthermore, in this industry, the diffusion of steam technology proceeded at two very different paces in the two areas. In West Riding, atmospheric returning engines were rapidly and rather successfully adopted for power carding and spinning machines (jennies). Table 3.2 indicates that about 100 engines were installed in West Riding by 1800. Instead in the other wool regions of the West of England (Gloucester, Wiltshire) and of Scotland, steam power technology was introduced very slowly (Jenkins and Ponting, 1982, pp. 50-56). The combined effect of these two contrasting patterns of adoption can help explain why the coefficient for wool mills is not significant in the majority of the specifications.

Tables 3.6 and 3.7 contain the results of the set of regressions having the number of Watt engines as dependent variable. As in the case of Newcomen engines, the tests on α and δ confirm the presence of overdispersion, upholding our choice of negative binomial estimations.

Table 3.6: "Adoption" equations for Boulton & Watt engines, 1775-1800

Model	(I)		(II)		(III)		(IV)	
Type	NB 2	NB 1	NB 2	NB 1	NB 2	NB 1	NB 2	NB 1
Number of counties	84	84	84	84	84	84	84	84
Constant	0.524	0.970***	0.036	0.616**	1.082*	1.420***	0.608	1.162***
	(0.469)	(0.366)	(0.399)	(0.296)	(0.628)	(0.337)	(0.388)	(0.318)
Dummy Coal	-0.831*	-0.555			-0.341	-0.934***	-0.821*	-0.541
	(0.466)	(0.355)			(0.555)	(0.328)	(0.463)	(0.357)
Water wheels	0.001	0.002	0.001	0.002	0.004	0.003		
	(0.003)	(0.002)	(0.003)	(0.002)	(0.004)	(0.002)		
Engines	0.113***	0.033***	0.101***	0.038***			0.113***	0.034***
	(0.028)	(0.007)	(0.027)	(0.005)			(0.028)	(0.006)
Blast furnaces	0.0002	0.061***	0.044	0.076***	0.054	0.060**	0.006	0.066***
	(0.055)	(0.022)	(0.052)	(0.019)	(0.057)	(0.026)	(0.052)	(0.021)
Cotton mills	0.008	0.011***	0.015	0.013***	0.008	0.010***	0.009	0.013***
	(0.010)	(0.003)	(0.011)	(0.003)	(0.012)	(0.004)	(0.009)	(0.002)
Wool mills	0.002	-0.016	0.009	-0.016	-0.011	-0.014	0.003	-0.006
	(0.014)	(0.011	(0.014)	(0.011)	(0.016)	(0.011	(0.014)	(0.006)
α	2.351***		2.452***		4.165***		2.346***	
	(0.516)		(0.542)		(0.821)		(0.515)	
δ		10.805***		10.457***		14.941***		10.916***
		(3.076)		(2.956)		(4.350)		(3.095)
Log likelihood	-166.275	-164.164	-167.919	-165.364	-181.911	-170.660	-166.329	-164.754
Pseudo R^2	0.114	0.125	0.105	0.119	0.031	0.090	0.114	0.122

Notes: see Table 3.4.

The coal dummy is significant with a negative sign in three specifications (equation I (NB 2), equation III (NB 1) and equation IV (NB 2)). It is worth noting that the (negative) coefficient is lower than in the Newcomen case. In our interpretation, rather than reflecting a direct impact of coal price on the adoption of Watt engines, this result is due to the fact that a number of counties with high levels of coal prices were also "peripheral" or "rural" counties with low demand for steam power. In particular, this is true for the "northern" Scottish counties. In fact, when the model is specified in terms of coal prices (as we have said, this reduces the sample to 41 counties, centred essentially on "industrial" counties (North of England, Wales, South of Scotland), see Appendix 3.2), the coal price coefficient appears to be generally *positive* and significant, providing support for the idea that high coal prices tend to enhance the adoption of Boulton and Watt engine, on account of their superior fuel efficiency.

The coefficient for the variable "engines erected during the previous period" is positive and significant in all specifications (as it was for Newcomen engines). The coefficient for the number of water wheels, instead, is never significant.

Table 3.7: "Adoption" equation for Boulton & Watt engines, 1775-1800

Model	**(I)**		**(II)**		**(III)**	
Type	NB 2	NB 1	NB 2	NB 1	NB 2	NB 1
Number of counties	41	41	41	41	41	41
Constant	0.794*	1.111***	0.554	1.053**	1.502***	1.918***
	(0.426)	(0.426)	(0.391)	(0.415)	(0.436)	(0.378)
Coal price	0.003**	0.002*	0.003**	0.002*	0.002	0.0004
	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.001)
Water wheels	-0.003	-0.001				
	(0.002)	(0.002)				
Engines	0.046***	0.033***	0.044***	0.032***		
	(0.011)	(0.006)	(0.011)	(0.006)		
Blast furnaces	0.076**	0.060***	0.058**	0.058***	0.064*	0.057**
	(0.034)	(0.018)	(0.030)	(0.018)	(0.034)	(0.022)
Cotton Mills	0.017***	0.014***	0.014***	0.013***	0.013**	0.012***
	(0.006)	(0.003)	(0.005)	(0.002)	(0.006)	(0.003)
Wool Mills	0.005	-0.003	0.0004	-0.007	-0.006	-0.004
	(0.010)	(0.009)	(0.009)	(0.006)	(0.010)	(0.006)
α	0.854***		0.891***		1.479***	
	(0.221)		(0.227)		(0.329)	
δ		7.847***		7.948***		13.339***
		(2.338)		(2.363)		(3.937)
Log likelihood	-121.9162	-123.5604	-122.6542	-123.6762	-132.7414	-131.1648
Pseudo R^2	0.1154	0.1035	0.1101	0.1027	0.0369	0.0483

Notes: See table 3.4.

Turning our attention to the role of application sectors, tables 3.6 and 3.7, in a number of specifications, report a positive and significant sign for the number of cotton mills and the number of blast furnaces. (In table 3.6 the sectoral variables are significant only in NB 1 regressions, as in the case of Newcomen engines, the NB 1 is characterized by a better fit as measured by the "pseudo R^2"). Notably, the size of these coefficients is similar to the ones reported for Newcomen engines. This finding is indeed fully in line with historical accounts that pointed out that ironworks and cotton mills were among the first intensive users of the Watt engines. However, it should be noted that in the case of Watt engines as well, our adoption equations do not include a number of application sectors which were intensive users of Watt engines such as (non-coal) mining ventures, breweries, etc., and that, for this reason, the estimates of the impact of application sectors should be considered with care. Finally, as in the case of the Newcomen engines, the coefficient for wool mills is not significant.

3.4. Concluding remarks

In this chapter we have provided a reconstruction of the patterns of diffusion and adoption of steam engine technology during the eighteenth century. Furthermore we have also attempted to assess the influence of various explanatory factors on the diffusion process. Our findings indicate that the level of coal prices was indeed one of the major determinants of the distinctive patterns of adoption of Newcomen and Watt engines, giving further support to the previous studies of von Tunzelmann (1978) and Kanefsky (1979). However, it is also clear that, together with the level of coal prices, a number of other factors were also at work. In this respect it must be also acknowledged that Newcomen and Watt are rather "broad" categories. As we have noted in chapter 2, different versions of these designs were actually available. The specific design of the engine did not only determine its fuel efficiency, but also the *quality* of the power delivered (smoothness and regularity of motion, susceptibility to breakages, easiness of maintenance etc.). Not surprisingly, particular engine designs turned out to better suited for specific applications than others (in some cases, despite their level of fuel efficiency). This issue is examined in more detail in the next chapter.

Our exploration of the patterns of diffusion has revealed that steam engine technology was, from a very early stage, integrated rather successfully into the different regional production systems which comprised the British economy during the eighteenth century (see Pollard, 1981 for an overview of these regional economies). However, our econometric analysis also indicates that, in the course of the eighteenth century, the regional patterns of usage of steam technology displayed considerable spatial diversity, reflecting the direct influence of locational determinants such as the price of coal and the production structure of the various counties, but, possibly, also of more complex and idiosyncratic factors impinging on the absorptive capabilities of the individual counties. In a more general perspective, this finding confirms the need of taking regional differences properly into account when examining the process of technical change during the British industrial revolution (Hudson, 1989).

These considerations also provide some indications for further research. As noted by Dosi:

....[T]he 'logistic curves' approaches to technological diffusion.....show the same descriptive usefulness as well the same limitations of the epidemic curves (or, for that matter, probability models) to which they are formally similar: they show the pattern of diffusion of, say cholera, and they can also relate it to some broad environmental factors, such as the conditions of hygiene of a town, the reproduction time of bacteria, etc. but they cannot explain *why* some people get it and other do not, which relates to the immunological mechanisms of human bodies, the precise ways bacteria are transmitted, and so on. (Dosi, 1984, p. 286, italics in the text).

Thus, our reconstruction of the patterns of diffusion needs to be supplemented by further research on the "microbiology" of the diffusion process. In this respect, it would be wrong to assume that the diffusion of Newcomen and Watt engines proceeded neatly along "equilibrium" paths. Some of the available evidence on individual adoption decisions reveals that at the county level, the process of diffusion was driven by an "epidemic" information spread. For example, Boulton and Watt frequently asked their "first" customers in different counties to let potential buyers inspect the engines they had just installed (Hills, 1970, p.156 and p.158). Furthermore, one should also consider the "proactive" role played by the suppliers of the new technology. As a consequence, the high rates of diffusion of Watt engines estimated in table 3 are not simply determined by the superior fuel efficiency of the Watt engine, but they also reflect the effectiveness of Boulton and Watt's organisation of steam engine production and marketing techniques. The wider spread of Watt engines should be also considered in this light. As we have already noted, historians such as Dickinson (1936) and Roll (1930) have highlighted the critical role played by Boulton's entrepreneurial and marketing abilities, which ensured that steam power, in the form of the Watt engine, was quickly adopted in a wide range of industrial applications (e.g. the food industry especially breweries, textiles, etc.). Overall, the early diffusion process of steam technology in each county appears to have been driven by a complex interplay of factors (coal prices, production structure, local endowments of engineering skills, but also information delays and entrepreneurial failures) acting contextually both on the user's and the supplier's side. On theoretical grounds, one could consider this proposed interpretation (which, of course, needs to be corroborated by further research) as broadly consistent with "evolutionary" types of diffusion models, where patterns of technological diffusion are conceived as the emerging outcome of micro-processes of technological learning and market selection among boundedly rational agents (Silverberg, Dosi and Orsenigo, 1988).

Appendix 3.1: The Moran I statistic

Moran I statistic is essentially a correlation coefficient which assesses the degree of spatial autocorrelation of a spatial variable. Assume that the variable x is defined over a number locations n. We can construct a matrix W (spatial contiguity matrix) which indicates whether two counties have borders in common or not. The matrix is symmetric and each element w_{ij} is equal to 1 when the locations i and j a border in common and to 0 otherwise. The elements on the main diagonal of the contiguity matrix are equal to 0. In this case Moran I statistic is equal to

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} z_i w_{ij} z_j}{2\cdot(\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij})\cdot\sum_{i=1}^{n} z_i^2}$$

where is $z_i = x_i - \bar{x}$ (the deviation of x_i from the mean). Higher values of I indicate a stronger degree of (positive) spatial autocorrelation. Cliff and Ord (1981, pp. 42-46) illustrate how to compute significance intervals for Moran's I under two different hypotheses: the first one is that the observations x are normally distributed (normality assumption) whereas the second one (randomised) assumes that the realizations of x were extracted from one of the possible $n!$ permutations of the n values of the variable x over the n locations.

Appendix 3.2: Sources and construction of the data

Number of steam engines ("atmospheric" and Boulton & Watt) installed during the period 1775-1800 and number of engines installed in the period 1734-1774.
Data taken from the updated version of the Kanefsky and Robey (1980) list.

Price of Coal, c. 1800.
Data taken from von Tunzelmann (1978, p. 148). The 41 counties for which coal prices were available are:
Cornwall, Devon, Wiltshire, Hampshire, Berkshire, Surrey, Middlesex (London), Kent, Cambridge, Northampton, Oxford, Leicester, Warwick, Worcester, Gloucester, Monmouth, Glamorgan, Shropshire, Stafford, Anglesey, Caernarvon, Denbigh, Cheshire, Derby, Nottingham, Lancashire, East Riding, West Riding, North Riding, Durham, Northumberland, Cumberland, Ayr, Renfrew, Lanark, Stirling, Argyll, Clackmannan, Midlothian, Fife, Angus.

Coal dummy, c. 1800.
The variable distinguishes between "cheap" and "dear" coal counties. Counties with coal prices higher than 16 s. per ton are considered as having a "high" price of coal. The counties have been assigned on the basis of the price list in von Tunzelmann (1978, p. 148) and of the maps and discussion of Flinn (1984), von Tunzelmann (1986) and Turnbull (1987).

Low coal price counties:
Cheshire, Cumberland, Derby, Durham, Lancashire, Leicester, Monmouth, Northumberland, Nottingham, Shropshire, Stafford, Warwick, Worcester, West Riding, East Riding, Carmarthen, Denbigh, Flint, Glamorgan, Pembroke, Angus, Ayr, Berwick. Clackmannan, Dunbarton, East Lothian, Fife, Kinross, Lanark, Midlothian, Renfrew, Stirling, West Lothian.

High coal price counties:
Bedford, Berkshire, Buckingham, Cambridge, Cornwall, Devon, Dorset, Essex, Gloucester, Hampshire, Hereford, Hertford, Huntingdon, Kent, Lincoln, Middlesex (London), Norfolk, Northampton, Oxford, Rutland, Somerset, Suffolk, Surrey, Sussex, Westmorland, Wiltshire, North Riding, Anglesey, Brecknock, Caernarvon, Cardigan, Merioneth, Montgomery, Radnor, Aberdeen, Argyll, Banff, Caithness, Dumfries, Inverness, Kincardine, Kircudbright, Moray, Nairn, Peebles, Perth, Ross and Cromarty, Roxburgh, Selkirk, Sutherland, Wigtown.

Water-wheels, c.1800.
Data taken from Kanefsky (1979), pp. 215-216. The data have been constructed on the basis of contemporary maps (i.e. they are presumably likely to underestimate the actual figures). For more details, see Kanefsky (1979).

Blast furnaces, c.1800.
Data taken from Scrivenor (1854). The original source is a government survey after the proposal of a tax on coal. The data refer to the year 1796 .

Cotton Mills, c. 1800.
Data taken from Chapman (1970, pp. 257-266). Chapman's figures are based on insurance records and they mostly refer to the year 1795. For Lancashire we have estimated a figure of 204 mills, which is based on the assumption that the county had 50% of large mills (types B and C) and 50% of type A (i.e., small) mills. This is in line with the considerations contained in Chapman's paper.

Wool Mills, c. 1800.
Data taken from Jenkins and Ponting (1982, pp. 34-38). The data refer to the year 1800. When more detailed information was lacking, an equal share of wool mills was assigned to the counties contained in the larger regions for which Jenkins and Ponting provide figures for the number of wool mills.

4. The Early Development of the Steam Engine: An Evolutionary Interpretation using Complexity Theory[1]

4.1. Introduction

Traditional accounts of the history of the steam engine, such as Thurston (1939) or Dickinson (1938), have described the early development of this technology as a "linear" succession of technological breakthroughs. In these works, the process of technical change is essentially conceived as a sequence of rather dramatic "acts of invention" with individual inventors successfully tackling the shortcomings of the existing "state of the art" by contriving technical improvements that made extant designs obsolete (the line Savery-Newcomen-Watt-Trevithick (Woolf), which also surfaces from the account presented in chapter 2). In this way, technological evolution seems to have been characterized by an almost inescapable logic of progression. Indeed, in the most extreme versions (Thurston, 1939), such a historical depiction is akin to chronicling a sort of "glorious march of invention". Implicit in this clean-line narrative is the notion that the evolution of a technology consists in a process of successive "discrete" innovations with novel (better performing) technologies replacing the established ones.

Of course, it must be recognized that the study of the specific technical merits of individual inventions *vis-à-vis* the existing state of the art is an inevitable component of any account of the long-term evolution of a technology. However, as emphasised by Rosenberg (1976), this perspective, although capable of illuminating some critical facets of technological development, leaves us with an incomplete appreciation of the overall process of technological change. A deeper understanding calls for a broader narrative frame in which attention is not only devoted to the original acts of invention, but also to the phases of adoption and diffusion of the technology. Innovations are not typically born "fully-developed" in clearly defined instants of time as is assumed in the traditional Schumpeterian distinction between invention, innovation and diffusion. In fact, during the diffusion phase, an innovation constantly changes, incorporating a number of refinements and design modifications. The aim of these "secondary" innovations is to increase the versatility of the technology so that it can satisfy different sets of users' requirements. As the evidence presented in the previous chapter indicates, at least to a degree, the diffusion process of steam engine technology was affected by the diverse needs of application sectors.

In this chapter we offer an interpretation of the early history of the steam engine, which tries to integrate patterns of invention and diffusion in a unified account. In order to do so, we represent the development of steam power technology as a search process in a multidimensional design space. This conceptualisation allows us to make use of recent insights emerging from complex systems theory. In particular, we will make use of a generalised version of Kauffman's NK model that regards technological evolution as a trial and error search process on a fitness landscape. The generalised version of the NK-model allows us to consider the role played by distinct selection environments, reflecting the different contexts of application of particular designs. We also set out a framework based on entropy statistics, which is susceptible of a relatively straightforward

[1] This chapter is based on Frenken and Nuvolari (2004).

interpretation in terms of the NK model. In this way, we are able to provide a systematic description of the patterns of variety and speciation characterizing the early history of the steam engine.
Our empirical results will show that technological evolution in early steam engines was characterised by growing variety and differentiation into distinct design species. Our interpretation of this pattern points to the crucial influence exerted by different application domains on the evolution of the technology. Early steam engine designs were characterised by a number of trade-offs between the relevant performance attributes, so that each of them resulted more or less "fit" into a specific "ecological" niche. In other words, application domains represented distinctive selection environments. These distinct selection environments prompted the emergence of differentiated design trajectories. As we will see, this process is akin to 'speciation' in biology.

4.2. Technical change as a search process on rugged fitness landscapes

In this section, we set out an interpretive framework for the study of technological evolution, which is based on Altenberg's (1994, 1997) generalisation of Kauffman's (1989, 1993) NK-model of fitness landscapes.

Our starting point is the notion of design space (Bradshaw, 1992), which allows us to describe technological change as a search process on a fitness landscape. A design space specifies the principal technical dimensions, or constituting elements, of a technology, so that each design can be represented by a point in a multi-dimensional space. Let N denote the principal dimensions of the technology in question ($i=1,\ldots,N$). Each dimension i can assume A_i possible states, which, maintaining the biological term, we will call 'alleles', coded as "0","1", "2", etc. For example, in the steam engine case, we can distinguish, among others, the dimension "steam pressure" (0=low/1=high) and the dimension "condenser" (0=present/1=absent). In this way, each possible design s can be described by a string $s_1s_2...s_N$, such that:

$$s \in S \; ; \; s = s_1 s_2 ... s_N \; ; \; s_i \in \{ 0 , 1 , ... , A_i - 1 \} \qquad (1)^2$$

Correspondingly, the overall size of the design space is constituted by all possible combination between alleles and is given by the product of the number of alleles per dimension:

$$S = \prod_{i=1}^{N} A_i \qquad (2)$$

We assume that each point of the design space is endowed with a certain level of overall technological performance ("fitness") and that the designers' task consists in the identification of those points of the design space capable of delivering high levels of fitness.

As technological artefacts are typically constituted by many dimensions and by many alleles for each dimension, they have enormous design spaces. In these conditions, searching for the optimal design by simply testing all possible combinations between alleles would generally be a too costly strategy, given the high number of possibilities.

[2] Note that, since the first allele is labelled as "0", for each dimension the possible alleles range from 0 to A_i-1.

Furthermore, it is likely that the constituting elements of the technology will be in some interdependent, that is to say, that the "functioning" of each constituting element will depend not only by the present configuration of its own state (allele), but also by the state of some of the other elements. In this way, each time one tries to improve the functioning of one element by means of variation of its state, new problems may arise in other components that will have to be accordingly re-designed.

For these reasons, search activities on the design space, in most cases, will not simply boil down to the straightforward combinatorial problem of finding the optimal design configuration by changing each constituting element in succession, rather the design task amounts to applying search strategies that permit to find a string with reasonable performance (*fitness*) in a relatively short time. Designers will typically follow satisficing rather than optimising strategies (Simon, 1969; Frenken, 2001). Accordingly, designers will apply search rules that allows to economise time and resources by examining only subsets of the design space. Thus, only a restricted of the design space will be actually searched, and an even more restricted part will be actually introduced on the market.

The NK model was developed by Kauffman (1989; 1993) to study the properties of evolving systems characterized by varying degrees of complexity. In Kauffman's NK model, each of the constituting elements of the system performs a distinct function, that contributes in a strictly proportionate way to the total fitness of the system. In our steam engine case, as we have noted above, constituting elements include design dimensions such as one or two cylinders, open or closed top, condensing or not condensing, etc. Correspondingly, functions of the technology include performance attributes such as fuel-efficiency, maintenance cost, power, safety, etc. The interdependencies among between the constituting elements of the system are called "epistatic relations". The existence of epistatic relations implies that when a component changes its own state, this mutation does not affect only the functioning of the component in question but the functioning of all the components that are "epistatically related" to it. The ensemble of all epistatic relations is called "architecture" of the system (Frenken, 2001). Given these assumptions, the total fitness of the system is given by:

$$W(s) = \frac{1}{N}\sum_{i=1}^{N} w_i(s) \tag{3}$$

where $W(s)$ is the total fitness of the string s, N the number of constituting elements and $w_i(s)$ the individual fitness of element i.

Table 4.1: Example of the architecture of a system with N=3 and K=1

	i=1	i=2	i=3
w_1	**x**	x	-
w_2	x	**x**	-
w_3	x	-	**x**

The parameter N indicates the number of constituting elements of the system and the parameter K the number of epistatic relations. For example, the class of systems with K=1 refers to systems with an architecture in which the functioning of each component depend on its own state and on the state of one of the other components. Thus, the parameter K is an indicator of complexity with K=0 being the least complex architecture (in this case the functioning of each component depend only by its own state) and

$K = N - 1$ the most complex one (in this case the functioning of each component depend by its own state and by the states of all the other dimensions of the system).

Consider as explanatory example a system with N=3 and K=1 whose architecture is specified in table 4.1. In table 4.1, changes of state (mutations) in the components in the columns affecting the functioning of the component in the row are indicated with "x". Vice versa, the symbol "-" indicates that there is no epistatic relation between the component in the row and the one in the column. In our case, the functioning of the first component w_1 is affected by mutations of the first and the second component, the functioning of the second component w_2 is affected by mutations in the first component and in the second component, and the functioning of the third component w_3 is affected by mutations in the first and in the third component. To construct a simulated fitness landscape corresponding to the architecture presented in table 4.1, each time one of the components is mutated by a variation of its allele, it is necessary to assign a new fitness value $w_i \in [0,1]$ to all the functions that are affected by the change according to the system's architecture.[3]

Strings	w_1	w_2	w_3	W
000:	0.7	0.2	0.3	0.40
001:	0.7	0.2	0.6	0.50
010:	0.9	0.3	0.3	0.50
011:	0.9	0.3	0.6	0.60
100:	0.8	0.7	0.1	0.53
101:	0.8	0.7	0.4	0.63
110:	0.3	0.5	0.1	0.30
111:	0.3	0.5	0.4	0.40

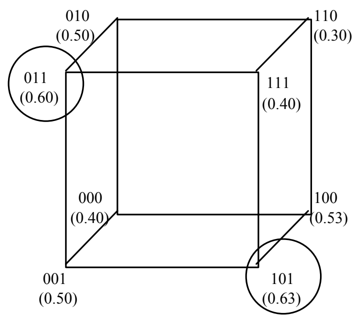

Figure 4.1: Simulation of a fitness landscape with N=3 and K=1

A simulated fitness landscape for a system (with only two possible alleles 0 and 1 for each constituting element) corresponding to the architecture of table 4.1 is given in figure 4.1.

The two circled strings (011 and 101) are local optima or "peaks" of the rugged fitness landscape. All the neighbouring points (i.e., strings that are different only in one the allele of one single component) of these designs have lower levels of total fitness. The global optimum for the system is the string 101 with a total fitness level of 0.63.

We would contend that the conceptualisation of the design space as represented using the NK model nicely captures the salient features of the model of blind variation and selective retention proposed by Walter Vincenti in his studies of engineering design activities in the aircraft industry (Vincenti, 1990, chap. 8; Vincenti, 1994). Starting from a given point in the design space, search proceeds by introducing a mutation in one of the constituting elements (blind variation). The introduction of the mutation means that the designer is moving in a neighbouring string in the design space. If this newly discovered

[3] In simulated NK landscapes the fitness values are usually extracted from the uniform probability distribution over the interval [0,1].

design has a level of total fitness $W(s)$ higher than the original string, the mutation is accepted, whereas it is rejected in case the mutation brings about a decrease of total fitness (selective retention). When a mutation is accepted, search will proceed from the newly discovered design. On the contrary, when the mutation is rejected search continues from the original string.

Following this procedure, a designer can improve the fitness of the system until the attainment of a local optimum. When the local optimum is reached, it is clearly not possible anymore to achieve improvements in the total fitness of the system by means of mutations in one dimension. Hence, this type of search procedure can be considered as an "adaptive walk" over the fitness landscape towards local optima ("hill climbing"). Search will end when a local optimum design is reached.

It should be stressed that we have used the relative simple case if N=3 exclusively for explanatory purposes. In real-world engineering design activities the number of design dimensions will obviously be much higher. Consequently, search will typically take place in much larger design spaces and the probability of reaching a locally (rather than a globally) optimum design will correspondingly be much higher.

Altenberg's generalised NK approach

Recently Altenberg (1994, 1997) has suggested a rather straightforward generalisation of the NK model. In Altenberg's model, the fitness landscape is constructed by assigning individual fitness values to a number F of functions ($f=1,\dots,F$) for each possible point s of the design space. In this respect, one can note the analogy with genetic strings that are also composed by a set of alleles describing the genotype of the organism, and by a list of traits (phenotype), which are subject to the selection pressure of the environment. The difference between Altenberg's and Kauffman's models is that in the former the number of dimensions N is not necessarily equal to the number of functions F while in the latter approach it is assumed that N is equal to F. Hence, Altenberg's model is a generalisation of Kauffman's because it can represent a complex system with any number of design dimensions and with any number of functions.

The first step to apply Altenberg's model to the study of technological evolution is to identify the N constituting elements, or design dimensions, of the technology in question and the F functions it performs. In this way, the 'architecture' of the system can be represented by means of a "genotype-phenotype map".

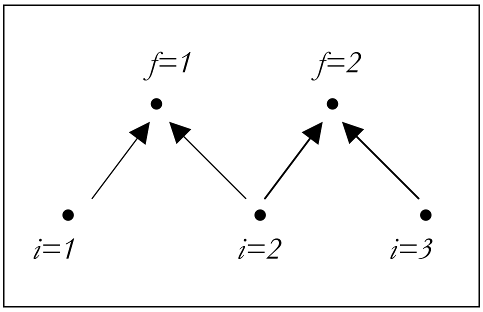

Figure 4.2: Example of a genotype-phenotype map (*N=3*, *F=2*)

In case of technologies, the map (or matrix) indicates which design dimension affects which function. Figure 4.2 gives an example of a map for a system with three design dimensions ($N=3$) performing two functions ($F=2$). Note that the mapping of the N design dimensions (describing the internal structure of the technology) to the F functions (describing the services that the technology performs for its users) is a way to represent the "imaging" of technical characteristics onto service characteristics posited by Saviotti and Metcalfe (1984).

The *pleiotropy* of a design dimension is defined as the number of functions that are affected by changes of its allele. Correspondingly, the *polygeny* of a function is defined as the number of design dimensions whose changes have an effect on its fitness.[4] In the example of figure 4.2 the *polygeny* of both functions is equal to two, while the *pleiotropy* of design dimensions *i=1* and *i=3* is equal to one and the *pleiotropy* of design dimensions *i=2* is equal to two. It is also possible to represent architecture of the system by means of a matrix of size F x N analogous to the one displayed in table 4.1.

Table 4.2: Example of a generalized genotype-phenotype matrix.

	i=1	i=2	i=3
f=1	x	x	-
f=1	-	x	x

Table 4.2 presents the matrix corresponding to the genotype-phenotype map of figure 4.2. As in the notation above, "x" indicates that the element in the columns affects the function in the row, whilst "-" indicates that the function in the row is not affected by the state of the element in the column.

Any complex system can be described by N, F and the matrix specifying the relationships between design dimensions and functions. *Polygeny* of functions implies that for maximising the value of one function is necessary to properly tune all the dimensions that have an effect on it. However, since designs dimensions are generally *pleiotropic* (i.e. they typically affect more than one function), maximising one function by tuning several dimensions will generally imply a loss of performance in other functions.

To construct the fitness landscape corresponding to a particular dimension-function map, it is necessary to assign a new fitness value w_f for each function f of the system, when a mutation occurs in one of the dimensions that affect function f. In other words, each time a dimension is mutated by changing its allele, all the functions that are affected by the change according to the genotype-phenotype map are assigned a new fitness value $w_f \in [0,1]$. The total fitness *W* of a design string *s* can be expressed as the mean of the fitness values of all the *F* functions:

$$W(s) = \frac{1}{\mathrm{F}} \cdot \sum_{f=1}^{\mathrm{F}} \mathrm{w}_{\mathrm{f}}(s) \qquad (4)$$

A simulation of the fitness landscape example of the genotype-phenotype map of figure 4.2 is given in figure 4.3. Local optima are circled reflecting the strings of alleles that are *complementary*: any mutation in one dimension would lead to a decrease in total fitness. As in the previous example, hill-climbing search leads a designer to a local optimum. The precise local optimum that is found depends on the starting string and the sequence of mutations that followed hereafter The existence of local optima reflects the trade-offs

[4] Kauffman's (1993) original NK model can now be interpreted as a special case of Altenberg (1994, 1997) model with F=N and polygeny equal to K+1 for all the N dimensions.

between functions: in our example, increasing the fitness of one function can only be achieved by lowering the fitness of the other one and *vice versa*. Design 000 is optimal with regard to the first function and design 110 with regard to the second function, while there exists no design that is optimal in terms of both functions. The number of local optima in a fitness landscape (or its "ruggedness"), increases for increasing polygeny (complexity of the artefact) and increasing N (dimensionality of its design space) (Kauffman, 1993; Altenberg, 1994). [5]

String	w_1	w_2	**W**
000:	0.8	0.9	0.85
001:	0.8	0.6	0.70
010:	0.4	0.3	0.35
011:	0.4	0.2	0.30
100:	0.2	0.9	0.55
101:	0.2	0.6	0.40
110:	0.9	0.3	0.60
111:	0.9	0.2	0.55

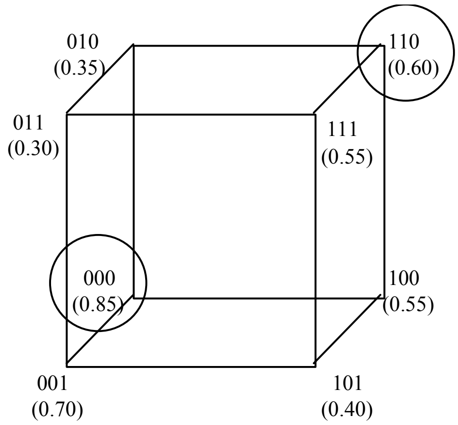

Figure 4.3: Simulation of the fitness landscape for the genotype-phenotype map of table 4.2

Alternative fitness functions

It is possible to introduce a second generalisation in Kauffman's original NK-model by adopting a more general specification of the fitness function. The fitness function in equation (4) assumes that the total fitness of the system is equal to the mean of the fitness of the individual functions (i.e., each function is equally weighted by users). Though in simulation models this formulation may be convenient, the equation obviously does not account for the (more general) case in which users apply different weights to different functions (as is assumed in hedonic price regressions). In fact, users will generally rank the various functions differently giving more importance to some performance attributes rather than to others. A simple specification capturing the different ranking of functions is given by:

$$W(s) = \sum_{f=1}^{F} \beta_f \cdot w_f(s) \qquad (5.1)$$

$$\sum_{f=1}^{F} \beta_f = 1 \ , \ \beta_f > 0 \qquad (5.2)$$ [6]

[5] If polygeny is equal to one for all functions, only one global optimum exists in the fitness landscape, which is always found by hill-climbing. In this case, all functions are only affected by one dimension, so that the state of each dimension will never interfere with the state of another element. Furthermore, note that a polygeny value of one for all functions corresponds to K=0 in Kauffman's original NK model (given F=N).

[6] This is a relatively simple fitness function. One can envisage other functional forms, including for example a Cobb-Douglas type of fitness function $W_g(s) = \prod_{f=1}^{F} w_f(s)^{\beta_f}$. The choice of the specific

The concept of a fitness landscape does not change when total fitness is computed as a weighted sum instead of the simple mean of fitness values. However, the values of total fitness of each design *W(s)* will be different depending on the values of the weights that are applied.

User heterogeneity

Another rather straightforward generalisation of the NK model is to allow for demand heterogeneity among users (Frenken, 2001). So far, we have implicitly assumed that each user of a particular design applies the same set of weights β_f and thus assigns the same fitness value *W* to a design *s*. However, users can evaluate differently the functional attributes of the technology and apply different weights to them (Lancaster, 1979). In this way, different users' groups can assign different values of total fitness to one and the same design.

Formally, the weights assigned to functions as specified above $\{\beta_1, \beta_2, \dots, \beta_F\}$ reflect one homogeneous user group. When there exist more than one user group, we can characterise each user group by a different set of weights. For a *G* number of user groups ($g=1,\dots,G$), the fitness W_g for user group *g* of a design is derived by the following equation:

$$W_g(s) = \sum_{f=1}^{F} \beta_{fg} \cdot w_f(s) \tag{6.1}$$

$$\sum_{f=1}^{F} \beta_{fg} = 1 \ , \ \beta_{fg} \geq 0 \tag{6.2}$$

When users' preferences are more dispersed, it is less likely that one design will be optimal for all user groups, and one might expect product differentiation to arise in the multi-dimensional Hotelling-like space (Hotelling, 1929) spanned by the *F* functions. In the extreme case, given a sufficiently large design space, a different design may be found for each different user group. Furthermore, when user groups exist for which the available designs do not provide extremely satisfactory solutions, search for designs can be prompted in new directions in order to find configurations of alleles better suited to their demands ("induced innovation"). Also note that when users are heterogeneous, the concept of local optima change: strings are no longer necessarily locally optimal for all users, but locally optimal for one or more user groups.

Implications

A number of implications follow from the generalised NK-model:

(i) When demand is homogeneous (*G=1*) and complexity is absent (i.e., polygeny is equal one for all functions and pleiotropy is equal to one for all elements) there exists only one global optimum (Kauffman, 1989, pp. 544-545).

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functional form, of course, will depend on the specific features of system (in particular, the various degrees of "substitution" and "complementarity" among functions) that the model is supposed to represent.

(ii) When demand is heterogeneous (G>1) and complexity is absent there exists only one global optimum, which is the same string for all the user groups. In this case, since there is no interdependency among design dimensions, each function can be optimised independently from the others. The global optimum is the point of the design space with the highest fitness level for each function and, for this reason, it is preferred by all user groups (note that this result does not hold in case - not considered in formula 6.2 - some functions are valued negatively by some user groups).

(iii) When demand is homogeneous and complexity is present (i.e. polygeny is greater than one for at least one function), the fitness landscape might contain local optima. The expected number of local optima is a function of polygeny (Kauffman, 1989, p. 563). Thus, technological differentiation can occur when different designers come up with different, locally optimal solutions that have similar total fitness values. Differentiation means here that multiple designs are more are less equally capable of meeting the functional requirements of the homogenous users.

(iv) When demand is heterogeneous and complexity is present, both differentiation and speciation can occur. Differentiation among designs may occur within a user group because of the possibility of local optima as in (iii). Speciation, which in this context is understood as the "specialisation" of different designs into different areas of application (constituting distinct selection environments), can occur as heterogeneity in preferences may render different designs to be (globally or locally) optimal for different user groups.

In this perspective, the processes of innovation and technological substitution can be related to the degrees of complexity and demand heterogeneity of the technology in question. When complexity is absent (or very low), the introduction of an innovation (modelled as the introduction of a new string) will trigger a process of technological substitution provided that the new design has higher overall fitness. Instead, when complexity is high, due to the existence of interdependencies, the new design may have higher fitness values for some functions and lower fitness values for others (with a similar value for total fitness). In this case the two designs represent local optima, and, in so far they are both capable to attract some portion of users' demand, the degree of variety of the product population will increase.

Analogously, homogeneity of users groups implies that all users will evaluate a new design in the same way (i.e., as either positive (accept) or negative (reject)). On the other hand, in case of demand heterogeneity (assuming the existence of some degree of interdependency among design dimensions) a novel design may well be considered as an improvement by some user groups, while being considered a worsening by others, leading to a growth of the variety of designs in the product population.

Note that in the case of heterogeneous user groups, design variety is expected to be *more persistent* than in the case of homogeneity of preferences. In the case of homogeneous preferences, variety may slowly disappear as different locally optimal designs lose ground to the one design with highest fitness. In case of heterogeneity, instead, the speciation of one design into two distinct designs (each suited to the requirements of one specific user group) is self-enhancing: further development of each design is localised and subjected to the pressures of the specific selection environment in which it is successful.

4.3. The design space of eighteenth century steam engine technology

In our interpretation, the design space for early steam power technology can be conceived as constituted by seven basic dimensions. For each dimension, we can distinguish two possible alleles, except for one dimension for which we can individuate three possible alleles. Hence, the size of the design space is equal to $2^6 \cdot 3 = 192$ possible steam engine designs. Throughout the following, we label each dimension as X_i ($i=1,\ldots,7$). The design dimensions and alleles are given in Table 4.3.[7]

Making use of this conceptualisation of the design space, we can represent each steam engine design as a unique string of alleles. In Table 4.4, we list 13 types of steam engines characterizing the development of steam power technology up to 1812. Note that these 13 designs constitute only a small subset of all 192 possible designs (about seven percent). This already illustrates the non-random selective nature of search activity, as the large majority of designs that are technically conceivable, were never introduced on the market.

Also in this chapter, we make use of Kanefsky's updated version of the list of British steam engines orginally compiled by Kanefsky and Robey. The coverage of these data has been discussed in detail in the previous chapter.

Table 4.3: Description of the design space.

Element	Allele 0	Allele 1	Allele 2
X_1	Low pressure	High pressure	
X_2	Without separate condenser	With separate condenser	
X_3	Single acting	Double acting	
X_4	Not compounding	Compounding	
X_5	Reciprocating	Rotary	Water returning
X_6	Open top	Closed top	
X_7	Single cylinder	Double cylinder	

It is worth noting that we do not consider Savery type of engines.[8] In fact, our conceptualisation of the design space takes into account only engines based on the cylinder-piston arrangement. Some historians have actually argued that (not having moving parts) Savery type of engines ought to be more properly considered as steam pumps rather than as actual steam engines. Following Usher (1954, p. 347), we consider the Newcomen engine to have set out, as the first steam engine design, the dimensions of the design space, in which further technological developments have taken place.

We limit ourselves to the period 1760-1800. The choice of the period has been motivated by the fact that before 1760 only Newcomen reciprocating engines (0000000) and Savery engines are present in the dataset, and consequently there are no "visible" inventive activities in our design space. [9]

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[7] The dimensions we have identified represent the "major" first-order components of the steam engine layout. As Vincenti has pointed out, complex artefacts are typically constituted by a nested hierarchy of components and sub-components (Vincenti, 1990, p. 9). In this perspective, processes of blind variation and selective retention occur at all levels of the design hierarchy. Hence, the emergence of new design is usually followed by incremental improvements of performance as the alleles at the sub-component level are progressively fine-tuned. Our analysis considers only the combinatorial design problem at the highest level of design hierarchy.

[8] In our data-set only 33 Savery engines are present. Omitting these does not affect our results.

[9] As we have seen in chapter 2, the period 1720-1760 was characterized by a series of incremental improvements to the basic Newcomen engine design. In our conceptualisation of the design space, these inventive activities are interpreted as changes at lower levels of the design hierarchy.

Table 4.4: Description of different steam engines types as strings of alleles.

String	Engine type	Date	Main producer/developer
(0000000)	Newcomen atmospheric engine*	1710	Newcomen & Calley (1712)
(0000200)	Newcomen water returning*	1731	Oxley (1762)
(0000100)	Newcomen rotary*	1762	J. Pickard (1780)
(0100010)	Watt engine*	1769	Watt (1769)
(0100210)	Watt water returning*	1774	Boulton & Watt (1774)
(0100110)	Watt rotary		Boulton & Watt (1782)
(0101011)	Hornblower compound*	1779	Hornblower (1781)
(0110110)	Watt rotary double acting engine*	1780	Boulton & Watt (1785)
(0100000)	Symington*	1787	Symington (1792)
(0000101)	Newcomen two cylinders engine*	1788	Bateman & Sherratt (1794); Thompson (1793)
(1010110)	Trevithick's "Puffer"*	1799	Trevithick (1802)
(1100010)	Trevithick "Cornish"engine		Trevithick (1812)
(1101011)	Woolf "Cornish" engine		Woolf (1814)

Note: Designs indicated by * occur in Kanefsky's dataset. For these designs, the dates in the third column refer to the first appearance in the dataset. These may differ from the date used traditionally by historians of technology (*e.g.*, 1712 for the first Newcomen engine). The last column is taken from Farey (1827) and indicates the main producer/developer of the engine design. The date corresponds to the erection of some particular noteworthy engine of that particular design.

In the database, we have 1369 engines (of known type) for the period 1760-1800. Each of these engines has been coded as a string of alleles, as illustrated in tables 4.3 and 4.4. Unfortunately, we were not able to distinguish in our data between the Watt single-acting rotary engine (0100110) and the Watt double-acting rotary engine (0110110). We have decided to consider all the Watt rotary engines as double acting. Only few single acting rotary engines are known to have been erected by Boulton and Watt. In addition, from 1787, the double acting became the typical standard proposed by the two partners for rotary applications (Farey, 1827, p. 444; Dickinson and Jenkins, 1927, pp. 139-172).

Using the information on the sector of application of each engine provided by the database, we also classified each engine in one out of nine application sectors ($m \in M$), namely:

(i) coal mining
(ii) other mining (comprehending lead, copper, tin, iron and other mines)
(iii) cotton
(iv) other textiles (comprehending wool and other textiles)
(v) metal working (comprehending ironworks, brass works, tinplate works, lead works and copper works)
(vi) food (comprehending distilleries, breweries, oil-mustard mills, flour mills, chocolate factories)
(vii) waterworks and canals
(viii) others
(ix) unknown

This classification tries to capture the distinctive sets of functional requirements (representing different selection environments) of the various application sectors. Accordingly, we have distinguished between coal mining and other mining. The mining industry employed steam engines mainly for pumping water. Coal mining, however, can be considered a specific selection environment as in coal mines, engines could be very cheaply fed with 'slack' coal of inferior quality. In the case of manufacturing applications, there were some sectors, as the food industries (in particular breweries, see Mathias, 1959) in which machinery could be easily powered by steam, while textile industries imposed tough requirements on the smoothness and steadiness of the motion that the engine was supposed to deliver. Within textiles, cotton fibres could be more easily subjected to mechanised processes.[10] This explains our choice of distinguishing between cotton and other textiles. The category 'others' consists of a number of niche applications including paper mills, sawmills and potteries. The 'unknown' category consists of 39 engines for which no data were available.[11]

4.4. Entropy statistics

The installation of a steam engine of a given design in a given year constitutes an observation in our seven-dimensional design space. In each year the product population is represented by the aggregation of all the engines constructed in that period (Saviotti, 1996, pp. 66-69). Our data do not contain information on the "fitness" of individual engines. However it is plausible to assume that the relative fitness of the different steam engine designs will be reflected, at least to a degree, in their share in the product population.

A straightforward way to analyse the evolution of multi-dimensional frequency distributions is to use entropy statistics. Entropy is a macroscopic measure that indicates the degree of randomness of a distribution. In our case, entropy indicators capture what might be called the macroscopic "emerging properties" of the underlying micro-processes of variation and selection unfolding on the design space.

Maximum entropy occurs when all designers randomly move around in design space, which implies that all possible designs have an equal probability to be selected by designers. This hypothetical situation refers to a situation in which designers are completely indifferent about the functional attributes of different designs (i.e. they lack an internal fitness function and/or an external selection environment to test the relative performance of the various designs). Non-random search in design space will typically lead to skewed distributions with some designs occurring with higher frequency than others. In this case, designers will not move randomly on the design space, but they will try to develop designs that fit closely the demands of users. For example, the application of a hill-climbing search heuristic will lead designers to introduce locally optimal designs. Minimum entropy indicates maximum skewness and occurs when all designers opt for one and the same design. In this case, all designers are clustered in one 'corner' of the multi-dimensional design space. As such, entropy can be used as an indicator of technological standardisation, with low entropy values indicating the existence of a dominant design (Frenken, 2001). Following the notation in (1), the N-dimensional entropy of a product population is given by (Theil, 1972):

$$H(X_1, \ldots, X_N) = -\sum_{s \in S} p_s \cdot \ln p_s \qquad (7)^{12}$$

[10] "[C]otton proved to be the most tractable fibre technically. One could adapt it to machinery at every process more readily than wool – a more delicate, more complicated fibre – and more easily than flax and jute which were too stiff" (Mathias, 1983, p. 117).

[11] Admittedly, "others" and "unknown" are residual categories. Our results presented below are robust to the exclusion of the engines listed in these fields.

[12] $0 \cdot \ln(0) \equiv 0$. We use the natural logarithm to compute entropy (as in physics). Alternatively, one can use base two logarithm to express entropy in bits as in information theory (Theil, 1972).

where p_s is the relative frequency of design *s* in the product population. Entropy is maximum when all *S* possible designs have an equal frequency $p = 1/S$, which results in an entropy value of $H = - S \cdot (1/S) \cdot \ln(1/S) = \ln(S)$. Conversely, entropy is minimum when all products present in the population are designed according to one and the same design: $H = - 1 \cdot \ln(1) = 0$. A pure substitution process between an "old" and a "new" design will determine a growth of entropy from zero (when all users adopt the old design) to ln(2) when the two competing designs have a fifty-fifty market share, dropping to zero again (when all users have adopted the new design).

To understand to what extent the variety indicated by the entropy of the product population reflects the existence of complementarities among the various design dimensions, we will make use of mutual information indicators. Mutual information is given by (Theil, 1972; Frenken 2001):

$$T(X_1, \ldots\ldots, X_N) = \sum_{s \in S} p_s \cdot \ln \frac{p_s}{\prod_{i=1}^{N} p_{s_i}} \tag{8}$$

where p_{s_i} stands for the marginal frequency of allele *s* of dimension *i* in the population. Mutual information indicates to what extent particular alleles along different dimensions co-occur in the technological designs of the product population. Statistically, mutual information indicates the degree of dependence between design dimensions. Mutual information is equal to zero when there is no dependence between any of the dimensions. In that case, the joint frequency of alleles corresponds exactly to the frequency that could be expected from the product of the marginal frequencies. When the product of marginal frequencies does not correspond to the joint frequency, there is dependence between dimensions and *T* assumes a positive value. The greater the difference between the joint frequency and the product of marginal frequencies, the higher the value of the mutual information, the more alleles along particular dimensions co-occur in "design families".

The existence of local optima implies that specific alleles along one dimension typically co-occur with specific alleles along other dimensions, as local optima by definition have at least two alleles not in common. In other words, the more alleles are clustered in particular regions of the multi-dimensional design space, the higher the mutual information. A process of progressive differentiation into distinct design families is thus indicated by a rising trend in entropy (variety) accompanied by a rising trend in mutual information (differentiation). Mutual information can be computed for any number of dimensions greater than one. Below, we will apply mutual information both to the seven-dimensional distribution and to each two-dimensional distributions of two design dimensions. The seven-dimensional analysis captures the overall degree of differentiation, while the two-dimensional analysis individuates the couples of design dimensions in which differentiation has been most pronounced. The latter analysis allows one to discern the major interdependencies between each pair of dimensions. We will further apply the mutual information formula to the two-dimensional distributions constituted by one design dimension and the different sectors of application. In this way, we can analyse the dependence of sectors of application on each of the seven design dimensions. This will indicate which design dimensions discriminate most among sectors of application.

As mentioned above, our main hypothesis not only holds that the product population evolved towards increasing variety (entropy) and differentiation (mutual information), but also that this increased variety is due to speciation of different designs becoming dominant in different selection environments.

To find out whether the variety of applications has indeed increased over time, we can compute the entropy of sectors of applications given by:

$$H\,(M) = -\sum_{m \in M} p_m \cdot \ln p_m \tag{9}$$

where p_m stands for the share of sector *m* over the total product population. Computing the entropy of designs for each sector of application separately provides an indication of the existing degree design variety within each sector *m* (Theil, 1972):

$$H_m\,(X_1, \ldots, X_N) = -\sum_{s \in S} \frac{p_{sm}}{p_m} \cdot \ln \frac{p_{sm}}{p_m} \tag{10}$$

where p_{sm} stands for the share of design *s* in sector *m* over the entire product population ($\sum_{s \in S} p_{sm} = p_m$ and $\sum_{m \in M} p_{sm} = p_s$). The average sectoral entropy of designs in the product population is then given by the weighted sum of entropy values at the sector level, where weights are based on the sectors' relative share of designs in the total product population p_m (Theil, 1972, p. 19):

$$\overline{H}_M\,(X_1, \ldots, X_N) = \sum_{m \in M} p_m \cdot H_m\,(X_1, \ldots, X_N) \tag{11}$$

This formula indicates to what extent design variety is present at the level of each sector. $\overline{H}(X_1, \ldots.., X_N)$ assumes a minimum value of zero when all sectors are completely dominated by a single design (which may or may not be the same design across sectors). It can be shown that the maximum possible value of $\overline{H}(X_1, \ldots.., X_N)$ is equal to $H(X_1, \ldots.., X_N)$ (Theil, 1972, p. 65), and this value is obtained when design variety in each sector corresponds exactly to the design variety present at the level of the complete product population. Given that $0 \leq \overline{H}(X_1, \ldots.., X_N) \leq H(X_1, \ldots., X_N)$, one can calculate a relative measure that indicates to what extent the overall variety in the product population is due to intra-sectoral or inter-sectoral variety, by dividing the average sectoral entropy by the total entropy:

$$\overline{H}'_M(X_1, \ldots, X_N) = \frac{\overline{H}_M(X_1, \ldots, X_N)}{H(X_1, \ldots, X_N)} \tag{12}$$

We call this measure the "relative average sectoral entropy". When the relative average sectoral entropy is small, design variety in the product population is mainly due to inter-sectoral variety and when the relative average sectoral entropy is large, design variety in the product population is mainly due to intra-sectoral variety.[13] In the former case (for a given level of variety in the total product population) we have a high degree of speciation, while in the latter case we have a low degree of speciation.

4.5. Technological evolution in the early development of the steam engine

Let us now turn the attention to the results for our population of steam engine designs. Throughout the following, we will consider three-year moving averages of the yearly values of entropy and mutual information in order to smooth short-term fluctuations. This transformation does not affect in any way our conclusions.

Variety and differentiation

Figure 4.4 shows the behaviour of the seven-dimensional entropy $H(X_1,\ldots,X_7)$ and mutual information $T(X_1,\ldots,X_7)$ of the product population. The results clearly indicate that both variety (entropy) and differentiation (mutual information) have increased rapidly from the year 1774. At that time the Watt reciprocating engine became a popular design next to the Newcomen reciprocating engine.

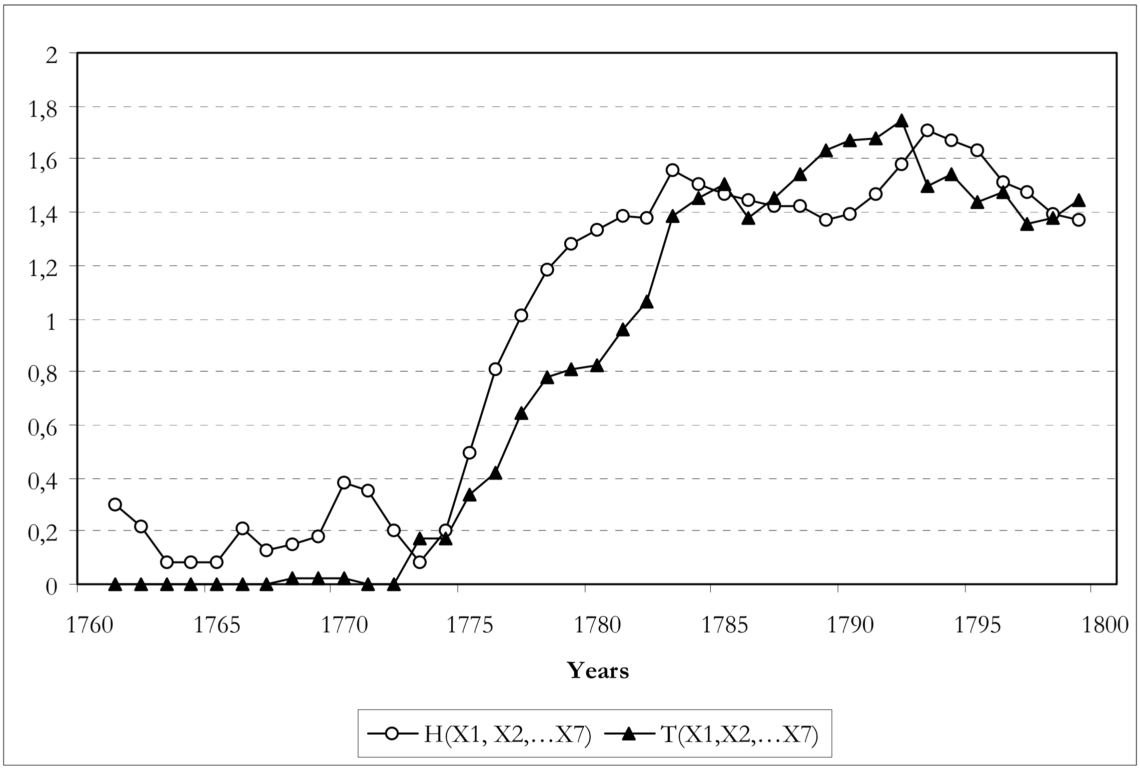

Figure 4.4: Entropy $H(X_1,\ldots,X_7)$ and mutual information $T(X_1,\ldots,X_7)$ of the product population.

In our interpretation, figure 4.4 suggests that, starting from the mid 1770s, the development of the technology engine has been characterised by the introduction of new alleles along several dimensions, which accounts for the growth of variety. Inventive activity also led to a process of differentiation into an increasing number of design

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[13] Clearly when $\overline{H}'(X_1,\ldots\ldots,X_N)=1$ the relative shares of engine designs in each sector are exactly equal to the shares in the total product population.

families. Thus, inventions (new alleles) in separate dimensions have been combined in such a way that the product population increasingly clustered in some specific corners of the multi-dimensional design space. In other words, from the mid 1770s we have a phase exploration and discovery of new areas of the fitness landscape followed by concentration (rising mutual information) in some points that may well represent local optima. The "levelling off phase" starting in the late 1780s seems to indicate a stabilisation of the pattern of differentiation that had emerged earlier.

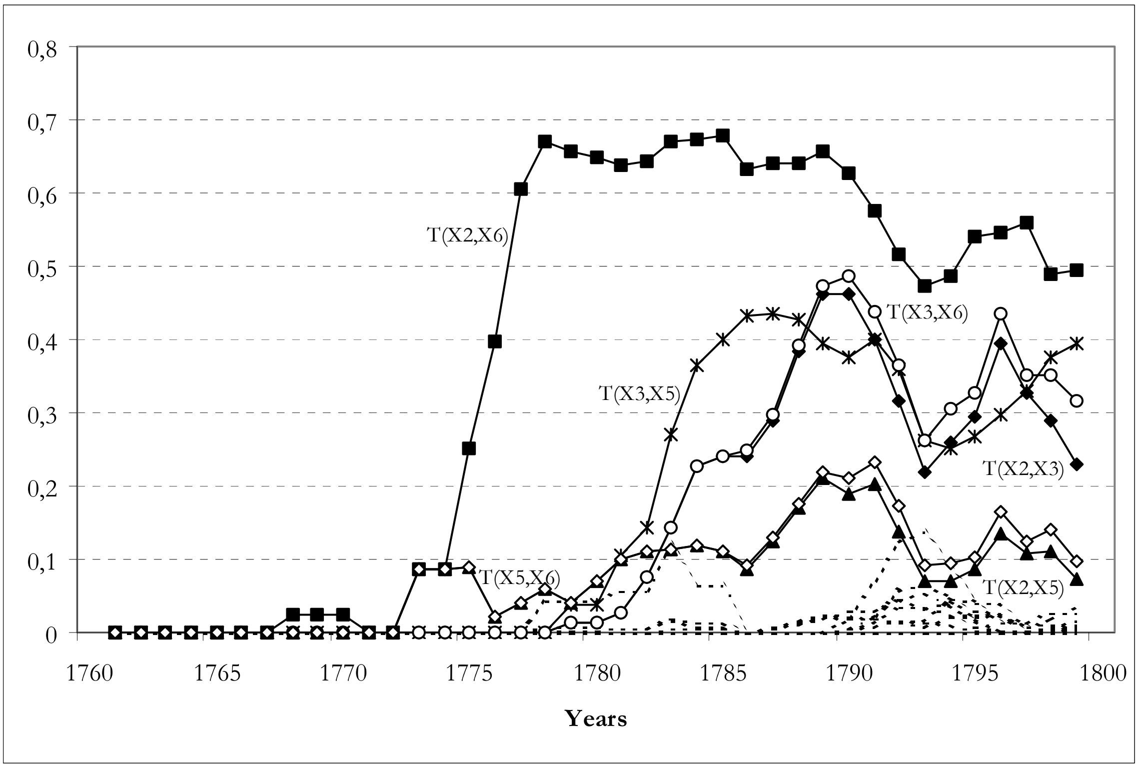

Figure 4.5: Two-dimensional mutual information ($T(X_1,X_2)$,.......$T(X_6,X_7)$) of the product population

Figure 4.5 displays the evolution of the pair-wise mutual information. These results are informative on the nature of the technological interdependencies among design dimensions that were responsible for the process of differentiation into distinct design families. The highest mutual information values are reached by the pair $T(X_2,X_6)$, which reflect the interdependency between with/without condenser and open/closed top cylinder. Separate condensation and the closed top cylinder are the two salient features distinguishing Watt type of engines (0100010) from Newcomen atmospheric engines without condensation and open top (0000000).

Importantly, high values of $T(X_2,X_6)$ are not a temporary phenomenon but continue during the whole period considered. These results thus indicate the emergence of a pattern of continuing differentiation rather than technological substitution between Watt and Newcomen engine designs beginning in the early 1770s.

In Figure 4.5, couples that did not reach high levels of mutual information are represented by thin dotted lines, and couples with relatively high levels of mutual information are represented by continuous lines with markers. What becomes clear from these results is that the interdependencies among design dimensions are limited to four dimensions: X_2, X_3, X_5, and X_6, respectively, with/without condenser, single/double acting, reciprocating/rotary/water returning, and open/closed top. As explained above, dimensions X_2 and X_6 differentiate Newcomen and Watt engines. Dimensions X_3 and X_5 concern different solutions to deliver particular types of motion. Double action was a typical feature of Watt rotary engines (0110110), while Newcomen engines delivering rotary motion either returned a stream over a waterwheel (0000200) or they acted directly by means of a crank and flywheel (0000100). From the early 1790s, Newcomen rotary engines with two cylinders (0000101) also became a popular solution constituting yet another differentiation.

It is interesting to note that within the two main design families constituted by Newcomen and Watt engine designs, a process of further differentiation took place driven by the need of adapting the engine to the functional requirements of the sector in which it was employed. In particular, the type of motion delivered by the engine was another dimension in which steam engine designs tended to differentiate. Whereas Watt rotary engines employed double action, Newcomen rotary engines did not make use of that feature.

There are three designs, the Hornblower, Symington and Trevithick's engines, which cannot be ascribed neither to the Newcomen or to the Watt family and constitute three additional groups. The Symington engine (0100000) represents a hybrid solution between a Newcomen and a Watt engine, whereas Trevithick (1010110) and Hornblower's (0101011) engines embody design features (high pressure and compounding, respectively) which would characterize nineteenth century developments. Their impact in terms of diffusion during the late eighteenth century, however, has been quite small (a total of respectively 18 and 20 engines were erected till 1800)).

Variety and speciation

Figure 4.6 charts the one-dimensional entropy H(M) for application sectors using the shares of sectors in each year. The figure shows the growing extension of the range of possible applications of the steam engine. In particular, the range of possible of applications of early steam engines grew during the period of 1770s and 1780s, stabilizing from the late 1780s. In fact, up to the early 1770s, steam engines were only adopted in the mining and metal working sectors (especially in iron blast furnaces, see Hyde, 1977, pp. 71-75), while thereafter the technology began to be adopted in a host of new applications such as textiles, foods, and water-working.

It remains to be established whether the rise in design variety (figure 4.4) and the rise in the variety of sectors in which steam engines were applied (figure 4.6) were coupled in a process of speciation.

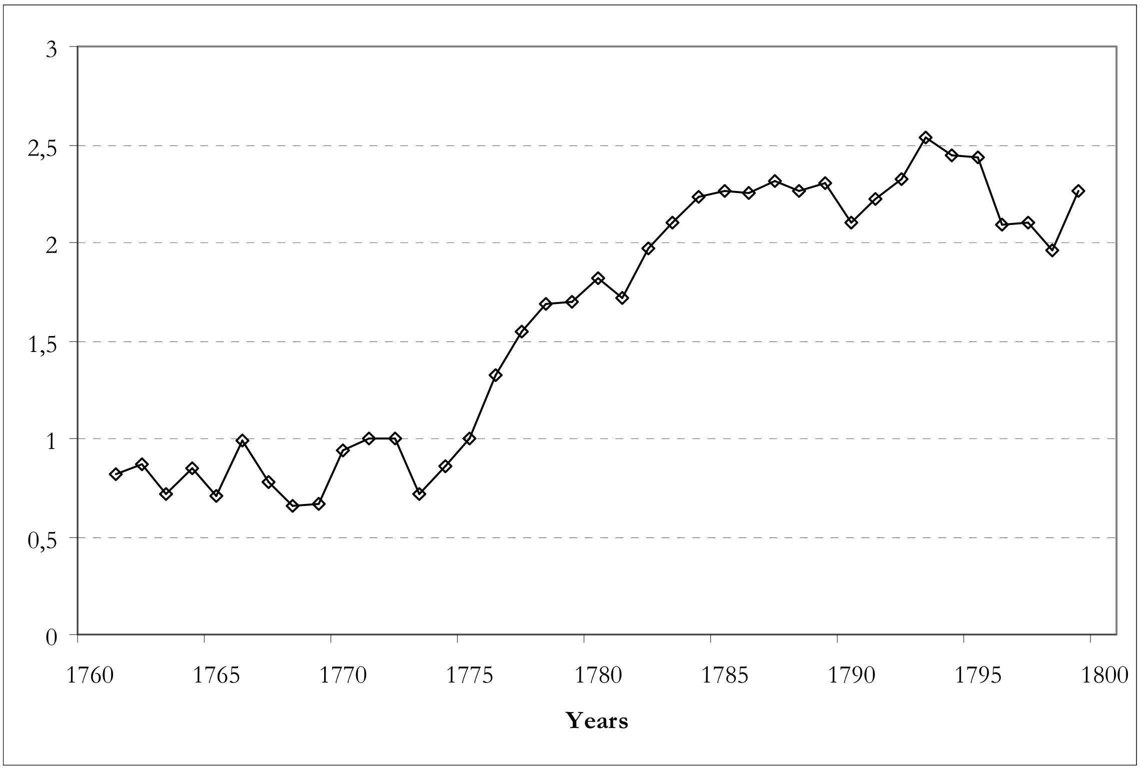

Figure 4.6: Entropy H(M) of application sectors.

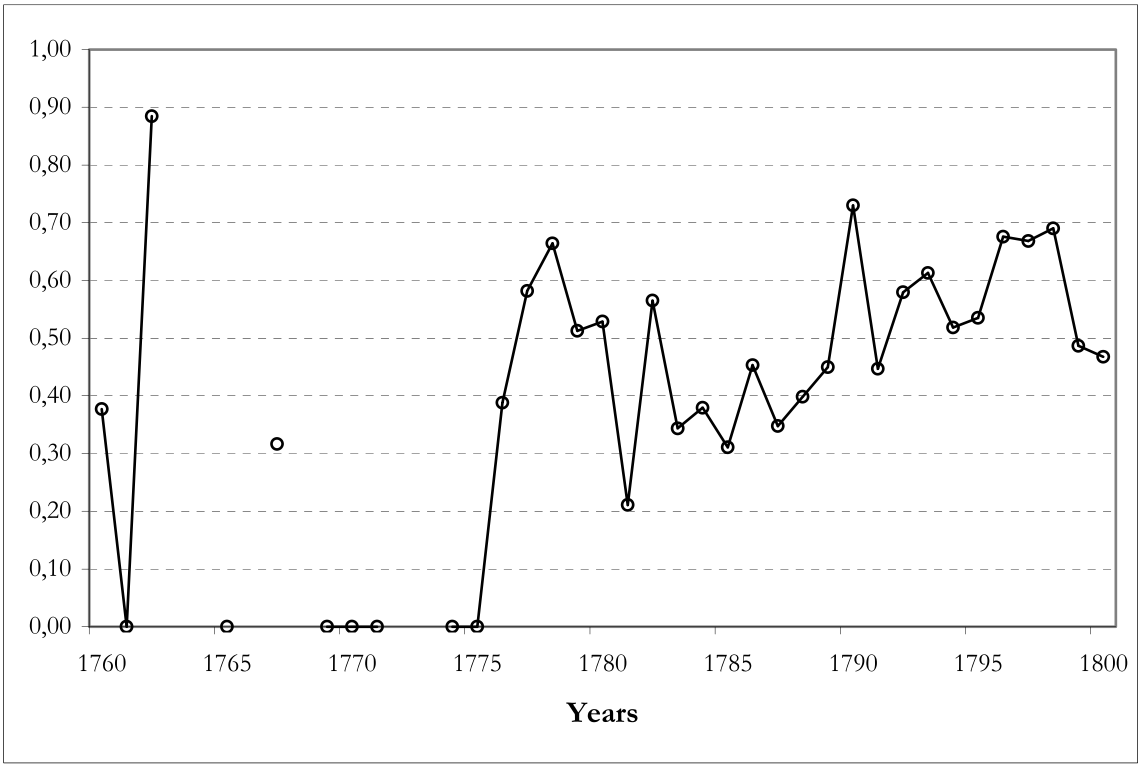

Figure 4.7: Relative average sectoral entropy $\overline{H}'_M(X_1,....,X_N)$

Figure 4.7 displays the relative average sectoral entropy $\overline{H}'_M(X_1,...,X_N)$. Recall that the lower this value, the higher the extent to which application sectors are dominated by few designs indicating speciation. Before 1775 $\overline{H}'_M(X_1,...,X_N)$ is mostly equal to zero,[14] which reflects the fact that the two engines constructed in the period, the Newcomen reciprocating engine and the Newcomen water-returning engine, established themselves in distinct niches (respectively coal mining and metal working). From 1775 onwards the relative average sectoral entropy is characterised by a phase of steady growth, followed by what seems to be a fluctuating behaviour, indicating that application sectors were characterised by the presence of different designs. In this phase, the design variety in the total product population is due both to *intra-sectoral* variety (reflecting the existence of multiple local optima within one application sector) and to *inter-sectoral* variety (reflecting the specialisation of different designs in distinct application sectors).

Table 4.4: Specialisation of engine designs in application sectors, 1760-1800

Engines	**String**	**Coal**	**Other Mining**	**Cotton**	**Wool & other textiles**	**Metal working**	**Foods**	**Waterworks & Canals**	**Others**	**Unknown**	**Number**
Newcomen (reciprocating)	(0000000)	**0.22**	-0.01	-0.73	-0.72	-0.25	-0.84	-0.11	-0.60	**0.16**	*630*
Pickard (Newcomen rotary)	(0000100)	**0.08**	-0.74	-0.16	**0.23**	**0.17**	**0.25**	-0.63	**0.09**	-0.51	*107*
Watt (reciprocating)	(0100010)	-0.34	**0.54**	-1	-1	**0.12**	-0.79	**0.61**	-0.28	-0.37	*152*
Newcomen (rotary two cyl.)	(0000101)	-0.12	-0.59	**0.22**	**0.05**	-0.51	-0.27	**0.51**	**0.47**	**0.06**	*31*
Hornblower	(0101011)	-1	**0.60**	-1.00	-1	-0.28	-0.01	-1	**0.41**	**0.32**	*18*
Watt (rotary, double acting)	(0110110)	-0.62	-0.86	**0.51**	**0.44**	**0.11**	**0.49**	-0.45	**0.39**	-0.13	*316*
Symington	(0100000)	**0.01**	**0.09**	-1	**0.26**	-1	**0.56**	-1	**0.36**	-1	*20*
Trevithick's puffer	(1010110)	-1	**0.78**	-1	-1	-1	-1	-1	-1	-1	*6*
Newcomen (water returning)	(0000200)	-0.14	-1	**0.37**	**0.46**	**0.39**	-0.03	-1	-0.14	-0.04	*76*
Watt (water returning)	(0100210)	-1	-0.23	-0.14	-1	**0.65**	**0.16**	-1	**0.63**	-1	*13*
Number		*615*	*170*	*140*	*40*	*135*	*77*	*57*	*96*	*39*	*1369*

Note: values>0 indicating a relative specialization of a particular engine design in a specific sector are in bold. The last column and the last row report the total number of engines.

In our interpretation, the co-existence of intra- and inter-sectoral variety indicates that in most sectors different designs were capable of delivering satisfactory levels of performance (reflecting the existence of local optima on the fitness landscape of the technology). Thus, design variety in most sectors is positive, yet substantially lower than the design variety at the level of the product population as a whole, showing a certain degree of speciation of different designs into distinct application sectors.

In order to provide an outline of the pattern of specialisation of engine designs in application sectors, we have computed an indicator of (relative) technological specialisation similar to the revealed technological advantage (RTA) index used in the patent literature (Soete and Wyatt, 1983). The results are presented in table 4.4. Our indicator of specialisation SP is computed as follows:

[14] In this period, in some years both the value of the average sectoral entropy and of the entropy of the total product population are equal to zero, indicating that in that year in all the sectors the same type engine was constructed. These cases are represented by missing values of the relative average sectoral entropy.

$$SP = \frac{\sigma_{sm} - 1}{\sigma_{sm} + 1} \quad (13)$$

with $\sigma_{sm} = \frac{(p_{sm}/p_m)}{p_s}$ where in this case the shares p_s and p_{sm} are computed using all the engines constructed during the 1760-1800 period. The SP formula transforms σ_{sm} in an index symmetric between –1 and 1. A value of the indicator larger than zero indicates that a particular engine design is (relatively) specialised in the application sector in question; conversely, values lower than zero stand for (relative) de-specialisation. The table shows that some sectors are dominated by only one or two designs (coal mining and waterworks and canals), while other sectors have witnessed a considerable design competition, in particular, between the various Newcomen and Watt types of engines.

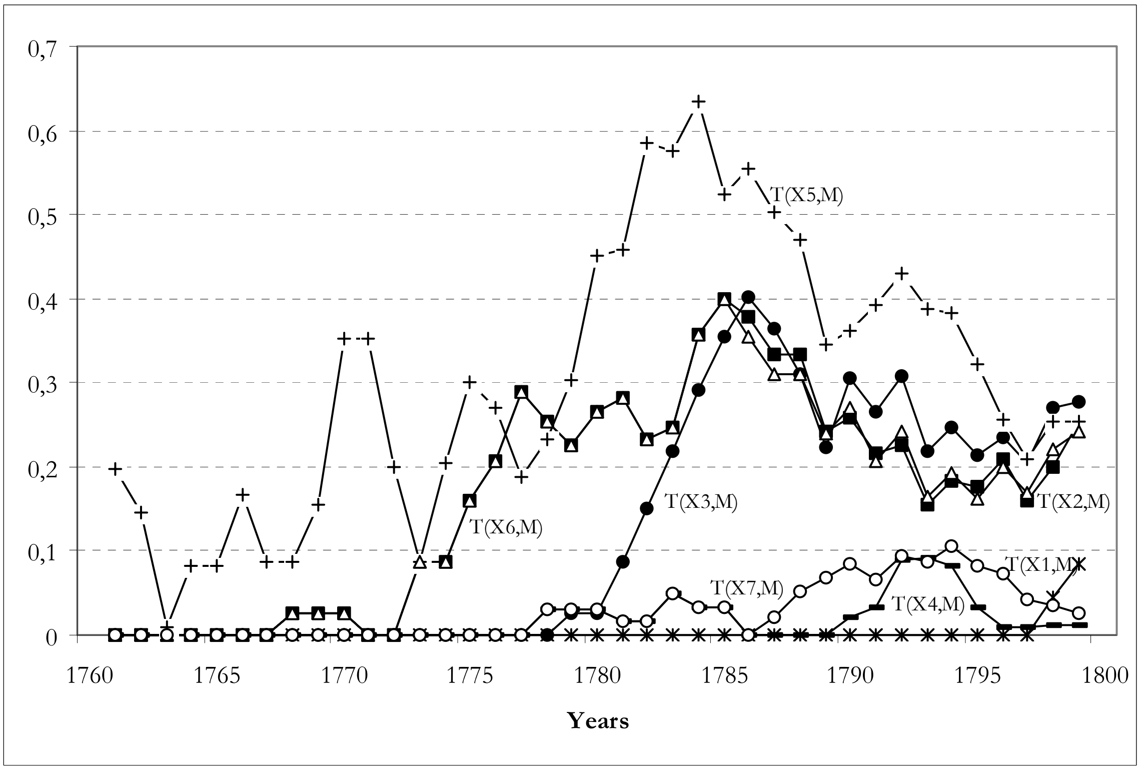

Figure 4.8: Mutual information design dimensions/sectors ($T(X_1,M)$,….$T(X_7,M)$)

To unveil the determinants of speciation that gave rise to inter-sectoral variety, we must consider the design dimensions that discriminate most between sectors of application. Figure 4.8 displays the mutual information between each individual design dimension and the dimension of sector of application. The dependence of each design dimension with sectors of application shows pronounced differences. Four out of seven design dimensions are powerful in discriminating among application sectors (X_2, X_3, X_5, and X_6). In accordance to the NK-model, these dimensions are precisely those that exhibit the strongest internal design interdependencies (figure 4.5), and thus create the trade-offs among the various functional attributes of the technology.

The highest value in figure 4.8 is found for the type of motion delivered by the engine $T(X_5,M)$. This results indicates that sector of applications differed primarily in the type of motion that was required. Reciprocating engines were primarily installed in coal mines, other mines and waterworks for lifting purposes. Rotary motion and water returning motion were generally required in textiles and food sectors. The values of $T(X_2,M)$ and $T(X_6,M)$, representing with/without condenser and open/closed top distinguishing Newcomen from Watt engines, move closely together and have discriminatory power among application sectors. This can be understood from the superior fuel-efficiency performance of Watt engines compared to Newcomens. In sectors where coal was relatively cheap like coal mining, Newcomen engines dominated while in other sectors Watts became the leading technology. Finally, high values for $T(X_3,M)$ indicate whether the engine works with single or double acting motion. The double acting motion delivered by the Watt rotary engines was superior in terms of smoothness of motion to single-acting types of rotary motion. Watt rotary engines rapidly established dominance in sectors as cotton, foods, paper mills and potteries where the smoothness of motion was a crucial performance requirement. In other sectors, the single-acting rotary engines were typically used. Note that the values of $T(X_2,M)$, $T(X_6,M)$, $T(X_5,M)$ and $T(X_3,M)$, after a phase of rapid growth, exhibit a "falling off" phase starting approximately in the late 1780s. In our interpretation, this is due to the fact that some applications were indeed "opened" by a specific engine design, but this dominance did not last for long. With some delay, other type of engines entered the application sectors leading to lower values of mutual information.[15] To repeat, the pattern of speciation was not perfect.

4.6. Towards a re-examination of the early history of the steam engine

Our major result holds that the Watt engine should not to be considered as a "linear successor" of the Newcomen engine but rather as a speciation event that opened up new applications. This result supports studies that pointed to the continuing attraction of the Newcomen engine technology. In his *Treatise on the Steam Engine* published in 1827, John Farey already noted that for pumping purposes in coal mining Newcomen engines were still "universally employed" (Farey, 1827, p. 307). Dionysius Lardner made a similar remark as late as 1840 (Cardwell, 1963, p. 54). The continued success of the Newcomen engines can be attributed to its cost and maintenance advantages. Von Tunzelmann (1978, p.75) has estimated that prices of Newcomen engines ranged between 75 to 95 percent of those of Watt engines of the same power.[16] In addition, Newcomen engines were also characterised by much lower maintenance costs. Hence, as we have also seen in the previous chapter, in areas where coal was cheap enough, the Newcomen engine detained an important advantage due to its lower costs of installation and maintenance. Besides being cheaper in erection and maintenance, the Newcomen engine had the advantage of being well within the engineering capabilities of the time, whereas the Watt engine imposed very compelling requirements on the degree of accuracy of its various components, in particular the boring of the cylinder. This points to the existence of a fundamental trade-off concerning fuel-efficiency versus simplicity of construction and maintenance.[17]

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[15] The decline $T(X_5,M)$ is to be ascribed to the progressive adoption of rotary engines in mining (for winding ore) and in metal working. The decline of $T(X_2,M)$, $T(X_6,M)$ and $T(X_3,M)$ instead reflects the increasing competition between Watt and the various rotary versions of the Newcomen engine in textiles and other manufacturing applications requiring rotary motion.

[16] According to Andrew (1995), Newcomen and Watt engines had the same costs for equal power and for a "similar engineering standard". However, one has to take into account that Newcomen engines were normally constructed adopting a lower engineering standard than Watts. So the figures proposed by von Tunzelmann (1978) can be considered more representative of a typical situation.

[17] Joseph Bramah stated that the Newcomen engine detained over Watt "an infinite superiority in terms of simplicity and expense". John Smeaton, one of the leading engineers of the time, considered that the Watt

The existence of a trade-off between fuel-efficiency and cost of installation and maintenance is confirmed by the diffusion of the Watt reciprocating engine in mining districts located in areas where the high price of coal had so far prevented the widespread use of the Newcomen engine. The most important of these districts is Cornwall.[18] However, even in areas where coal prices were relatively high, the Watt engine had to face the fierce competition of other engine designs. In Cornwall, for example, the Watt reciprocating engine (0100010) had to compete with the compound double cylinder engine developed by Hornblower (0101011) in the early 1780s. As recalled in chapter 2, according to contemporary accounts, the two engines delivered a very similar performance in terms of fuel efficiency (Farey, 1827, pp. 387-393). One has to add here that the diffusion of the Hornblower engine was severely limited by the legal actions of Boulton and Watt who claimed that the engine was infringing their patent, deterring in such a way potential buyers of the Hornblower engine. Recent research has actually argued that Boulton and Watt allegations of infringement were unwarranted (Torrens, 1982 and 1994).

Interestingly enough, there was also an attempt of developing an "hybrid" engine combining the simplicity of Newcomen with the fuel-efficiency of Watt. This was the "improved atmospheric engine" patented by Symington in 1787 (0100000). We know that about twenty engines of this type were erected (mainly in Scotland) and that they generally proved rather successful. [19] Some historians of technology have dismissed Symington simply as "schemer" who tried to circumvent Watt's patent (Dickinson and Jenkins, 1927, p. 318; Farey, 1827, p. 656). The prolonged co-existence of Watt and Newcomen engines, in our judgment, instead suggests that Symington's attempt of merging the two separate design trajectories of Newcomen and Watt was genuinely aimed at combining the merits of both engines.

A second major result of our analysis points to another speciation event centred about the dimension of the quality of motion. We consider the development of Watt's double-acting rotary engine as a speciation event rather than a "successor" of earlier technologies. The main effect of the introduction of the Watt double acting rotary engine in 1780 has been the opening up of steam power to new industrial applications, in particular cotton and foods. Although Watt's inventions for supplying rotary motion were highly celebrated (Dickinson and Jenkins, 1927), they can not by any means be considered as definitive. In "older" industrial applications, Watt double acting rotary engines did not achieve anything close to dominance. In metal working, for example, Newcomen water returning engines remained widely used (see again table 4.4 illustrating the pattern of relative specialisation of the engine designs). Furthermore, in textiles some adopters still preferred Newcomen rotary or water returning engines over Watt rotary engines. We are aware of many cases of unsatisfactory performance of Watt rotary engines in textile mills compared to water returning designs (Hills, 1970, pp. 179-186).[20] Concerning Newcomen engines delivering rotary motion by means of the crank and flywheel arrangement (0000100), John Farey wrote:

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engine demanded too higher standards for construction and maintenance (Harvey and Downs Rose, 1980, pp. 22-23).

[18] On the diffusion of the Boulton and Watt engine in Cornwall, see Tann (1996).

[19] On the Symington engine, see Harvey and Downs-Rose (1980, chap. 3).

[20] Well into the nineteenth century, many contemporary engineers believed that the rotary drive produced by a water returning engine was much more regular and, in the end, "better" than the one delivered by a Watt rotary engine (von Tunzelmann, 1978, pp. 142-143).

About the years 1790 to 1793, when steam mills began to be introduced into all large manufacturing towns, with Mr. Watt's improved engines, great numbers of atmospheric engines were also made for turning mills, particularly in districts were coals were cheap.........It is still a very common practice, in districts where coals are cheap to work machinery by Newcomen's engines (Farey, 1827, p. 422).

.....[These atmospheric engines] answered tolerably well for some purposes, which did not require a very regular motion, such as drawing coals out of mines, grinding corn, crushing seeds....(Farey, 1827, p. 658).

However, in applications, most notably cotton spinning, where a very smooth motion was required, the development of the Watt double-acting engine in 1784 initially led to an almost complete market dominance. In response, design activity in Newcomen engines focused on ways to mimic direct double acting motion. A solution was found in the use of two cylinders in Newcomen engines that acted alternatively on the same crank (0000101). The leading engineers in the development of this technical solution were Bateman and Sherrat and Francis Thompson. According to Musson and Robinson (1969, p. 408), in the Manchester textile district, in the 1790s these type of engines were widely adopted. Again, the older Newcomen technology was able to adapt in such a way that the dominance of the Watt engine technology was halted.[21]

Though traditional accounts have also emphasised the role of Watt's inventions in opening up new application sectors to steam power, these accounts most likely underestimated the fierce competition faced by Watt engines. Of course, one of the major determinants behind the competition has been the high royalties that adopters of Boulton and Watt engines had to pay. However, in our view, technological factors should also to be taken properly into account. Watt engines were far from being a complete and satisfactory solution for all the needs of the different user groups, the main problem being in most cases the much too high degree of engineering sophistication required by the Watt engine in its various versions.[22] Jennifer Tann describes the choice of technique dilemma faced by engine adopters in these terms:

...[W]hen information was more accessible and there were more engines to be seen, potential adopters quite frequently carried out a simple comparative cost/benefit analysis. From their limited inputs of information it was clear to them that the most rational answer was not necessarily to purchase a Boulton and Watt engine. Indeed at some locations it would have been a folly (Tann, 1979, p. 181).

So, together with attempts of circumventing the Watt's patent, in order to skim off some of the profits that Boulton and Watt were reaping, there were also more genuine attempts of improving the "fitness" of the engine in various application sectors.[23] Interestingly enough, in retrospect, one can identify two main trajectories in this process of improving the various functional attributes of the steam engine. The first trajectory consisted in trying to expand on the Newcomen design, exploiting its virtues of simplicity and reliability. This was essentially the direction taken by Symington, Pickard, Thompson and Bateman and Sherratt.[24] In a sense, this can bee seen as a sort of 'sailing

[21] Unfortunately most of the double cylinder engines erected by Bateman and Sherrat have left no trace in the records (Musson and Robinson, 1969, p. 410). Hence, our dataset is likely to underestimate the contribution of this type of engine to variety and differentiation.
[22] Concerning the Watt rotative engine, Hills (1989, p. 75) aptly comments: "[t]he world of mechanical engineering was then in its infancy and the Boulton and Watt rotative engine demanded higher standards in its manufacture than anything in its scale at the time".
[23] Note that in our conceptualisation of the design space, Watt "pirate" engines, even when incorporating some minor modifications as in the case of the Bull engine, are counted as Watt engines, so that they do not contribute to variety and differentiation.
[24] A very good overview of the producers of "improved" Newcomen engines in Britain in the late eighteenth century is contained in Tann (1979).

ship effect', although we should take into account that it was not so much a "defensive", but rather an "offensive" action. The Newcomen engine was not threatened by Watts in its main application domain (coal mining). In fact, the improvements were aimed at expanding the range of application of the original design. The second trajectory, instead, was the attempt of finding out new viable designs. This was the direction taken by Hornblower and Trevithick, whose designs are clearly precursors of nineteenth century developments. Thus, rather than a "linear" process of introduction of novel features and replacement of old designs, the early development of the steam engine seems to have been characterised by the formation of a variety of design families, each of them aimed at satisfying a rather specific set of user needs. A similar interpretation, stressing the role of persistent variety, has been also proposed by von Tunzelmann:[25]

> It is misleading to see the pattern of progress [in steam engine technology] as linear and inevitable: in explaining the direction and the chronology of 'technical progress' in the economist's sense, it is vital to keep this diversity in mind (von Tunzelmann, 1978, p. 24).

4.7. Concluding remarks

In this chapter we have presented an interpretative framework for the analysis of patterns of technological evolution. We have applied this framework to the case of the early development of the steam engine technology. In the second half of the eighteenth century, the introduction of Watt's separate condenser and Pickard's adoption of the crank and the flywheel extended the possible range of applications of steam engine technology. As suggested by Saviotti (1996) and Levinthal (1998) the adaptation of a technology to a new application domain (in so far the new domain imposes specific requirements on the functional attributes of the technology) is akin to a 'speciation' event in biology. Accordingly, the adaptation of the technology to the new application sector requires the introduction of a number of design modifications. The modified design is then subjected to a distinctive set of selection pressures. This is likely to trigger a new localised search process in the neighbourhood of the new design configuration. Over time, divergent evolutionary trajectories may be expected to unfold.

Our analysis of the evolution of early steam engine technology broadly confirms these insights. In our interpretation the (imperfect) specialisation of designs in different users' niches was the outcome of process of localised search in response to sector-specific functional requirements.

In this respect, traditional accounts of the evolution steam technology such as the one of Thurston (1939) have frequently remarked the existence of a discontinuity in the patterns of innovation in steam technology. According to this view, the early history of the steam engine (up to 1800) is characterized by a succession of "discrete" inventions. Watt's inventions (separate condenser, double action, parallel motion) completed the "infant stage" in the evolution of the technology, so that in 1800 the steam engine had finally become a sufficiently reliable "prime mover". In the words of Thurston:

> At this point [in 1800], the history of the steam engine becomes the story of its applications in several different directions, the most important of which are the raising of water – which had hitherto been its only application – the locomotive engine, the driving of mill machinery, and steam navigation......Since the time of Watt, improvements have been made principally in matters of mere detail, and in the extension of the range of application of the steam engine (Thurston, 1939, p. 142-143).

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[25] An analogous view is also sketched in Cragg (1989).

The findings presented in this chapter point in a rather different direction. Since the *second half of the eighteenth century* (with Watt's invention of the separate condenser and Pickard's adoption of the crank and flywheel for delivering rotary motion), the overall pattern of technical change in steam engine appears to have been characterized by the emergence of differentiated trajectories of development. By and large the emergence of these different trajectories was dictated by attempts of catering effectively the diverse sets of users' needs of the application sectors. Rather consistently with the findings of this chapter, Halsey (1981) has identified four different design families characterizing the use of steam power in different application sectors in the early nineteenth century, namely the high pressure engine, the Watt low pressure engine, the Newcomen engine and the Cornish engine. Clearly, the emergence of these different design families is to be related to the increasing specialisation between designs and application sectors that we have outlined in this chapter.

In the next three chapters, we will narrow down our perspective and we will examine in detail the evolution of one of these designs namely the Cornish engine. As we will see, the analysis of the patterns of technical change at this more circumscribed level will make necessary a detailed reconstruction of a number of specificities of the historical context of application.

PART III. THE APPLICATION OF STEAM ENGINE TECHNOLOGY IN THE CORNISH MINING DISTRICT

5. Collective Invention during the British Industrial Revolution: the Case of the Cornish Pumping Engine[1]

5.1. Introduction

As we have seen in the previous chapter, at the beginning of the nineteenth century, steam engine technology was differentiated in various design families, each of them tailored to the requirements of specific application sectors. Specialization of engine designs across application sectors, also meant, to a major extent, geographical specialization: at least, so far as industries displayed a trend towards concentration in specific locations. Considering Britain and the United States in the early nineteenth century, Halsey (1981) has identified four distinct (stationary) steam engine regions, each of them dominated by a specific design. In Britain, we have three main regions: coal mining locations, industrial areas in the north and the Cornish mining district. In coal mining areas, where steam engines could be fed very cheaply with "slack" coals, Newcomen engines predominated (on grounds of their low cost of erection and maintenance). In the manufacturing districts of the North and in the Midlands (areas with moderate coal prices) the low-pressure Watt engine with separate condenser was the prevailing design. Finally, in the Cornish mining district (the location characterized by the highest coal price), the Cornish high pressure condensing engine was adopted because of its superior fuel efficiency. In the United States instead, one can distinguish two regions: the East coast where low pressure condensing engines of the Watt type were mainly used, and the West regions, where high pressure engines (sometimes employing a surface condenser) were adopted. It is worth noting that high pressure engines in use in the United States were of the type introduced by Oliver Evans in 1801 and made use of steam pressures above 100 psi. Cornish engines, instead, were operated at steam pressures between 30 to 50 psi. Finally, Watt low pressure engines worked with a maximum steam pressure of about 10 psi (see chapter 2 above, for more details on the differences between these three engine designs). After having outlined this broad pattern of geographical specialization, Halsey remarks:

> …[A]fter 1800 the diffusion of different type of steam engines types across regional boundaries in Britain was minimal. Technological progress consisted mainly in improving each engine type within the region it dominated (Halsey, 1981, p. 726).

The following three chapters will be devoted to a study of the development of steam power technology in the Cornish mining district, which was the technological leading area in early nineteenth century steam engineering. The present chapter is essentially focused on the particular institutional set-up governing the generation and diffusion of new technological knowledge. The next two chapters instead will examine in detail the patterns of technological learning characterizing the dynamics of innovation in Cornish steam engines.

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[1] Nuvolari (2004) contains a condensed version of this chapter.

5.2. The nature of technical change in the British Industrial Revolution

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 industrialization as the "heroic age" of individual 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 industrialization 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 fully manifest their technical and economic potential. This process of incremental improvements, stemming from various learning processes occurring on both the producer's and the user's side is, as argued 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").[2] Many 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). According to Mokyr, an appropriate "technological definition" of the industrial revolution is "a clustering of macroinventions leading to an acceleration in microinventions" (Mokyr, 1999, p. 23).[3]

The economic significance of these streams of incremental improvements during early industrialization has been stressed in several accounts (see among others Landes, 1969; Mathias, 1969; and David, 1975). Appropriately, Landes terms this type of innovations as "anonymous" technical change, to emphasize that their nature is markedly different from the most "visible" individual acts of invention, that 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).

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[2] Mokyr' s conceptualisation of technical change has clearly many commonalities with the approach in terms of technological paradigms and trajectories originally proposed by Dosi (1982, 1988).

[3] O'Brien, Griffiths and Hunt (1996) noticed that in the case of textiles, patent figures suggest the existence of an uncertain and exploratory phase (1733 to 1785) during which macroinventions were attained, followed by a phase (1790 to 1850) in which technologies evolved gradually and in more predictable ways. Interestingly enough, in the first phase a good number of inventors had occupations *outside* the textile industries. Furthermore, their 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, characterized by a microinvention profile, is instead dominated by inventors professionally linked with the textile industries.

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), iv) *collective invention settings*. In collective invention settings, competing firms freely release *pertinent* technical information on the construction details and the performance of the technologies they have just introduced to one another. Allen has noticed this type of behaviour in the iron industry of Cleveland (UK) over the period 1850-1875. In the Cleveland district, iron producers devoted few resources to the discovery of new technical knowledge, instead they freely disclosed to their competitors technical information concerning the construction details and the performance of the blast furnaces they had erected. In the words of Allen,

> ....if a firm constructed a new plant [i.e., a blast furnace] of novel design and that plant proved to have lower costs than other plants, these facts were made available to other firms in the industry and to potential entrants. The next firm constructing a new plant build on the experience of the first by introducing and extending the design change that had proved profitable. The operating characteristics of the second plant would then also be made available to potential investors. In this way fruitful lines of technical advance were identified and pursued (Allen, 1983, p.2).

Information was normally released through both formal (presentations at meetings of engineering societies and publications of design details in technical journals) and informal channels (such as visits to plants, conversations, etc.). Additionally, new technical knowledge was normally not protected by patents, so that competing firms could *liberally* make use of the released information when they had to erect a new plant.[4] As a consequence of the proliferation of these "voluntary" knowledge spillovers, in the period considered, 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 the 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 identification of a specific institutional arrangement which constitutes one of the most favourable environments for micro-inventive activities.

The main contention of this chapter is that together with individual inventors, *collective invention settings* were a crucial source of innovation during the early phases of industrialization. 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. As we will see, innovations in Cornish steam engines originated from

[4] Note that Allen's notion of "collective invention" does not refer to the exchange of information between users and producers studied by Lundvall (1988). In fact, Allen is describing an exchange of information among *competing* entities. "Collective invention" also differs from the case of "know-how trading" described by von Hippel (1987). In "know-how trading", engineers "trade" proprietary know-how in the sense that the information is exchanged on a bilateral basis (non-participants to the transaction in question are excluded). Within collective invention, *all* the competing firms of the industry have free access to the potentially proprietary know-how, see von Hippel (1987), pp. 296-297. Cowan and Jonard (2003) have recently proposed a model which analyzes the diffusion of knowledge in collective invention settings.

collective invention processes of the type described by Robert Allen. We will study in detail the specific economic and technical circumstances that led to the formation of this particular collective invention setting and we analyze its consequences for the rate of technological innovation. Our study will point out (once more) the historical significance of "anonymous" incremental technical advances, but it will also demonstrate that economic historians cannot rely on the emergence of the intellectual property rights regimes to account for the acceleration of technical change that seems to characterize this historical phase.

5.3. Patent institutions and individual inventors

Historians of technology have produced detailed accounts of the generation of new technologies during the industrial revolution. In many of these accounts, individual inventors are put centre stage (Cardwell, 1994a, 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 nature of the connections between science and technology in this critical 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, instead, 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, 1994, 1999).

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. 164-166) 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.[5]

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 an imperfect protection and requiring the fulfillment of cumbersome and costly bureaucratic procedures, was nevertheless capable of stimulating inventors' efforts. Many inventors devoted time and resources to inventive activities with the perspective of appropriating economic returns through patent

[5] 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 and 2002, pp. 263-275). According to Mokyr, the issue of "why Britain was first" (among the western economies) calls for a different answer from the broader issue of why industrialization began in the second half of the eighteenth century in Western Europe and in her offshoots. The answer to these latter questions calls for an inquiry into the emergence of modern science-based technology, a complex historical process that set off during the eighteenth century, see Mokyr (2002, ch. 2).

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 instead 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. 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 United States). 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 United States.

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 United States 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 United States, 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) specializing in inventive activities, and firms in the production and commercialisation phases.[6] Hence,

[6] More specifically, Sokoloff, Lamoreaux and Khan distinguish two phases characterizing the historical evolution of nineteenth century inventive activities in the United States (Lamoreaux and Sokoloff, 1996, pp. 12686-12687). The first phase covers approximately the period, 1790-1846. In this period, inventive activities are widely widespread across the entire population ("democratization of invention"). The rather simple nature of technology permitted to ordinary citizens with common skills to be engaged in inventive activities. The second phase covers the period 1840-1920. In this period (due to the spread of mechanization and the increasing complexity of technology) inventions were primarily produced by individuals with technical backgrounds that were strongly committed to inventive activities. The market for technology reinforced this process of specialization.

the coupled development of the patent system and of the market for technology determined 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) specialized trade journals disseminating general information and providing detailed descriptions of patent specifications; ii) specialized 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 characterized by little glass production. In their view, this finding indicates that "learning by doing" and "localized knowledge spillovers" (two factors that have been prominently put forward to explain the connection between the localization 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 draw robust generalizations, 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 the 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 United States, 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 United States. In addition, high patent fees in Britain may have also induced a specialization 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 concise summary of their contributions, Lamoreaux, Sokoloff and Khan have elaborated a complex account of technical change in the course of the industrialization of the United States, 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.

On the other hand, as we have already pointed out in the previous section, many accounts of the industrial revolution have instead emphasized 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. 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.

5.4. Boulton and Watt in Cornwall

As we have in seen in chapter 2, due to their advantages in terms of fuel economy, in the last quarter of the eighteenth century, Watt engines were a particularly attractive proposition in locations where coal was expensive. Not surprisingly, the first important market for this type of engine 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 & 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 & 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 & Watt engine.

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 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 to 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 rather favourably accepted by Cornish mine adventurers. However, after some time, the pricing policy of Boulton and Watt was perceived as extremely oppressive. Firstly, 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 in general least productive. Secondly, mine adventurers knew the exact amount of payments they owed to Boulton and Watt only at the end of the month when these were actually due (Dickinson and Jenkins, 1927, p. 333).[7] Finally and most importantly, in the late eighteenth century, several engineers in Cornwall had begun

[7] The calculation system was cumbersome and the figures computed were frequently objected to, so that in a number of cases, Boulton and Watt decided to switch to an annual fix sum based on the general fuel saving potentialities of the engine they had installed, in the hope of avoiding the problems related with the computation of the actual coal savings, see Barton (1965), p. 31. However also the fixed annual sums were frequently disputed, especially when mines were not profitable. It must be remembered that from the early 1780s, the exploitation on large scale of the Parys Mountain copper mines in Anglesey determined a reduction in copper prices putting the profitability of many Cornish mining ventures under strain, see Rowe (1953, pp. 71-72 and p. 76).

to work on further improvements to the steam engine, but their attempts were frustrated by Boulton and Watt's interventions. 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 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, 1978).

The most famous case in this respect was that of Jonathan Hornblower who had taken a patent for the first compound engine in 1781 and who found the further development of his invention obstructed by the actions of Boulton and Watt. In 1782 a first engine of the Hornblower type was erected for the Radstock colliery near Bristol. Initially the performance of the engines was far from being satisfactory. After a period of experimentation, however, this engine was capable of delivering a performance comparable to the one of Watt engines. In 1791, Horblower began to erect engines in several Cornish mines, threatening Boulton and Watt's monopoly position. Concomitantly, he applied to Parliament for an extension of his 1781 patent. The argument on which Hornblower based his petition to Parliament was the same underlying Watt's petition of 1775: the engine had required a long and costly period of refinement after the patent was taken, so an extension was necessary to enable him to reap a fair profit from his invention. Boulton and Watt opposed the petition on the grounds that the salient features of the engine were a clear plagiarism of Watt's invention. As in the case of the prolongation of Watt's 1769 patent, Boulton's powerful influence succeeded in gaining the favour of Parliament on his side so that Hornblower and his partners decided to withdraw the petition.[8]

Yet, the conflict was far from being settled. After the Parliament's decision, Hornblower went on erecting his engines in Cornish mines. Many Cornish adventurers saw in his engines the possibility of further curtailing their costs, by avoiding the payment of the high royalties claimed by Boulton and Watt. At the same time, another Cornish engineer, Edward Bull began to install steam engines for several Cornish mines. Bull's engines were essentially a simplified version of Watt (they dispensed the beam, the piston rod acting directly the pumps) and thus a much clearer case of piracy than Hornblower's, but at this point of time the majority of Cornish mine entrepreneurs were ready to explicitly challenge the validity of Watt's patent monopoly.

Boulton and Watt had no other choice but to sue Bull for infringement. In his defence, Bull called explicitly in question the validity of Watt's patent on the basis of the insufficiency of the specification. 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.

During the lawsuit, Watt published an insertion in the Bristol newspapers claiming that his 1769 patent covered *all* the following features: 1) cylinder with closed top, 2) piston pressed by steam (instead of atmospheric pressure as in the Newcomen engine, 3) steam case to cylinder, 4) separate condenser, 5) air pump, 6) piston kept tight by oil or grease

[8] On the conflict between Boulton and Watt and Jonathan Hornblower, see Rowe (1953), pp. 90-95 and Torrens (1982).

(Dickinson and Jenkins, 1927, p. 305). In practice, it is impossible to move away from the design of the Newcomen engine, without making use of some of these features (Jenkins, 1931).

Hornblower, instead, considered Watt's patent limited to the separate condenser. In his engine steam condensation took place in the lowest part of the second (low-pressure) cylinder and for this reason Hornblower was convinced that he was not infringing Watt's patent. He later found out that the separate condenser could greatly improved the performance of his engine. Basically, Hornblower could not fully exploit his invention without infringing Watt. This was indeed the main motivation behind his decision to apply to Parliament for an extension (Hornblower patent of 1781 would have expired in 1795). In this way, he could have enjoyed a period of protection after the expiration of Watt's patent. As we have seen Parliament, by virtue of Boulton's influence, was not ready to meet the request. At that point Hornblower decided to adopt the separate condenser in his engines relying on the insufficient specification of Watt's patent. The performance of the Hornblower engine in its final form was roughly equal to a Watt engine in good conditions.[9]

After the clash on the prolongation of patent, Boulton and Watt and Jonhatan Hornblower did not meet again in court. Boulton and Watt adopted the cautious strategy of starting their campaign of legal actions by suing makers of engines who were clearly infringing the patent. The first lawsuit was the one directed against Edward Bull; a second lawsuit was directed against Jabez Hornblower (brother of Jonathan) and Maberley who had started erecting pirate rotative engines in the London area. On the basis of the victory obtained in these two cases, Boulton and Watt sent injunctions to all the other users of "pirate" engines they could identify (including the owners of Jonathan Hornblower's ones). At this point, none of them was available to fight further and so they all came to some form of settlement for the payment of the royalties. In Cornwall, 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. 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 William Murdock, their engineer working in the county, back to Birmingham. However, it is also important to mention that, at this stage, the market for industrial power had become the main focus of the company.

5.5. 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.

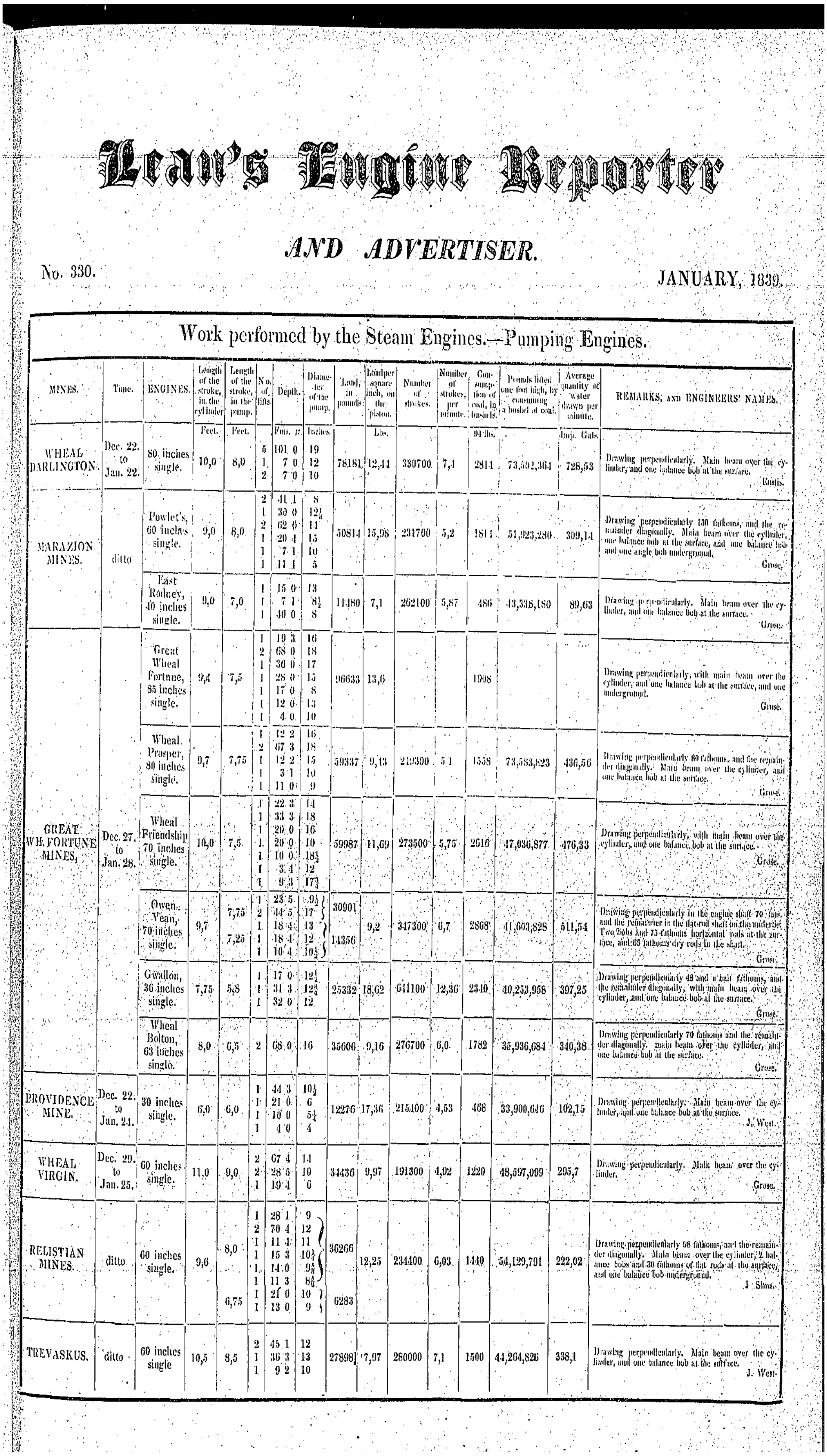
[9] Working at low pressures, the Hornblower engine could not exploit the advantages of compounding. Interestingly enough, about 1785, Hornblower discussed with Davies Gilbert (who would also engaged in a long correspondence with Richard Trevithick on the subject of the efficiency of steam engines) the possibility of adopting in his compound engines "the condensation of steam raised by quick fire" (i.e., high pressure steam and expansion), see, Todd (1967, p. 94).

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

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

MINES.	ENGINES, and the diameters of the cylinders.	Load per square inch, on the piston. Lbs.	Length of the stroke, in the cylinder. Ft. ins.	No. of lifts.	Depth. Fms. ft.	Diameter of the pumps. Inches.	Time.	Consumption of coal, in bushels.	Number of strokes.	Length of the stroke, in the pumps. Ft. ins.	Load, in pounds.	Pounds lifted one foot high, by consuming a bushel of coal.	Number of strokes, per minute.	REMARKS, AND ENGINEERS' NAMES.
DOLCOATH . .	76 inches, single.	11 . 5	9 0	1 9 3	2 0 179 1 23 3	8⅛ 12 13	April 28th. to May 27th.	3042	256000	7 6	64880	40,987.278	6,1	Drawing perpendicularly, 179 fathoms, and on the underlay, 33 fathoms. Main beam over the cylinder. Five balance bobs under ground, and one at the surface. GRIBBLE.
DITTO	Stray-Park, 64 inches, single.	8 0	8 0	1 3 2 1 3 1 1 1	6 0 60 5 43 0 18 0 49 0 2 0 5 3 10 0	11⅛ 11¼ 11 9⅛ 7 6 8½ 6	ditto	1251	182800	5 6 3 9	37739 736	30,733,268	4,38	Drawing perpendicularly, 110 fms. and on the underlay, 24 fms. Main beam over the cylinder. Two balance bobs under ground, and one at the surface. 180 fms. of horizontal rods, at the surface, and 132 fms. of dry rods, under ground. JEFFREE.
TIN-CROFT .	66 inches, single.	8 4	9 0	1 1 1 1 1 1 1 1	36 4 24 3 21 5 21 1 5 0 3 3 4 0 12 0	14⅛ 13⅛ 11 10 5 7 9 6	ditto	2466	345540	7 0 5 0	25638 1270	34,990,759	8,26	Drawing perpendicularly, 104 fathoms, and on the underlay, 12 fathoms. Main beam over the cylinder. One bob at the surface, and one under ground. GRIBBLE.
WHEAL CHARLOTTE	36 inches, single.	3 9	9 0	1 1 1	45 0 23 0 1 3	6 7 6	May 8th. to June 4th.	201	67840	6 3	5728	12,082,945	1,7	Drawing all the load perpendicularly, with horizontal rods. SIMS.
WHEAL VOR	Pearce's, 63 inches, double.	17 0	8 0	1 4 3 1 1 1 1 1	2 0 83 0 69 3 20 0 9 3 10 0 10 0 4 0	10 13 14 6 12½ 15 10⅛ 9	May 3rd. to June 5th.	6837	412060	6 3	68100	25,689,897	8,30	Drawing perpendicularly, 87 fms. and on the underlay, 70 fms. Main beam over the cylinder. Five bobs, and 55 fms. of horizontal rods, under ground. SIMS AND RICHARDS.
DITTO	Woolf's, 53 inches, single, gt. cylinder; 27 inches, single, small cylinder.	19 6	8 9	1 1 2 3 1	3 0 25 3 59 1 56 3 5 3	10 12½ 13 14 6½	ditto	5080	431180	7 3	52341	32,208,380	9,0	Drawing perpendicularly, 121 fathoms, and on the underlay, 20 fms. Main beam over the cylinder. Two bobs under ground, and one at the surface. SIMS AND RICHARDS.
DITTO	Old engine, 48 inches, single.	10 8	7 9	1 3 1 3 1 2	2 3 56 0 15 0 42 0 8 3 14 0	8½ 10 9 10 7 7½	ditto	1275	338430	5 6 6 6 6 0	14308 9442 1610	39,742,830	7,0	Drawing perpendicularly, 85 fms. and on the underlay, 17½ fms. Main beam over the cylinder. 200 fms. of horizontal rods, and 4 bobs, at the surface. One bob under ground. SIMS AND RICHARDS.
WH. VREAH	48 inches, double, working singly.	15 4	6 9	1 4 1 1 1 1	25 3 102 0 19 3 10 1 9 0 9 3	9 9½ 10 9 8 6	ditto	2075	402300	5 3 6 0	23053 7550	32,247,640	8,45	Drawing 6 lifts perpendicularly; and 3 lifts by means of 150 fathoms of flat rods, connected by two bobs at the surface, and one bob under ground. SIMS AND RICHARDS.
CRENVER . .	70 inches, single.	11 0	8 6	4 1 1 1 1 1	80 0 2 0 13 3 24 0 20 0 11 0	16 12 9 8¾ 8⅝ 7⅛	April 28th. to May 27th.	3996	357880	7 6 4 6	44716 8066	33,286,332	8,5	Drawing all the load perpendicularly. Main beam over the cylinder. One balance bob at the surface. Drawing 140 fathoms of horizontal rods, connected by two bobs. WOOLF.
OAT-FIELD .	70 inches, single.	7 3	8 6	2 1 1	44 5 21 3 12 0	14¾ 14¼ 11	ditto	3060	362680	7 6	31633	28,119,255	8,6	Drawing perpendicularly. Main beam over the cylinder. One balance bob at the surface, and two under ground; and 110 fathoms of dry rods, under ground. WOOLF.
WHEAL ABRAHAM . .	Middle, 66 inches, single.	9 6	8 6	1 1 1 1 2 1 1	4 0 22 3 35 0 21 0 43 4 20 1 20 2	7¾ 13 12⅛ 11¾ 10 9 8	ditto	3834	411690	7 3	39674	30,883,690	9,8	Drawing perpendicularly, 140 fathoms, and on the underlay 60 fathoms. Main beam over the cylinder. Two balance bobs, and 70 fathoms of dry rods, under ground. WOOLF.
DITTO	Woolf's, 45 inches, single, great cylinder	10 1	6 9	1 2 1 1 1 1	12 3 65 0 22 0 10 4 10 0 10 3	6 12 9 8⅛ 8 7⅞	ditto	1422	365200	6 9	28892	50,085,562	8,7	Drawing perpendicularly, 67 fathoms, and on the underlay, 48 fms. Main beam over the cylinder. Two balance bobs, and 70 fathoms of dry rods, under ground. WOOLF.
DITTO	Woolf's, 60 inches, single, great cylinder	12 4	8 9	1 1 1 3 1	33 4 34 0 26 0 32 3 6 0	14⅛ 14 12¼ 10 7¼	ditto	4302	337870	7 3	42642	24,280,341	8,1	Drawing perpendicularly, 120 fms. and on the underlay, 24 fms. Main beam over the cylinder. One balance bob, connected to 70 fms. of horizontal rods, at the surface, and 80 fms. of dry rods under ground. WOOLF.
WHEAL CLOWANCE.	Gundry's, 40 inches, single.	16 3	7 6	1 1 1 1 3	2 3 19 0 22 0 18 0 27 0	8¼ 8 13 11⅛ 10	April 29th. to May 27th.	844	115460	7 6	20423	20,954,143	2,9	Drawing perpendicularly, with main beam over the cylinder. JEFFREE.
DITTO*. . . .	Simpson's, 53 inches, single.	12 4	7 0	1 1 1 1 1 1 1	5 0 42 0 19 0 11 0 11 0 11 0 11 0	13 12 11½ 11 10¼ 10⅛ 8	ditto	1436		4 0 7 0	1728 26342			Drawing all the load perpendicularly, in three shafts. Main beam over the cylinder. 200 fathoms of horizontal rods, connected by six bobs at the surface.—70 fathoms of dry rods in the shafts. JEFFREE.
CARZIZE . .	22½ inches, double, working singly.	23 2	4 9	1 1 1 1 1 1	11 0 3 3 20 3 10 4 9 3 20 3	3 3½ 10½ 9 8 6	May 8th. to May 27th.	666	396530	4 9	9214	28,058,163	14,5	Drawing perpendicularly, with main beam over the cylinder. One balance bob at the surface. WOOLF.

Figure 5.1: page of Lean's Engine Reporter (May 1823)



Lean's Engine Reporter

AND ADVERTISER.

No. 330. JANUARY, 1839.

Work performed by the Steam Engines.—Pumping Engines.

MINES.	Time.	ENGINES.	Length of the stroke, in the cylinder	Length of the stroke, in the pump.	No. of lifts.	Depth.	Diameter of the pump.	Load, in pounds	Load per square inch, on the piston.	Number of strokes.	Number of strokes, per minute.	Consumption of coal, in bushels.	Pounds lifted one foot high, by consuming a bushel of coal.	Average quantity of water drawn per minute.	REMARKS, AND ENGINEERS' NAMES.
			Feet.	Feet.		Fms. ft.	Inches.		Lbs.			94 lbs.		Imp. Gals.	
WHEAL DARLINGTON.	Dec. 22. to Jan. 22.	80 inches single.	10,0	8,0	5 1 2	101 0 7 0 7 0	19 12 10	78181	12,44	330700	7,4	2814	73,502,364	728,53	Drawing perpendicularly. Main beam over the cylinder, and one balance bob at the surface. Eustis.
MARAZION MINES.	ditto	Powlet's, 60 inches single.	9,0	8,0	2 1 2 1 1 1	41 1 30 0 62 0 20 4 7 1 11 1	8 12¼ 14 15 10 5	50814	15,98	231700	5,2	1814	51,923,280	309,14	Drawing perpendicularly 130 fathoms, and the remainder diagonally. Main beam over the cylinder, one balance bob at the surface, and one balance bob and one angle bob underground. Grose.
		East Rodney, 40 inches single.	9,0	7,0	1 1 1	15 0 7 1 40 0	13 8½ 8	11480	7,1	262100	5,87	486	43,338,180	89,63	Drawing perpendicularly. Main beam over the cylinder, and one balance bob at the surface. Grose.
GREAT WH. FORTUNE MINES,	Dec. 27. to Jan. 28.	Great Wheal Fortune, 85 inches single.	9,4	7,5	1 2 1 1 1 1 1	19 3 68 0 30 0 28 0 17 0 12 0 4 0	16 18 17 15 8 13 10	96633	13,6			1908			Drawing perpendicularly, with main beam over the cylinder, and one balance bob at the surface, and one underground. Grose.
		Wheal Prosper, 80 inches single.	9,7	7,75	1 2 1 1 1	12 2 67 3 12 2 3 1 11 0	16 18 15 10 9	59337	9,13	219390	5,1	1558	73,583,823	436,56	Drawing perpendicularly 80 fathoms, and the remainder diagonally. Main beam over the cylinder, and one balance bob at the surface. Grose.
		Wheal Friendship 70 inches single.	10,0	7,5	1 1 1 1 1 1 1	22 3 33 3 20 0 20 0 10 0 3 4 9 3	14 18 16 10 18½ 12 17¼	59987	11,69	273500	5,75	2616	47,036,877	476,33	Drawing perpendicularly, with main beam over the cylinder, and one balance bob at the surface. Grose.
		Owen Vean, 70 inches single.	9,7	7,75 7,25	1 2 1 1 1	23 5 44 5 18 4 18 4 10 4	9½ 17 13 12 10½	30901 14356	9,2	347300	6,7	2868	41,603,828	511,54	Drawing perpendicularly in the engine shaft 70 fms. and the remainder in the flat-rod shaft on the underlie. Two bobs and 75 fathoms horizontal rods at the surface, and 65 fathoms dry rods in the shaft. Grose.
		Gwallon, 36 inches single.	7,75	5,8	1 1 1	17 0 31 3 32 0	12½ 12¾ 12	25332	18,62	641100	12,36	2340	40,253,958	307,25	Drawing perpendicularly 48 and a half fathoms, and the remainder diagonally, with main beam over the cylinder, and one balance bob at the surface. Grose.
		Wheal Bolton, 63 inches single.	8,0	6,5	2	68 0	16	35606	9,16	276700	6,0	1782	35,936,684	340,38	Drawing perpendicularly 70 fathoms and the remainder diagonally, main beam over the cylinder, and one balance bob at the surface. Grose.
PROVIDENCE MINE.	Dec. 22. to Jan. 24.	30 inches single.	6,0	6,0	1 1 1 1	44 3 21 0 10 0 4 0	10½ 6 5¼ 4	12276	17,36	215400	4,53	468	33,900,646	102,15	Drawing perpendicularly. Main beam over the cylinder, and one balance bob at the surface. J. West.
WHEAL VIRGIN.	Dec. 29. to Jan. 25.	60 inches single.	11,0	9,0	2 2 1	67 4 28 5 19 4	14 10 6	34436	9,97	191300	4,02	1220	48,597,099	295,7	Drawing perpendicularly. Main beam over the cylinder. Grose.
RELISTIAN MINES.	ditto	60 inches single.	9,6	8,0 6,75	1 2 1 1 1 1 1 1	28 1 70 4 11 4 15 3 14 0 11 3 21 0 13 0	9 12 11 10¼ 9⅝ 8⅝ 10 9	36266 6283	12,25	234400	6,03	1440	54,129,701	222,02	Drawing perpendicularly 98 fathoms, and the remainder diagonally. Main beam over the cylinder, 2 balance bobs and 30 fathoms of flat rods at the surface, and one balance bob underground. J. Sims.
TREVASKUS.	ditto	60 inches single	10,5	8,5	2 1 1	45 1 36 3 9 2	12 13 10	27898	7,97	280000	7,1	1500	44,264,826	338,1	Drawing perpendicularly. Main beam over the cylinder, and one balance bob at the surface. J. West.

Figure 5.1: page of Lean's Engine Reporter (January 1839)

The explicit intention was twofold. First the publication would permit the rapid identification and diffusion of best-practice techniques. Secondly, 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 descendents and lasted until 1904.[10] Two pages of the reporter are reproduced as figure 5.1.

Concomitant with the beginning of the publication of *Lean's Engine Reporter*, Richard Trevithick and Arthur Woolf installed 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).[11]

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 used expansively.

Figure 5.2 displays the evolution over time of the efficiency of Cornish steam engines (based on the collation 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 and conversely the phase of recession after the 1850s translated itself into a slow decline of average duty followed by a period of substantial stagnation (Barton, 1961 and 1965).

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[10] The first three reports were published on the *West Briton*, a local newspaper. From 1812 *Lean's Engine Reporter* appeared as an independent publication. Joel Lean died in September 1812. After his death the reporter was continued by his two sons Thomas (I) and John for the years 1812-1827. In the period 1827-1831 the two brothers compiled two separate reports. The period 1831-1837 was covered by Thomas I alone and the period 1837-1847 by Thomas I in collaboration with his brother Joel (II). After that, Thomas II (Thomas I's son) took charge of the reporter for the period 1847-1897. The final years 1897-1904 were covered by J. C. Keast. See Howard (2002a) for biographical details of the various compilers of steam engine reports in Cornwall.

[11] In fact, Trevithick had an ambiguous attitude towards patents (arising from an unsolved tension between appropriation and desire of the widest possible dissemination of his discoveries). Although he did not patent the Wheal Prosper design, he took five patents for other inventions in steam technology. It must also be noted that Trevithick's travel in South America in the topical period 1816-1827 prevented him from controlling the adoption of his inventions, leaving free ground to imitators and improvers. Another famous contemporary mining invention non patented was the miner's safety lamp contrived by Humphry Davy (another famous Cornishman!) in 1815. Davy explicitly refused to take a patent for his invention in order to ensure its wide and quick diffusion, see Knight (1992, p. 112).

The case of the Cornish pumping engine seems to be indeed an "exemplar" case of collective invention in the sense of Allen. In his paper, Allen individuates 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;
iii) firms employ this common pool of technological knowledge to further improve the technology in question. All these three propositions are amply corroborated in the case of the development of the Cornish engine.

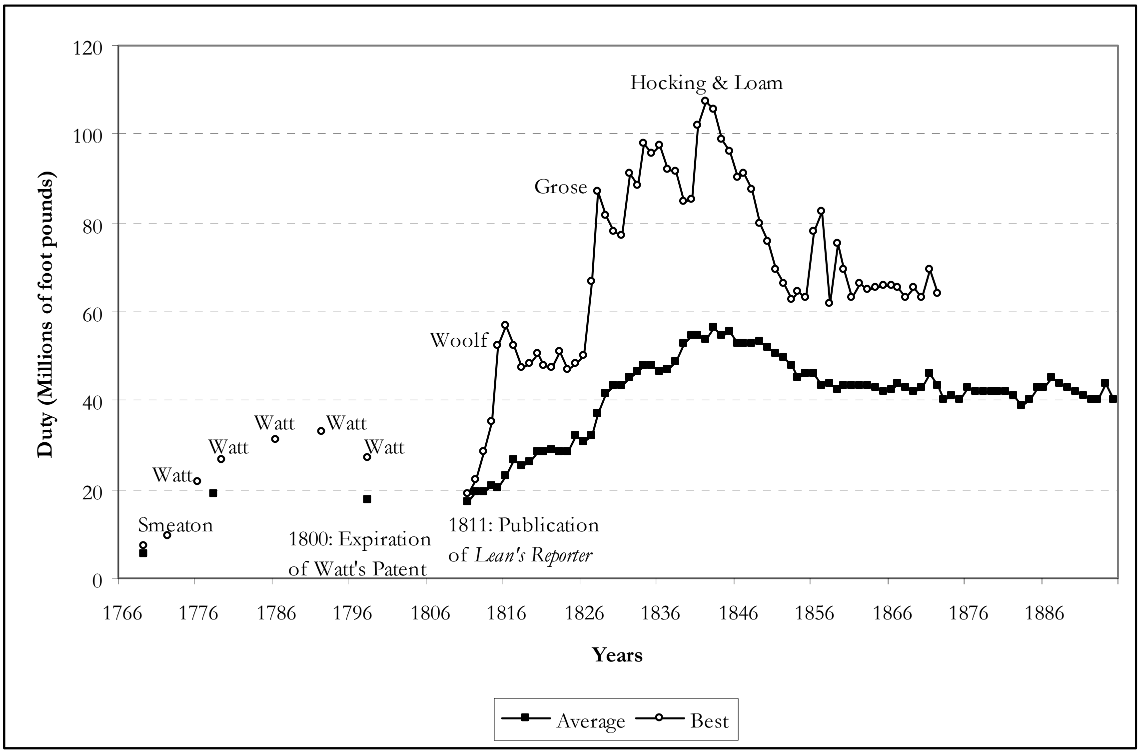

Figure 5.2: Duty of Cornish Engines, 1769- 1895

Sources: 1769,1772, 1776, 1778 (Lean, 1839);1779,1786, 1792 (Dickinson and Jenkins, 1927);1798 Gilbert (1830); 1811-1872 (Lean II, 1872); 1873-1895 Trestrail (1896).

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.180-181). 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. 62-63, 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.45-46).

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

Bridget Howard (2002a) has recently suggested a different interpretation of the foundation of *Lean's Engine Reporter*. In her view, the idea of setting up the engine reporter was actually due to Arthur Woolf and the real aim was to promote the Woolf compound engine among Cornish adventurers and managers. In support of her argument, she notices that in the 1810s, *Philosophical Magazine* (a London based journal, whose editor at the time was Alexander Tilloch, one of the "patrons" Woolf during his sojourn in London, who had paid the expenses for his experiments and his patents) published extracts of the *Lean's Reporter* with the not so veiled purpose of advertising the Woolf engine (Tilloch, 1815). Furthermore, Howard observes that from September 1827, Thomas and John Lean published two separate editions of the engine reporter (each of them reporting engines of different mines). In the second issue of "his own" engine reporter (October 1827), John Lean published the following statement:

As few, probably, even of those into whose hands the engine reports have regularly fallen, have adequate conceptions of the striking improvements within the last sixteen or seventeen years, it may not be unadvisable to state that my father began to make his observations in the year 1811. Among the first of the engines which fell under his inspection were those of Dolcoath mine. One of these accomplished in the first month 13 *millions*, and the other two, 8 *millions each* – (I am now speaking of the engines used in drawing water from the mine) – The last of these three has since risen to 30 nearly, the other to 35 and the third to 45 ! In the year 1811 the amount of bills for coal consumed in that mine was £ 11179 15*s.* 10*d.*- in the year 1823 it was only £ 4592 10*s.*11*d.*; difference £ 6587 4*s.*11*d.*! The price of coal in 1811 was rather greater than that of 1823; but to overbalance this very considerably, I have to mention that in the year 1811, the adventurers had only six steam-whims at work, whereas in 1823 they had eight, besides a steam stamping mill, which of itself consumed from five to six hundred or, perhaps, I may even say seven hundred bushels of coal monthly. But the loss which was sustained, independently of this, was incalculable; for such a wretched state were things reduced by the *inattention* and *carelessness* of engineers, and engine-men, that not a winter passed by without leaving a very considerable portion of the mine deluged. Now these are a few of the many happy facts which might be clearly demonstrated to have resulted from the *publicity* which has been given to the duty of steam engines. Numerous others might be stated, if there yet remained an individual so prejudiced as to question the utility of such monthly exposures. Engine-reports have been rendered a blessing to the community. They have excited a spirit of inquiry among all those concerned in mining speculations; and among engineers and engine men, *especially*, they have been the means of raising and maintaining a commendable emulation; and of stimulating to increased exertions, diligence and attention. Nor the will cease to be of vital importance as long as they continue to be made with *scrupulous regard to truth and equity* - as long as he to whom the office of engine-reporter has been intrusted, is not to be intimidated by the menaces of self-interested men, or shaken from that inflexible integrity which he should steadfastly hold as the *dearest*, the *brightest* gem of his life ! (John Lean, 1827, italics in the text).

It is worth remarking that the entire tone of the statement is very much in line with traditional accounts which consider the origins of the practice of engine reporting as a rather successful way of raising the general level of engineering standards in Cornwall, by - using John Lean's words - exciting a "spirit of inquiry" and by "maintaining a commendable emulation". In fact, Howard pinpoints the last part of the statement linking it with Thomas and John Lean's decision of issuing two separate reporters . In her view, it can be argued that the statement and the separation of the reporters are revealing of a profound disagreement between the two brothers concerning the practices of reporting. In particular, she suggests that the conflict was related with the standard of correctness adopted in reporting the duty of the various engines. Thomas Lean (I), who emerges as rather deceitful figure in her historical reconstruction, was liable of being heavily conditioned by Arthur Woolf.

As we shall see more in detail in the following chapter, in 1827 Samuel Grose successfully developed a system of thermal lagging of the engine which determined a new quantum jump in engine performance (first above 60 millions and then above 80 millions, see figure 5.2). At the time, Woolf was the main competitor of Grose in the race for the highest duty. In October 1827, Woolf installed a new engine at Consolidated Mines (adopting Grose's system of thermal lagging, see Barton 1965, p. 47) which also scored duties above 60 millions. Howard suggests that John Lean's decision to publish a separate report, was precisely motivated by the undue favours that his brother Thomas was inclined to concede to Woolf when reporting the performance of his engines in the "duty race" against Grose. This would explain the last part of the statement published by John Lean in October 1827. However, John Lean's decision to "divorce" may not be just a consequence of the supposed irregular duties reported during the fierce competition between Grose and Woolf in the period 1826-1828, but "may well have been the culmination of a long period of unhappiness" (Howard, 2002a, p. 31). After the separation, Grose's best engine was reported in the John Lean's reporter whereas Arthur Woolf's best engine continued to be reported in the one issued by Thomas.[12]

At all events, another episode seems to indicate that Woolf's influence in "fixing" the duties reported, if it was ever exerted, was probably much more limited than what is supposed in Howard's account. As mentioned in chapter 2, in 1825 two engines – one on Woolf compound design and the other on the more popular single cylinder design – were ordered by John Taylor for the Wheal Alfred mine. The explicit aim of the order was to solve the "controversy" concerning the fuel efficiency of the single cylinder versus the compound design developed by Woolf. If Woolf could exert some effective influence in the registration of the duties reported, the trial would have probably been the most convenient opportunity for him for strengthening his position on the Cornish market. The two engines engaged in the trial, according to the duties registered by the Leans, delivered the same performance, so that, by virtue of its minor costs of erection, since then the single cylinder design was generally adopted. This, in practice, amounted to a definitive defeat for Woolf's compound design.

In our judgment, other shreds of available evidence indicate that engine performances were, by and large, considered as reported with a sufficient degree of accuracy by informed contemporaries not directly connected with Woolf and his supporters. Davies Gilbert (an intimate friend of Richard Trevithick, one of Woolf's main rivals in the early

[12] The compilation of two separate reporters by Thomas and John Lean did not result in a "perfect" segregation of engineers among the two reporters (the decision whether to have an engine reported or not was a prerogative of the mine captains). After the "divorce", most engineers continued to have engines (at different mines) reported with *both* Thomas and John. Grose, Sims, and Jeffree had engines in both reporters. In particular, William and James Sims, one of the main competitors of Arthur Woolf, continued to have a considerable number of their engines reported in Thomas' reports. As will see, in the period 1847-1858, William West would instead submit all his engines to the newly created Browne's Engine Reporter.

1810s) in a paper published on *Philosophical Transactions of the Royal Society* had no particular reservations in using the duty figures reported in the issue of July 1826 of *Lean's Reporter* to illustrate improvements attained in steam technology due to the adoption of the expansive principle (Gilbert, 1827). W. J. Henwood, a contemporary observer who in the late 1820s and early 1830s performed a number of tests on the performance of Cornish steam engines and who does not result to be connected with any particular Cornish engineer in his *Presidential Address to the Royal Institution of Cornwall* made extensive use of the duty figures published in *Lean's Engine Reporter* to document the historical evolution of the performance of the engines at work in Cornish mines in the period 1811-1870 (Henwood, 1873). Finally, James Sims, an engineer, who in partnerships with his father William was one of most prominent rivals of Arthur Woolf, in short essay published in 1849 on *Mining Almanack* discussed the performances of various Cornish engines employing the duty figures contained in *Lean's Reporter* (Sims, 1849).

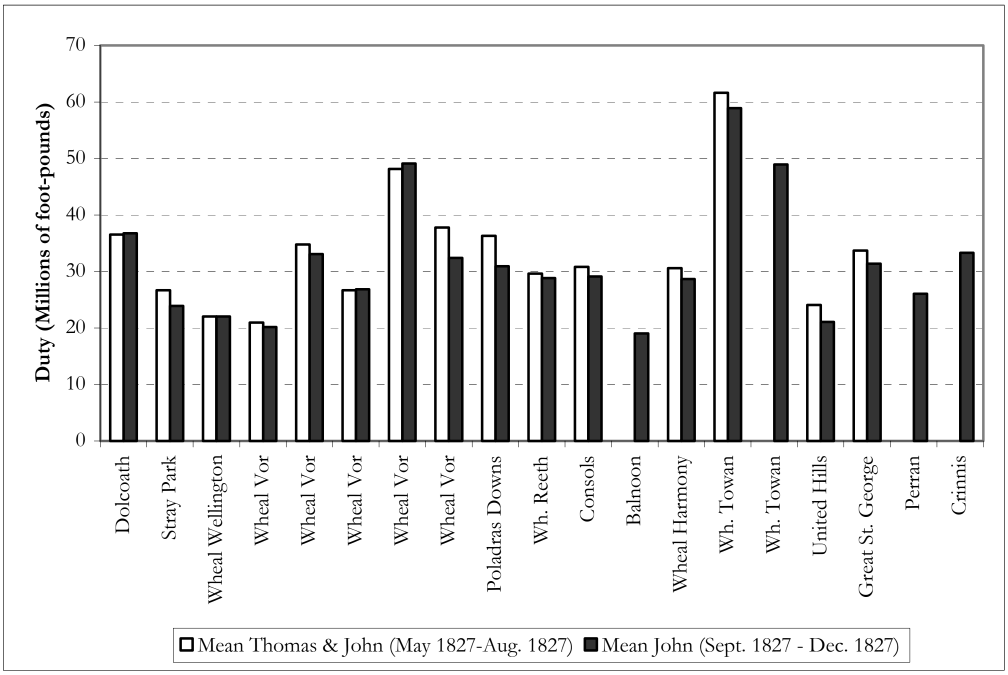

Figure 5.3: Duty for the engines in John Lean's Engine reporter (May 1827 – December 1827

Source: *Lean's Engine Reporter*

The upshot of these considerations, in our view, is that the traditional account of the foundation of the *Lean's Reporter*, such as the one given in Pole (1844) and which is repeated in most of the contemporary engineering literature (i.e., the reporter was set up in order to improve engineering standards and ensuring the rapid diffusion of best-practice techniques), ought still to be considered as broadly accurate. All this, of course, leaves unexplained what determined the decision of Thomas and John Lean of issuing separate reports. Concerning the issue of the accuracy of the duty figures reported, figure 5.3 shows the average duty of the engines reported by John Lean in the four months before and after the separation occurred in September 1827. As it is possible to see, there are no major changes in the duties reported. If the division between Thomas and John was actually motivated by disagreements concerning the "fairness" in the procedures adopted for calculating the duties, one would have expected that, after the separation of the two reports, the duty of some of the engines now reported by John would have undergone to some major change.

This is not to say that the duty figures reported in *Lean's Engine Reporter* were always peacefully accepted. Howard is undoubtedly correct in pointing out that the fierce competition among engineers, time and again generated heated debates on the relative performances of various engines. In fact, the duty of particular engines was frequently checked in public trials undertaken by purposely created commissions of independent experts (Lean, 1839). In our view, the separation between Thomas and his brother John and the ensuing compilation of two separate reporters in the period 1827-1831 cannot be with certainty linked to a conflict concerning the accuracy of the duties reported,[13] but the existing evidence does suggest that the (not very successful) attempt of setting up a new reporters by William Browne in the period 1847-1858 was clearly the outcome of the dissatisfaction of William West, one of the most active Cornish engineers of the period, towards the duty figures reported by Thomas Lean II (Barton, 1965, pp. 54-57). West ceased to have all his engines reported in *Lean's Engine Reporter* submitting them to the new reporter. Finally, it must recalled that there was another, still rather obscure, attempt of setting a new independent reporter, covering the period 1834-1841, by William Tonkin (Howard, 2002a, pp. 56-58).

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 – that is to say that the overall performance could be affected by a host of factors (boilers, steam pressure, engine, pitwork, etc.). Engineers could not rely on sound theoretical principles when they had to design a new engine. In this situation, the best engineers could do was to extrapolate from the relative performance of existing designs, attempting some small trial-and-error modifications. In such cases, one can expect that information disclosure will enhance the exploration of the space of technological opportunities. By pooling together all the accumulated experience, it was possible to gain a deeper understanding of the connections between specific designs features and engine performance and, consequently, focus the search process in the most promising directions. Furthermore, Cornish engines like the Cleveland blast furnaces are a rather typical example of "complex capital goods". Rosenberg (1982, pp. 120-140) has argued that for this type of products learning by using constitutes one of the main sources of improvement:

> …[L]earning by using refers to a very different locus of learning than does learning by doing. There are various reasons why this should be so. Perhaps in most general terms, the performance characteristics of a durable capital good often cannot be understood until after prolonged experience with it. For a range of products involving complex, interdependent components or materials that will be subject to varied or prolonged stress in extreme environments, the outcome of the interaction of these parts cannot be precisely predicted. In this sense, we are dealing with performance characteristics that scientific knowledge or techniques cannot predict very accurately. The performance of these products therefore is very uncertain. Moreover many significant characteristics of the products are revealed only after intensive or, more significantly prolonged use (Rosenberg, 1982, p. 122).

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[13] The statement published by John Lean, in our view, suggests that, if there was ever a conflict concerning the performances reported, this probably arose in the period immediately preceding the separation. In fact, the statement acknowledges the beneficial role that the reports had in the general growth of the duty of the engines employed in the Cornish mines. The tone of the statement seems also to suggest that, at least for an (unspecified) period following the creation of the reports, John Lean considered the duties of the engines as faithfully registered.

Cornish engines were run 24 hours a day. The use of high pressure in such conditions put under considerable strain the pit-work and many components of the engine itself (e.g. valves, beam). In these circumstances, the proper evaluation of the merits and pitfalls of a design modification might have needed a prolonged phase of experience. Furthermore, interdependence between components often meant that the introduction of a design modification often required adjustments and modifications of other parts of the engine. Again, the type of modifications required very often became evident only after a period of experience with the new design. In the Cornish context, the sharing of information relating to operating experiences of the various engines reinforced the feedback loop from learning by using to the further development and refinement of the original invention outlined by Rosenberg (1982, p. 125).

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. This holds also for the design of the various components of the engine such as valves, pipes, etc. 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 characterized by a peculiar form of industrial organization, centered 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 twenty-one years). The rent (called "dues") was paid in terms of a proportion of the ore extracted. This proportion varied according to the profitability of the mine. In deep and expensive mines, the lord's dues comprised between 1/18 and 1/15 of the ore excavated. In more profitable mines this proportion could rise to between 1/12 and 1/10. Before starting up the mining operations, adventurers met and each of them subscribed shares of the mine venture (normally the mine venture was divided into 64 shares). Shares were annotated in the mine cost book. One of the adventurers was appointed as the administrator of the venture ("purser"). At the same time, one or more mine captains were put in charge of the day-to-day management of the mine. Every two or three months, adventurers met and examined the accounts. If necessary a "call" was made and the adventurers had to contribute (in proportion to their share) to the coverage of mining costs until the next meeting. Failure to meet the call implied immediate forfeiture of the mine shares. Shares could be easily transferred, the only formality being notification to the purser. When the mine became productive and ore was sold, profits were divided in proportion to their shares. The "cost book" system had the advantage of allowing mine adventurers a limited financial liability (Rowe, 1953).

Adventurers were usually not tied to the fortunes of a single mine, but they often acquired shares of different mine ventures. Consequently, they tended to be more interested in the overall profitability of the district than in that of individual mines. Improvements in the *average aggregate performance* of the steam engines at work in Cornwall dictated an increase of the overall profitability of the district.[14] Further, improvements in the average aggregate performance of Cornish engines also had the positive effect of increasing the value of the Cornish ore deposits (a similar mechanism was at work in Cleveland where improvements in the performance of the blast furnaces were also reflected in increases in the value of Cleveland iron mines). Thus, the particular structure of the Cornish mining industry seems to have permitted (at a sort of second stage) the "internalization" of a consistent part of the positive externalities generated by the free disclosure of innovations. Note that in several instances there were suggestions of implementing a similar system of reports for steam engines at work in textile areas, but nothing followed (Hills, 1989, p.131). A partial exception is the case of the *Manchester Steam Users' Association*. This Association was founded in 1855 and its purpose was to provide its members with accurate reports on the safety and efficiency of the boilers they had in use.[15] In defining the scope of the Association and the procedures for the compilation of the reports the example of *Lean's Engine Reporter* was explicitly considered as a model (see, Manchester Steam Users' Association, 1905, p. 24).[16] The initiative had only limited success, being capable of attracting only a small portion of steam engine users (Bartrip, 1980, p. 87).

The third important characteristic of the Cornish mining industry that is worth pointing out is that engineers were recruited by mine captains on a one-off basis (this was also the case in the Cleveland blast furnace industry). Typically, engineers were in charge of the design of the engine and they supervised the erection works. They also provided directions for the day-to-day operation and maintenance of the engines they were entrusted with. It is worth noting that Cornish engineering were chiefly engaged in the design activities and not in the manufacturing of the actual components of the engine. Pole described the role of the Cornish engineers in these terms:

It is necessary to say something of the relations which subsist between the mining adventurer, the engineer and the manufacturer of the machinery in Cornwall, as their respective positions are somewhat peculiar, and different to those which obtain in the rest of the kingdom, and to this peculiarity may be traced much of the opportunity of improvement which has been afforded. In London and in the country, generally, parties who require steam engines are accustomed to apply for them directly to the manufacturers, who thus become the *designers* as well as the makers of the engines, or if a civil engineer intervene, it is usually only to the general arrangement of the works that he directs his attention, leaving the details of the construction of the engine to the manufacturer, as before. The *management* of the engine, when erected, is intrusted (except in the case of large works where a managing engineer is specially engaged) generally to the

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14 Besides the involvement of adventurers in different mining ventures, a long-lasting tradition of cooperation between neighboring mines was well established in the Cornish mining district: "Between the 16th and the 18th centuries a well-developed habit of cooperation had been created between the owners and managers of adjacent mines. Despite the impression of constant antagonism, litigation and even violence....the general rule was for mutual cooperation for mutual profit....Examination of the 18th and 19th century cost books for mines in St. Just, St. Agnes and Redruth parishes show that cooperation over something as vital as mine drainage was the norm among mine owners, managers and landlords in Cornwall"(Buckley, 1989, pp. 2-3).

15 The original name of the association was *Association for the Prevention of Steam Boiler Explosions and for Effecting Economy in the Raising and Use of Steam*. Article 18 of the Rules and Regulations of the Association stated: "[E]very member [can] have *free access* to the results recorded in the office of the secretary: but in all books and reports open to the inspection of the members each firm shall be designated by a number, and the names of firms shall only be given with their consent" (Manchester Steam Users' Association, 1905, p. 22, italics added).

16 William Fairbairn one of the promoters of the initiative in the evidence given on boiler explosion at Stockport in 1851 said: "It seems to me that there should be some association....by which registers should be kept, not only with reference to the safety of the public, but also to show what duty engines and boilers perform. The best results have arisen from such regulations in Cornwall and it has led there to the greatest possible economy" (Fairbairn, 1877, p. 265).

engine-men, or to parties having but little claim to the acquirements necessary for its skilful and economical performance. But in Cornwall things are otherwise arranged. There is a class of men known by the name of *engineers*, who have no connection at all with the manufacturers, and whose sole and proper occupation it is to take charge of the steam engines upon the mines, and to design and superintend the manufacture of new ones, when such are required. The manufacturers do not pretend to be engineers and would on no account undertake to supply engines, except through the intervention and under the direction of engineers....The advantages arising from this separation of the offices of the engineer and manufacturer are too important to be overlooked....[I]n Cornwall the *engineers* are able to devote their whole attention to the improvement of the engine, unharassed by the cares of the manufactory, and are alive to the consideration of all circumstances connected with its action which can influence its duty: they have opportunities of trying experiments with a view to improvement, which it would generally be impossible for a manufacturer to undertake; and when they find these successful, they have the power to extend their application and see the effect of their working. (Pole, 1844, pp. 159-160, italics in the text).

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. 104-105).

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 interested in publicly signalling the *above average performance* of the engines they had erected. Thus, *Lean's Engine Reporter* should be considered as an attempt of reconciling the tensions between collaboration (among mine adventurers) and competition (among engineers) existing in the Cornish mining district in a fruitful way. It is worth to add a word of caution in this respect. In fact, it is possible that the fierce competition between engineers might have induced some of them to "cheat" and have, at least for some engines, an overestimated duty credited in the reporter . This, however, was likely to be possible only if the person entrusted with the reporter was lenient towards a particular engineer or group of engineers.[17] In this respect, the episodes of defection towards *Lean's Engine Reporter* that we have discussed above well illustrate the difficulties of maintaining a stable context of cooperation among the engineers. The reporter was a powerful stimulus to competition and rivalry among engineers. However, (excessive) rivalry could undermine the very cooperation necessary for having the engines fairly reported on a useful comparative basis. It is our contention that, although with a number of difficulties, *Lean's Engine Reporter* was indeed sustained by a remarkable sense of co-operative behaviour between Cornish engineers and that for these reasons it is to be considered a rather successful vehicle for the exchanges of information which form the basis of collective invention processes. [18]

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[17] We will discuss more in detail the procedure adopted for calculating the duty and the accuracy of the figures reported in the next chapter.

[18] This was the view of contemporary engineers such as Farey, Wicksteed and Pole who paid visits to Cornwall in order to gain some insights on the sources of the high duty performed by Cornish engines: "...the practice [of reporting the duty of the engines] is thought to have been attended with more benefit to the county than any other single event except the invention of the steam engine itself" (Pole, 1844, p.147). See also Barton (1965, p. 48 and pp. 54-57). As already mentioned a rather different view is put forward by Howard (2002a) who seems to consider exaggerated reporting of duty as a rather systematic behaviour. Note however, that in this chapter we are mainly concerned in the impact of *Lean's Engine Reporter* on the *average* performance of the steam engines at work in Cornwall (a positive impact that also Howard acknowledges). Howard, instead, is more interested in shedding light on the rivalries among various

Table 5.1: Geographical Distribution of British Steam Engine Patents, 1698-1852

County	N.of Patents 1698-1852	% 1698-1852	N.of Patents 1698-1812	% 1698-1812	N.of Patents 1813-1852	% 1813-1852
Cheshire	14	1.23	0	0.00	14	1.39
Cornwall	17	1.50	8	6.25	9	0.89
Cornwall*	21	1.85	12	9.38	9	0.89
Derby	11	0.97	1	0.78	10	0.99
Durham	13	1.15	0	0.00	13	1.29
Essex	6	0.53	0	0.00	6	0.60
France	21	1.85	0	0.00	21	2.09
Gloucester	20	1.76	8	6.25	12	1.19
-Bristol	12	1.06	4	3.13	8	0.79
Hampshire	9	0.79	0	0.00	9	0.89
Ireland	13	1.15	1	0.78	12	1.19
Kent	31	2.73	1	0.78	30	2.98
Lancashire	145	12.78	5	3.91	140	13.90
-Liverpool	35	3.08	1	0.78	34	3.38
-Manchester	58	5.11	2	1.56	56	5.56
London & Middlesex	395	34.80	40	31.25	355	35.25
Northumberland	22	1.94	2	1.56	20	1.99
-Newcastle-up.-Tyne	11	0.97	1	0.78	10	0.99
Nottingham	13	1.15	1	0.78	12	1.19
Scotland	47	4.14	6	4.69	41	4.07
-Edinburgh	9	0.79	0	0.00	9	0.89
-Glasgow	22	1.94	3	2.34	22	2.18
Shropshire	6	0.53	3	2.34	3	0.30
Somerset	4	0.35	2	1.56	2	0.20
-Bath	2	0.18	1	0.78	1	0.10
Stafford	27	2.38	5	3.91	22	2.18
Suffolk	5	0.44	0	0.00	5	0.50
Surrey	88	7.75	10	7.81	78	7.75
USA	13	1.15	2	1.56	11	1.09
Wales	12	1.06	1	0.78	11	1.09
Warwick	58	5.11	8	6.25	50	4.97
-Birmingham	55	4.85	6	4.69	49	4.87
Worcester	11	0.97	1	0.78	10	0.99
York	63	5.55	11	8.59	52	5.16
-Bradford	11	0.97	0	0.00	11	1.09
-Kingston-up.-Hull	9	0.79	2	1.56	7	0.70
-Leeds	17	1.50	3	2.34	14	1.39
-Sheffield	6	0.53	0	0.00	6	0.60
Others	71	6.26	12	9.38	70	6.95
Total	**1135**	**100.00**	**128**	**100.00**	**1007**	**100.00**

* 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.

Besides the three factors mentioned above, the transition to a collective invention regime in Cornwall was also motivated by the disappointing experience of the Boulton & 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.

factions of Cornish engineers and on their impact on the accuracy of the reported performance of particular engines.

Table 5.1 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 Christine MacLeod (1988, pp.119-124), 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 specialized 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 there located. 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.

Over the entire period 1698-1852, the share of Cornwall in total patenting is 1.85 per cent, which does not reflect at all the major contribution of the county to the development of steam power technology. Breaking down the period 1698-1852 into two sub-periods (1698-1812 and 1813-1852), in order to take into account the publication of *Lean's Engine Reporter* is even more revealing. In the first period, Cornwall (including in the count also the patents taken out by Arthur Woolf who, at the time, was working for the Meux & Reid brewery in London) is the county with highest number of patents after the London and Middlesex area, with a share of 9.38 per cent. In the second period, the share of Cornwall drops to a negligible 0.89 per cent and this is exactly the period during which the Cornish pumping engine was actually developed. In our view, this finding is indicative of the widely perceived awareness in the county of the benefits stemming from the adoption of a collective invention regime for the rate of innovation. 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 & 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 & 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.188-189). [19] Later on, in 1823,

[19] This was also the fate of the circular calciner (which is considered an important step in the mechanization of the ore dressing processes) patented by William Brunton: "Although the advantages of

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. 109-110). He did not claim any patent right for this invention. In the same period, he also introduced notable improvements in the cataract regulator which he did not patent (Pole, 1844, p. 89).[20] Similarly, Samuel Grose did not patent the system of thermal lagging that he introduced in 1826, even when Davies Gilbert had advised him to do so (Todd, 1967, p. 101).

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. 110-112).

One can point to other Cornish inventions in steam technology which were not patented. The "Cornish water gauge", an instrument which allow a prompt check of the height of water in the boiler, invented by Richard Hosking in 1833, is a noteworthy case. In his *Treatise*, Pole describes it as "a very ingenious apparatus.....almost unknown out of the county" (Pole, p. 109). The invention was awarded a prize by the *Royal Cornwall Polytechnic Society* and a detailed description was published in the Society's *Reports.* In fact, since its foundation in 1833, the *Royal Cornwall Polytechnic Society*, a local learned society, awarded a yearly prize for "Inventions and Workmanship". A perusal of the yearly reports *Reports* of the society reveals that many inventions related to steam engineering. For the period 1833-1841, none of them was patented.[21] It is also interesting to note that leading mine entrepreneurs, such as John Taylor,[22] tried to steer the direction of inventive efforts by instituting prizes for inventions aimed at specific purposes (such as water meters for boilers, stroke counters, etc.). Overall, it is hard to tell the technological significance of these inventions. Remarkably, William Pole found some of them worthy to deserve a description in his *Treatise*, which indicates that they probably were not of trifling importance (see, Pole, 1844, p. 122).

Passages in the contemporary engineering literature seems also to indicate some awareness of the advantages arising from keeping technical innovations in the public domain. For example, John Taylor 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. 251-252)

To sum-up, in our interpretation, the realization of the three conditions outlined above (i.e., i)complex capital good technology, ii) dispersed and overlapping ownership of

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the calciner were evident, very few mines used it until the patent had expired, and then it was found in operation throughout the length and breadth of the county" (Ferguson, 1873, p. 147, remark made by T. S. Bolitho in the discussion of the paper).

20 The fact that Woolf did not patent these two inventions has been checked using Woodcroft (1854).

21 Again we have used Woodcroft (1854) to check that the inventions which were awarded a *Royal Cornwall Polytechnic Society* prize over the period 1833-1841 were not patented.

22 For an account of Taylor's life and business and engineering activities, see Burt (1977).

mining ventures, iii) existence of group of independent consulting engineers) combined with a rather widespread need of raising the efficiency of the steam engines after the period of "slackness" which had followed the expiration of Watt's patent and led, in the early 1810s, to the emergence of a sustainable collective invention setting. Over time, stimulated by the same process, it is possible to discern the formation in the Cornish engineering community of a rather original "professional culture", characterized by an enduring commitment to advancing technology. A similar type of process has been well described by Saxenian in the early stages of development of Silicon Valley (Saxenian, 1994).[23]

5.6. Concluding remarks

Recent research in economic history has pointed to the patent system and, relatedly, to the market for (patented) technologies, as institutional arrangements that greatly stimulated innovative activities during the nineteenth century. The case study of the Cornish mining district presented in this chapter 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 contains 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 (Berg and Hudson 1992, pp.38-39; 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, Griffiths and Hunt, 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 like in Cornwall, the organization of innovative activities was governed by specific institutional arrangements, alternative to the patent system, that 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.

In his account of the development of the high pressure engine for the western steamboats in the United States during the early nineteenth century, Louis Hunter has also emphasized the significance of various flows of incremental innovations (Hunter,

[23] For a discussion of Cornish identity in the nineteenth century, see Payton (2002). Payton (2002, p.126) notices in this period the consolidation of "an assertive Cornish identity based on industrial prowess".

1949, pp. 121-180). In the light of the present discussion this passage from Hunter's contribution is particularly intriguing:

> Though the men who developed the machinery of the western steamboat possessed much ingenuity and inventive skill, the record shows that they had little awareness of or use for the patent system. Of more than six hundreds patents relating to steam engines issued in this country down to 1847 only some forty were taken out in the names of men living in towns and cities of the western rivers. Few even of this small number had any practical significance. In view of the marked western preference for steam over water power and the extensive development of steam-engine manufacturing in the West, these are surprising figures. How is this meager showing to be explained and interpreted ? Does it reflect a distaste for patents as a species of monopoly uncongenial to the democratic ways of the West, an attitude sharpened by the attempts of Fulton and Evans to collect royalties from steamboatmen ? Or, were western mechanics so accustomed to think in terms of mere utility that they failed to grasp the exploitative possibilities of the products of their ingenuity ? Or, did mechanical innovation in this field proceed by such small increments as to present few points which could readily be seized upon by a potential patentee ? Perhaps each of these suggestions – and especially the last - holds a measure of the truth. At all events the fact remains that, so far as can be determined, no significant part of the engine, propelling mechanism, or boilers during the period the steamboat's development to maturity was claimed and patented as a distinctive and original development (Hunter, 1949, pp. 175-176).

One might indeed tempted to see a close analogy with the Cornish case examined in this chapter, suggesting that the patenting behaviour of western steamboats "mechanics" perhaps reveals the existence of another collective invention setting in early nineteenth century steam engineering. Interestingly enough, Hunter, suggests that the litigations related with the patents taken by Robert Fulton and Oliver Evans (mirroring the conflict between Boulton and Watt and Cornish engineers) could be one of the reasons accounting for the negative attitude of western mechanics towards patents (see Hunter, 1949, p. 10 and pp. 124-126 for a short overview of these litigation cases). Of course, this is a rather speculatively explanatory hypothesis of the development of the western steamboat engine. More extensive research on the exchanges of information among western mechanics would be necessary to corroborate this interpretation.

Another particularly interesting example is the case of the competition in the silk industry between Lyon and London (Foray and Hilaire Perez, 2000). In London, the organization of innovative activities was based on patents and secrecy, whereas in Lyon a sophisticated institutional architecture assured a rapid dissemination and an open use of technical innovations (Cotterau, 1997, pp.139-143; Hilaire Perez, 2000, pp. 73-82). During the first half of the nineteenth century the two districts fiercely competed. 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, surviving successfully market crises and other adversities (Sabel and Zeitlin, 1985, pp 156-157). It is worth stressing, however, that it is very difficult to draw generalizations. In fact, one can mention other cases of local 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; Berg 1993, p. 269). Note that in Birmingham most innovative activities were related to consumer product innovations (mostly variations in product design), whilst, as we have seen, in Cornwall, inventive activities consisted chiefly in incremental improvements to a process innovation.

In general, as Christine MacLeod (1992) has noticed, in this historical phase, strategies for reaping the economic returns of an innovation were likely to vary greatly according to the nature of the technology in question. In case of production machinery (textile machines, paper machines, food processing, etc.), "user-inventors" were responsible for the majority of inventions. By and large, "user-inventors" decided to work their innovations in secrecy or to control them tightly using patents (MacLeod, 1992, especially pp. 290-295). The two remarkable exceptions to this pattern were machine tool and steam engines. In the these two fields machine-makers rather than machine-users accounted for the major bulk of inventive activities. Although machine-makers also increasingly resorted to make use of patent protection, it seems that they tended to exert a less tight control on their intellectual property rights than machine-users and there is some evidence of the establishment of practices which ensured that licenses and royalties became increasingly object of unrestricted trade on moderate terms on a rather "uneventful" market for technology (MacLeod, 1992, p. 301). The Cornish case differs from this pattern in that the diffusion of technological knowledge was ensured by means of "collective invention" rather than through the emergence of a "market for technology".

In the United States, in a number of industries, processes of "collective invention" were implemented by means of patent pools. Note that in some cases, 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 determined 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-licenses and knowledge sharing (Usselman, 1991, 1999).

Finally, the examples we have 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), a strong enforcement of intellectual property rights might, in the end, hinder technological progress. In such cases, strong enforcement of intellectual property rights might either determine a case in which technical progress is stifled by a monopolist holding a particularly critical patent (this was the Cornish state of affairs at the end of the nineteenth century) or a situation in which the ownership of a critical body of knowledge is fragmented among different proprietors (so that each of them can exclude the others from making of use of the bit of knowledge in her possession) and the final outcome is a delay of technical progress due to impossibility of fully exploiting the body of knowledge subjected to fragmented ownership. Heller and Eisenberg (1998) have labeled these instances as "tragedy of anticommons". This seems indeed to have been the case of early Bessemer steel technology in the United States as described by Morison (1966).

In "cumulative system technologies", 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. [24] As we have shown, in the case of Cornish steam 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 industrialization 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.

[24] Furthermore, one might add that a number of empirical studies have noticed that in some contemporary "high-tech" industries the proliferation of spillovers does not seem to significantly reduce the private investment in inventive activities (see Levin, 1988 for empirical evidence based on the Yale survey). Levin's suggested interpretation of this finding that points to the cumulative nature of technical progress in such industries is fully in line with the perspective set out in this chapter: "[T]echnical advance in the electronics industries has been much more 'cumulative' than 'discrete'. This period's microelectronic device incorporates many features developed in previous periods, and the new technology it embodies is typically a foundation for next period's innovations. When innovations are 'building blocks' in this sense, spillovers of a rival's R&D may raise the marginal product of own R& D. In such a regime, a high degree of spillovers may not only spur technical advance but also encourage R & D investment." (Levin, 1988, p. 427).

6. ‘Unravelling the Duty’: *Lean’s Engine Reporter* and the Development of the Cornish Steam Engine[1]

6.1. Introduction

In the previous chapter we have analysed the institutional set-up supporting inventive activities in steam technology in the Cornish mining district during the early nineteenth century. We have shown that the type of innovation process underlying the development of the Cornish steam engine fits particularly well in Robert Allen’s notion of ‘collective invention’. In Cornwall, the main vehicle for sharing technical information concerning the performances of the various engines was constituted by a regular monthly publication, *Lean’s Engine Reporter,* sponsored by mining entrepreneurs. The availability of a data source tracing in quantitative detail the evolution of a technology such as *Lean’s Engine Reporter* is indeed a rather unique occurrence in the technological history of the industrial revolution. Furthermore, the *Reporter* portraits a particularly crucial phase in the overall development of steam power technology, namely the first systematic attempts of employing high pressure steam in combination with the “expansion principle”. In retrospect, it is not surprising that some of the most competent contemporary observers paid a great deal of attention to technological developments in Cornwall as portrayed in the engine reports. For example, John Farey, changing quite drastically his initial publication plan, devoted the major part of the (unfinished) second volume of his *opus magnum*, to the Cornish engine, making extensive use of the data contained in *Lean’s Engine Reporter*.[2] The superior fuel efficiency of the engines of the Cornish type was also widely discussed in France by scientists and engineers interested in the functioning of the steam engines.[3] Sadi Carnot himself concluded his *Reflexions sur la puissance motrice de feu* mentioning the duty of 56 millions achieved by the engine erected by Arthur Woolf at the Wheal Abraham mine.

The aim of this chapter is to reconstruct the patterns of innovation characterizing the development of steam technology in Cornwall. *Lean’s Engine Reporter* is of course the main historical source to be used in such an endeavour. We then sketch a suggested interpretation of the workings of the process of accumulation of technological knowledge in Cornish steam engineering, that can account for these patterns.

However, before turning our attention to the analysis of patterns of technical change in Cornish engines, it is worth devoting some space to discuss some factors accounting for the peculiar development of steam power technology in Cornwall in comparison with other steam using regions of Britain.

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[1] This chapter draws partially on Nuvolari and Verspagen (2003).

[2] According to the original plan, the second volume should have comprised of two parts: the first describing the developments in engine design occurred in the early nineteenth century, the second one outlining a scientific analysis of the working of the steam engine, see Woolrich (2002).

[3] In the 1810s the Cornish engine reports were reprinted regularly in *Annales de Chemie et de Physique* (see Cardwell 1971, p. 157, also for other examples of early French inquiries on the performance of Cornish steam engines). In the same period, the *Philosophical Magazine* edited by Alexander Tilloch (one of the “patrons” of Arthur Woolf during his permanence in London) published summaries of *Lean’s Reporter.*

6.2. Inducement factors and technical progress in early nineteenth century steam engineering

A large body of engineering literature on steam technology in the early nineteenth century was informed by the debate on the different choice of technique characterizing the use of steam power in Cornwall (where the high pressure expansive engine was adopted) versus the rest of Britain, especially the manufacturing districts of the North, where the favourite option was the Watt low pressure engine.

The superior fuel efficiency of the Cornish practice led some contemporary observers to describe this situation as a manifestation of a "technology gap". N. P. Burgh, in *A Practical Treatise on the Condensation of Steam* published in 1871, described the general complacent attitude towards the adoption of technical novelties in steam engines prevailing in the textile manufacturing districts during the early nineteenth century in these terms:

> The matter before them was all-sufficient because it answered up to a certain point of working duty, and thus *mutual contentment* reigned where an equal desire for further knowledge ought to have been (cited in Hills, 1989, p. 113, italics added).

In the same vein, William Fairbairn,[4] a highly influential character in the Lancashire engineering community, and one of the leading advocates of the technical merits of the high pressure expansive engine whose pleadings remained for a long period unfulfilled, wrote:

> For a great number of years a strong prejudice existed against the use of high pressure steam and it required more than ordinary care in effecting the changes which have been introduced: it had to be done cautiously, almost insiduously, before it could be introduced. The author of this paper believes he was amongst the first in the Manufacturing Districts who pointed out the advantages of high pressure steam when worked expansively, and for many years he had to contend with the fears and prejudices of the manufacturers... (Fairbairn, 1849, pp. 23-24)

Similarly, John Farey (1971, p. 307) denounced a widespread and culpable "state of apathy as to consumption of fuel" in the "great manufacturing districts of the North". [5]

According to James Nasmyth, the inventor of the steam hammer, the actual beginnings of the adoption of high pressure with expansion in Lancashire could be reasonably dated in the late 1840s when "timid and prejudiced traditions" had been finally dissipated. In a letter of 1852 which is quoted at length in the third volume of Marx's *Capital,* Nasmyth wrote:

> The engine power of this district (Lancashire) lay under the incubus of timid and prejudiced traditions for nearly forty years, but now we are happily emancipated. During the last fifteen years, but more especially in the course of the last four years (since 1848) some very important changes have taken place in the system of working condensing steam engines….The result has been to realize a much greater amount of duty or work performed by identical engines, and that again at a very considerable reduction of the expenditure of fuel….(Marx, 1992, p. 191).

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[4] On William Fairbairn, see Musson (1970).

[5] D.K. Clark described the English engines presented at the 1862 International Exhibition in London in these blunt terms: "[The engines of English builders] in general testified to a feeling of absolute indifference to economy of steam or fuel, and probably in some instances, to ignorance of the conditions on which economical working is to be established" (cited in Hunter, 1985, p. 600).

Thus, as the foregoing passages show, many engineers and practitioners had remained rather sceptical, at least till the late 1830s, about the fuel advantages of using high pressure steam expansively.[6] In particular, several doubts were voiced on the actual levels of fuel efficiency achieved by Cornish engines, denying the existence of a Cornish technological lead. This was also due to the fact that the superior fuel efficiency of the high pressure expansive engine remained theoretically unaccounted for. As a consequence, the dramatic early rise of the duty of the (best-practice) Cornish expansive engines (in the 1810s up to more than 40 millions and by the late 1820s to more than 80 millions) was not easily accepted outside Cornwall. In 1836 there was a heated debate in *Mechanic's Magazine* on the general reliability of the reported duty figures of Cornish engines. Two years later, G. H. Palmer published an article on *Transactions of the Institutions of Civil Engineers*, in which he contended that the levels of fuel efficiency claimed for the Cornish engine were undoubtedly exaggerated (because in open contrast with the caloric theory of heat):[7]

> If the statements given to the public by the Cornish engineers, whose sincerity I cannot doubt are correct, I dare not trust to call nature to account for the undue favouritism she confers upon our Cornish friends by enabling them to perform results that the London, Manchester and Birmingham engineers cannot approach.......Upon what principle then, permit me to ask, can the Cornish engines perform so much more than all other engines. Strong, indeed, should be the evidence that ought to outweigh or cancel the....laws of nature, and induce this Institution to sanction statements of duty more than double of the best Watt engine, and still more, surpassing the limits Nature has assigned steam to perform. (Palmer, 1838, pp. 44-46)

The most strenuous defender of Lancashire technical practice was perhaps Robert Armstrong. In his *Essay on the Boilers of Steam Engines* published in 1839, he declared that the Cornish duty figures were undoubtedly "gross exaggerations", the real duty probably being equal to about 30 millions. He concluded that "there is nothing in the Cornish system of management that can be profitably imitated by…..[Lancashire engineers]" (cited in Pole, 1844, p. 59).

In this section, expanding on previous research by von Tunzelmann (1978, chap. 4), we sketch a re-interpretation for these persistent differences in technical choice in early nineteenth century steam technology.

It is frequently held that concerns about safety exerted a dilatory effect on the adoption of the high pressure engine in Britain (von Tunzelmann, 1978, p. 88). Following this line of argument, one could then argue that propensity towards risk was different between Cornwall and other areas of Britain (with Cornish engineers more inclined to bear the risks of boiler explosions) and that this could explain the delayed shift to high pressure in counties such as Lancashire. However this interpretation can be considered valid only when it is couched in terms of different *perceptions* of the higher risk connected with the use of high pressure steam, rather than actual risks faced. Arguably, in this particular form, the explanation still acknowledges the existence of a technology gap between Cornwall and the rest of Britain (von Tunzelmann, 1978, p. 88). In fact, the available data indicate that in Cornwall high pressure steam was employed rather safely. Figure 6.1

[6] In 1827 the (London based) Institution of Civil Engineers passed a resolution which advocated the undertaking of research comparing systematically the performances of high and low pressure engines. Unfortunately the funds of the association did not permit the actual development of the research project (Buchanan, 1989, p. 63). The episode indicates the uncertainty surrounding the advantages of employing high pressure outside Cornwall.

[7] In the same article Palmer, on the basis of the caloric theory of heat, fixed the maximum duty attainable by a steam engine to 44 millions (Palmer, 1838, p. 46)

shows the number of boiler explosions and casualties in the Cornish mining district over the period 1811-1870.

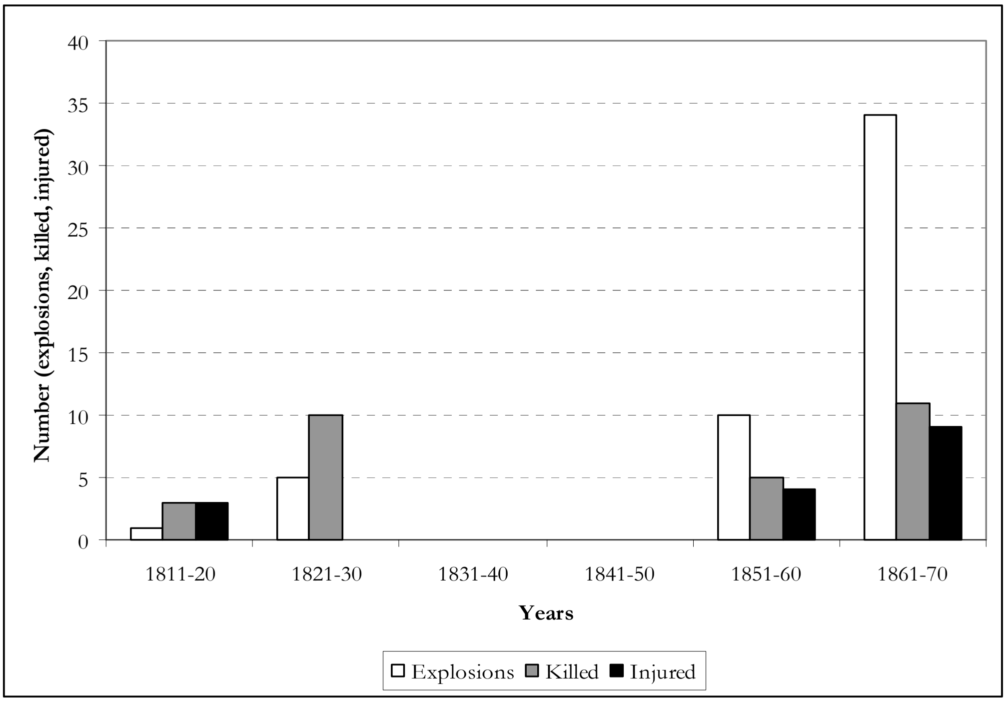

Figure 6.1: Number of boiler explosions: Cornwall, 1811-1869

Source: Marten (1870)

Figure 6.2 instead shows analogous data for Britain for the period 1800-1869. Figure 6.1 shows that, at least until the 1850s, the adoption of the high pressure steam engine did not result in a higher number of boiler explosions in Cornwall, rather the opposite seems to hold. In this respect, it is particularly interesting to note that no explosions are registered in Cornwall for the period 1831-1850 which constitutes the very "heyday" of the Cornish steam engine. On the other hand, if one considers that high pressure steam engines began to be adopted in the rest of Britain from the 1840s, figure 6.2 suggests that, when it occurred, the shift to high pressure in these areas was undertaken, *notwithstanding* the higher risks of explosions. In fact, in the 1840s, it was not infrequent to increase steam pressure by placing bricks on safety valves, with few concerns for the increased risks of explosions. (Bartrip, 1980, p.80).

These considerations, in our judgment, greatly circumscribe the possible role that concerns on boiler explosions might have played in delaying the adoption of high pressure steam outside the Cornish district (see also von Tunzelmann, 1978, p. 88-89). Hence, the search for the factors accounting for the lasting differences in technical practices between Cornwall and the rest of Britain cannot be resolved by invoking, different concerns over safety in the two areas.

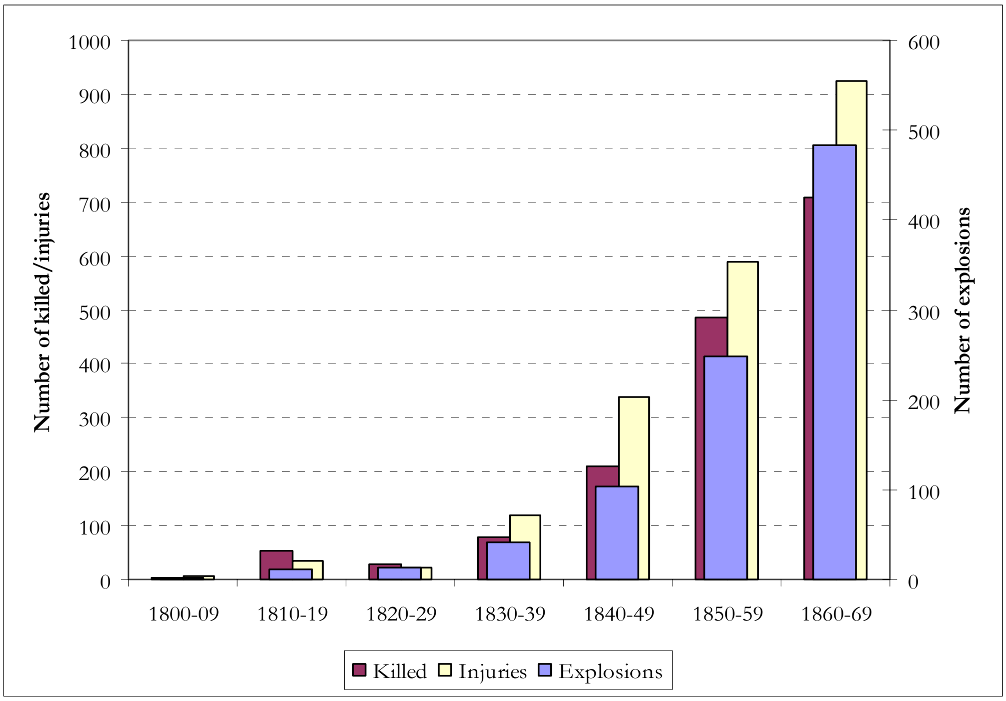

Figure 6.2: Number of boiler explosions: Britain, 1800-1869

Source: Bartrip (1980), p.80.

There exists a very rich stream of research contributions dealing with the simultaneous adoption of different techniques in the course of nineteenth century industrialization. One of the most well known examples is the debate concerning the Rothbarth-Habakkuk thesis on technological differences between United States and Britain (Rothbarth, 1946; Habakkuk, 1962). In their seminal contributions, Habakkuk and Rothbarth suggested that the adoption of relatively capital-intensive techniques in the United States, which had no counterpart in Britain (i.e., the so called "American system of manufactures" which aroused so much impression in many competent British observers visiting the United States) was determined by the different factor endowments of the two countries. For most of the nineteenth century, the United States were a "land abundant" country. This made the supply of industrial labour scarce and relatively inelastic, generating a systematic upward pressure on industrial wages. This, in turn, induced the adoption of a more capital intensive (and labour saving) technology in the United States. In a nutshell, this is what in the literature is considered as the "simplest version" of the Rothbarth-Habakkuk thesis (Broadberry, 1997, p. 70).

This connection between factor endowments and different choice of techniques can be easily explained using traditional neoclassical theory of production. However, the Rothbarth-Habakkuk thesis contends that, besides being more capital intensive, American techniques were, also, in a broad sense, more "progressive". This raises the question of why Britain persisted in its use of inferior techniques. In other words, the problem is to account for "[a] systematic bifurcation of the course of technological progress in these two societies whose cultural and scientific heritages held so much in common" (David, 1975, p. 22).

A re-interpretation of the Rothbarth-Habakkuk thesis has been proposed by Paul David (David, 1975, chap. 1). [8] David abandons the idea of a neoclassical production function and adopts the suggestion of Atkinson and Stiglitz (1969) that technical progress is, to a large extent, "localized" (that is to say, improvements in one techniques do not "spill over" to other points of the unit isoquant). In case of localized technical change, different factor endowments can lead to persistent differential rates of technical progress across countries.

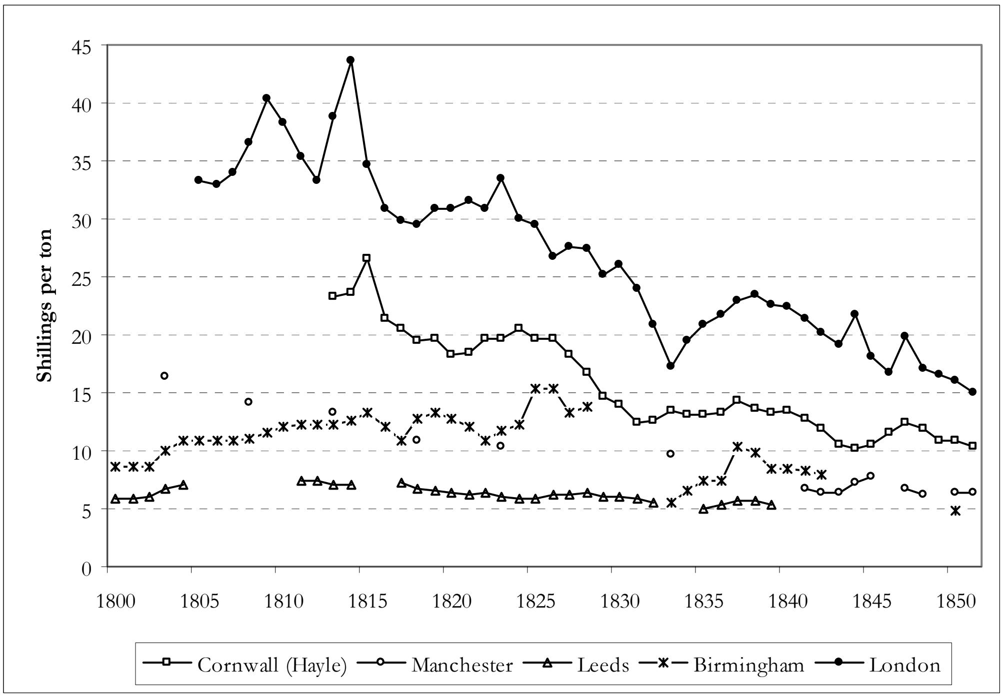

Figure 6.3: Coal prices, 1800-1850

Sources: for Manchester, Leeds, Birmingham and London: von Tunzelmann (1978, p. 97); for Hayle: von Tunzelmann (1974, pp. 199-200).

We would maintain that David's interpretive framework can be fruitfully applied to the case of differential rates of technical progress in steam engineering between Cornwall and the other manufacturing areas of Britain (say Lancashire) in the early nineteenth century. The available data suggest that coal prices were higher in Cornwall (the region could not rely on any local supply of coal and all the coal employed had to shipped from South Wales) than in Lancashire throughout the period in question. Figure 6.3 displays the behaviour of coal prices in various location for the period 1800-1850. In this time span, price of coals in Cornwall appear to have been higher than those prevailing in Lancashire (Manchster), Yorkshire (Leeds) and in the Midlands (Birmingham). Note that the price of coal in London, instead, was higher than in Cornwall.

We do not have information on the rental rate of capital in the two areas. Some evidence seems to suggest that interest rates were lower in the South West than in the North (von Tunzelmann, 1978, p. 85). However here we will focus on differences in coal prices, assuming equal interest rates between the two regions.

Concerning the factor proportions of the two techniques, it is clear that many improvements introduced by Cornish engineers involved higher capital outlays (mainly

[8] A particularly terse summary of David's analysis of the Rothbarth-Habakkuk thesis (on which what follows is partially based) is given in Broadberry (1997, chap. 4)

because of the higher costs of the high pressure boilers, see von Tunzelmann (1978, pp. 58-59)).

Given the foregoing assumptions, figures 6.4 and 6.5 illustrate the choice of technique for the entrepreneurs located in the two areas. The plan (C, K) represents all the possible combinations of coal (C) and capital (K) per HP-hour. Only, two techniques are available: the high pressure expansive engine (point A) and the Watt low pressure engine (point B). The high pressure engine has a higher fuel efficiency (i.e., lower C, coal consumed per HP-hour), but involves a higher capital outlay (K). Note that, in the first half of the nineteenth century, the fuel efficiency attained by using high pressure steam expansive engine was lower for rotary engines than for reciprocating ones (in reciprocating engines the early cut-off of steam in the cylinder could be exploited to a larger extent). Thus, the positions of the points representing the two high pressure engines are different. In particular, the high pressure reciprocating engine is represented by a point like A, while the rotary engine by a point like H. However, in both cases, the positions of the high pressure expansive engine compared to the Watt low pressure engine (in terms of relative fuel consumption and capital outlays) are analogous (i.e, both points lay on the area "North West" of point B in the (C,K) plan) . Thus, one can use diagrams such as 6.4 and 6.5 to represent the choice of technique both in the case of a reciprocating and of a rotary engine, taking into account that rotary high pressure engines were characterized by lower levels of fuel efficiency.

The availability of only two techniques constraints the possibilities of factor substitution in response to changes in factor prices. In figure 6.4, this is represented by the two Leontiev type unit isoquants corresponding to the points A and B. At least in principle, entrepreneurs could also decide to produce employing a linear combination of the two techniques. Thus, the linear combination of the two techniques represents the "available process frontier" (APF). Note that all the other points (techniques) spanning the traditional unit isoquant FPF (which David calls "fundamental production function") are *not* available. In a longer time span, entrepreneurs (perhaps responding to changes in factor prices) may be induced to attempt the development a new technique associated with new factor combination (i.e., a point of the FPF different from A and B), but this process (whose outcome is uncertain) ought to be conceived, as suggested by Rosenberg (1976, p. 65), as technical change and not factor substitution.

In figure 6.5 we have depicted the relative factor prices prevailing in the two regions. According to the evidence mentioned above, the slope of the line cc' (indicating the factor price ratio prevailing in Cornwall) is higher than the slope of the line ll' (indicating the factor price ratio prevailing in Lancashire). In these conditions, the factor prices ratio determines the adoption of the high pressure expansive engine in Cornwall (point A) and of the Watt low pressure engine in Lancashire (point B). [9] Note that when the ratio of factor prices is equal to the slope of the APF line, an entrepreneur will be indifferent among the two technologies (this value represent the threshold price used in diffusion studies).

[9] According to John Enys (1842, p.458) the cost-book system used in Cornwall, not allowing a precise evaluation of annual capital costs, tended to favour the adoption of a capital intensive techniques: "...the Cornish system of mining accounts, in which no reference is made to the capital expended, has afforded the mining engineeers more liberty in the adoption of whatever proportions appeared to be advantageous in the boiler surface in the flues, or in the size of the cylinder for expansion, and in an increase of strength of the pitwork...."

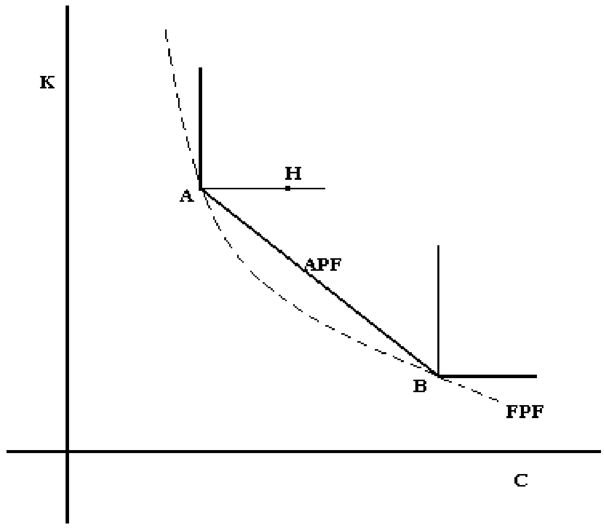

Figure 6.4: The main assumptions

In David's interpretation, the critical point of the Rothbarth-Habakkuk thesis is the assumption that opportunities for further technical progress are *unevenly* distributed along the spectrum of the available techniques. In the words of Habakkuk (1962, p. 168), "it is the capital-intensive end of the spectrum which has the greatest technical possibilities of improvement". This assumption combined with the hypothesis that the techniques currently in use tend to be improved by means of localized processes of technological learning leads to differential rates of technical progress in US and Britain. In our case, with the benefit of hindsight, it is clear that the potentialities for technical progress lay in the adoption of the Cornish practice of using high pressure steam expansively. This is represented in figure 6.6 (which is analogous to figure 4 in David, 1975, p. 66).

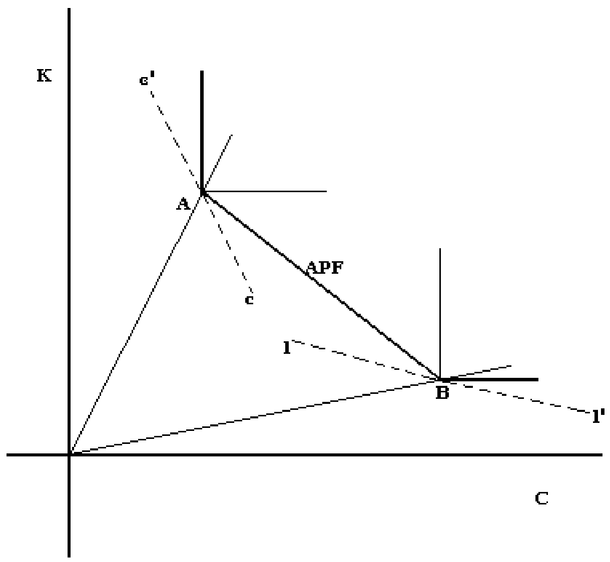

Figure 6.5: Choice of technique in Cornwall and in Lancashire

Localized technical change along the ray α, leads to the rapid improvements of the technique A (high pressure engine), whereas the movement from B (Watt low pressure engine) along the ray β is much more difficult. David represents the movement along the α ray as constrained by the two “elastic barriers” b and b’. (Note that also the (slower) movement along the ray β (not shown in figure 6.6) is also to be conceived as restricted by analogous barriers). The two barriers narrow the location in which the search for technical improvements takes place, so that the space (K,C) becomes fragmented into disconnected partitions. In this way, different choices of techniques in a specific historical instance may progressively “crystallise” into rather different courses of technical progress.

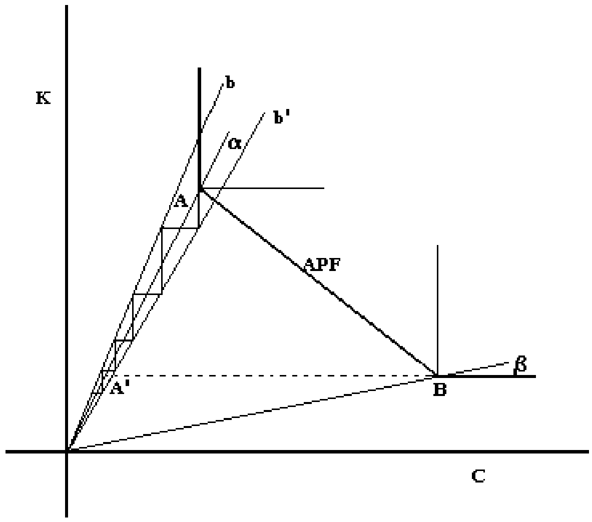

Figure 6.6: Differential rates of technical progress between Cornwall and Lancashire

The notions of an uneven distribution of technological opportunities and of localized technological advances seem to be consistent with the available evidence of the nature of technical change in early nineteenth century steam engineering. For example, the first high pressure engine pumping engine was erected in the London waterworks as late as 1838. The installation was preceded by a travel of Thomas Wicksteed to Cornwall where he conducted a detailed research on the merits of the Cornish engine (Wicksteed, 1836, 1838, 1841). In one of his papers, Wicksteed listed a number of technical features which characterized the Cornish high pressure practice, which had no counterpart in London (Wicksteed, 1836, pp. 122-125). In other words, in the period 1812-1838 a number of innovations had matured “locally” around the Cornish technique A (movement along the α ray), whereas the development of the low pressure engine (technique B) had stagnated. Although Wicksteed heartily encouraged the shift to the Cornish engine, the management of the waterworks was still rather reluctant and the engine was finally installed only under the condition that it would perform a duty of 90 millions over twelve consecutive months, otherwise a penalty had to be paid (Barton, 1965, p. 258).

This episode can be seen as a manifestation of the existence of differential rates of technical progress between Cornwall and the rest of the country, leading to the emergence of a technology gap, at least as far as reciprocating engines are concerned.

Further technical problems hampered the adoption of high pressure steam expansively in engines employed to power machinery. The Cornish practice of high practice expansive working could not be easily transferred to mill operations, where the application of the steam engine to industrial processes generally required a smooth piston movement:

It is a question, also, whether the extreme use of the Cornish system is suitable for those manufacturing engines, one great and essential quality of which is uniformity of motion. A steady velocity in the motive power, is of such consequence in cotton spinning, and several other of the arts, that any loss of it would be dearly by economic gain. The momentum of machinery, is but trifling: and an equivalent must be found for it, in order to obtain the whole value of the Cornish system (Parkes, 1842, p. 67).

So wrote Josiah Parkes in 1842. Some of the problems created by the irregular power cycle could be solved by expanding the steam in separate cylinders, reviving in this way, the Woolf compound design, which had not been crowned with much success in Cornwall.[10] This involved some loss of fuel efficiency. As William Pole noted:

Th[e] principle...[of expansion] has hitherto been applied to the greatest advantage in engines with a single cylinder, used for pumping purposes, as in Cornwall. In these cases the peculiar nature of the motion admits of the steam being cut off after a small fraction of the stroke has been commenced, and allowed to expand during the remainder. When however the principle of expansion is applied in this mode to engines for producing rotary motion, some difficulties arise, which limit considerably the extent that the expansion may be carried to, and therefore reduce in a corresponding degree the economy of fuel. The Double Cylinder Engine offers a mode of applying the expansive principle to rotary motion, which removes or at least greatly mitigates the objections to the single cylinder...(Pole, 1862, p. 242)

In terms of figure 6.6, the discussion concerning the difficulties in extracting a uniform rotary motion from high pressure expansive engines amounts to say that the movement along the ray α towards the origin was slower in case of rotary engines than for reciprocating ones. Thus, while for pumping engines it seems rather clear from the writings of Wicksteed, Pole and Fairbairn,[11] that since the early 1830s, technical progress had driven the high pressure engine to a point close A' in figure 6.6 (where it was the best technical choice for every conceivable level of relative factor prices), the issue remains unsettled for the case of rotary engines.

Von Tunzelmann (1978, p. 91) has calculated the "threshold" coal price at which, it would have been economically worthwhile to switch from a Watt low pressure engine to the high-pressure one for "rotary" applications in about 1835 as 12 *s.* per ton. As is apparent from the behaviour of the coal price series of figure 6.1 in the North (Lancashire and Yorkshire) coal prices were, at least since the early 1820s, below that level. In terms of figure 6.4, this means that, notwithstanding the progress achieved by technology A along the α ray, prevailing factor prices still dictated B as the best technology choice in Lancashire. In other words, the movement along the α had not reached yet the point A', where the high pressure engine had become the optimal choice for any configuration of factor prices. This result, according to von Tunzelmann, goes some way in the direction of rehabilitating Lancashire entrepreneurs from the "damnation" [12] to which contemporaries, such as Farey, had condemned them:

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[10] Josiah Parkes suggested an alternative solution: the adoption of Cornish pumping engines as "water returning" engines for cotton mills (Parkes, 1842, pp. 67-68).

[11] In 1840 William Fairbairn published a paper (Fairbairn, 1840) advocating the adoption of the Cornish engine to drain *collieries* in the North East.

[12] "From damnation to redemption: judgments on the late Victorian entrepreneur" is the title of a famous paper by McCloskey and Sandberg (1971), in which the thesis of an entrepreneurial failure (i.e.,

The failure may have been one of the inventors rather than the businessmen: inventors were unable to come up with a satisfactory high-pressure rotative engine until about the mid 1830s (von Tunzelmann, 1978, p. 90). [13]

By the early 1840s this situation had drastically changed. We can compute the threshold coal price between a low pressure condensing engine and a high pressure one for 1841 using a list of steam engines prices referring to the engines produced by Benjamin Hick. Hick was one of the pioneers of the introduction of compound high pressure engine on the Woolf plan in the textile industries and his engines are probably to be considered as best-practice for the time.[14]

Table 6.1: Capital costs for the engines produced by Benjamin Hick, 1841

	Low pressure condensing 40 HP (£)	Woolf compound 40 HP (£)	Low pressure condensing 50 HP (£)	Woolf compound 50 HP (£)
Engine	960	1130	1170	1350
Boiler	240	320	280	400
Total	1200	1450	1450	1750
Cost p.a.	162	197.25	195.25	238.75
Cost per HP p.a.	4.05	4.931	3.905	4.775

Source: Hills (1989), p. 119. In calculating capital cost p.a., following von Tunzelmann (1978), p. 72, we have made the subsequent assumptions: depreciation rate set at 7.5% p.a. for the engine and at 12.5% p.a. for the boiler, interest rate set at 5%.

In Table 6.1 we report Hick's prices and our estimates of annual capital costs for engines of 40 and 50 horsepower (these were probably the most typical sizes for mill engines at the time).[15]

In his price list, Hick also indicated figures for the fuel consumption of the engines: the low pressure engine consumed 14 lbs. of coal per HP-hour, whilst the Woolf compound, 5 lbs.[16] Note that 5 lbs. of coal per HP-hour correspond to a duty of approximately 37 millions (Pole, 1843, p. 171). The average duty of Cornish pumping engines (acccording to Lean's reports) in the same period (early 1840s) was above 50 millions (see figure 5.2).

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technological conservatism) of late nineteenth century Britain put forward by historians such as Landes (1969) is rebutted.

[13] The Woolf rotative engine was imported quite successfully in France by his former partner Edwards in the late 1810s. In 1824, a witness before a Parliamentary Committe declared that, to that date, about 300 Woolf engines had been erected in France by Edwards (Jenkins, 1933, p. 61). Rotative engines on Woolf design (although in very small numbers) were also produced by some manufacturers in Britain during the 1820s.

[14] A glowing appraisal of Hick's compound engines is given in Farey (1971, p. 306) :"Mr Woolf's engines have never been tried, and are scarcely known in the great manufacturing districts in the North of England and in Scotland. It should be mentioned that Mr Hick of Bolton, in Lancashire, has of late taken up the making of Mr Woolf's compound engines, and has made two engines of a larger size than any previous engine of the kind. They are excellent specimens, and improved proportions of the parts, with every perfection of execution which has hitherto been attained in the construction of steam engines; and although both have been sent abroad, one to France, and the other to Spain, they will probably lead to the introduction of such engines in the manufactories of Lancashire,"

[15] See, for example, Hills (1989), p. 116.

[16] Zachariah Allen estimated the average fuel consumption of the steam engines installed in Manchester in 1831 as 13 lbs. About ten years later in 1842, Fairbairn considered this to be about 10.5 lbs, see Hunter (1985), p. 600. In the same year Josiah Parkes considered 15 lbs to be more representative of the average coal consumption (Parkes, 1842, p. 67).

This difference can be taken as a (rough) indication of the loss in fuel efficiency determined by the use of the high pressure engine with a regular piston movement and not with the very irregular Cornish cycle.

With the level of fuel efficiencies stated by Hick, assuming that the engines worked on average 3800 hours a year,[17] the theshold coal price for the engines (of both sizes) in table 6.1 is equal to about 1 *s.* 1 *d* a ton.[18] This price is even lower than the cost of "slack" coal at the colliery pithead.[19]

Our profitability calculation, thus, suggests that in the early 1840s the high pressure technology had become economically viable for any (conceivable) configuration of factor prices. In terms of figure 6.6, also in the case of rotary engines, we are just above the point A' along the α ray (note that the high pressure steam engine still demand higher capital outlays). In fact, from the late 1830s, manufacturing areas begun *slowly* to install high pressure engines (see von Tunzelmann, 1978, p. 85).

These cases of early adoption did not amount to a slavish imitation of the Cornish practice. Lancashire engineers tried to "acclimatize" the high pressure engine to the local circumstances and find a balance between gains in fuel efficiency and the higher capital costs involved in the use of high pressure (von Tunzelmann, p. 86). Accordingly, the shift to high pressures was coupled with the introduction of a number of adaptations/modifications, such as the "compounding" of existing engines with the addition of a high pressure cylinder (McNaughting), the employment of smaller versions of Cornish boilers, etc. Nasmyth in the letter mentioned above described the early adoption of the high pressure condensing engines in Lancashire in these terms:

..[A]s the economic results of so increasing the pressure of steam….soon appeared in most unmistakable £ s. d. forms, the use of high-pressure steam boilers for working condensing engines became almost general. And those who desired to go to the full extent …soon adopted the employment of the Woolf engine in its full integrity, and most of our mills lately built are worked by the Woolf engines….By an ingenious arrangement, the Woolf system of double cylinder or combined low and high pressure engine has been introduced extensively to already existing engines, wherby their performance has been increased both to power and economy of fuel. The same result…has been in use these eight or ten years, by having a high-

[17] This can be considered a reasonable estimate for the textile industries. In other industrial branches, engines normally worked slightly less, see von Tunzelmann (1978), p. 73.

[18] The formula used is $p_t \Delta CH = \Delta K$, where p_t is the threshold coal price, ΔC the fuel saving (per HP- hour) deriving from the adoption of the high pressure engine, H the numbers of hours worked in the year, ΔK the difference in capital cost per HP p.a.

[19] Von Tunzelmann (1974, p. 63) gives a price of 2s. 8d. for slack coal for a Staffordshire colliery in the period 1828-36. Our calculation suggests that threshold price computed by von Tunzelmann for 1835 is probably overrated. The source of this over-estimation is in the estimated increase in capital costs resulting from the adoption of the Cornish high pressure boiler, which von Tunzelmann assumes to increase in direct proportion with heating surface (this amounts to multiply the price of the "corresponding" low pressure boiler by 7.5). Thus, for a 30 HP engine, he puts total boiler cost at £1500. Casual evidence seems to suggest that this errs far too much on the high side. In 1838 *three* boilers for a 60" engine for the Fresnillo Mine in Mexico were sold for £ 963 (Barton, 1965, p. 280). In 1841, James Sims offered, in an advertisement published on the *West Briton*, a 80" pumping engine for £2600, *inclusive of boilers* (Barton, 1965, p. 52). These figures are broadly consistent with the prices of table 6.1. In this respect, one has to take into account that in low coal price regions, steam engine manufacturers like Hick, generally avoided to construct the full-size Cornish boiler, opting for a "shortened" and cheaper version of the elongated Cornish cylindrical boiler, see von Tunzelmann (1978), pp.83-84. The upshot of these considerations is that already in the 1830s it could have been most probably economic advantageous to install (locally adapted) versions of the high pressure engine even in low coal prices regions, vindicating Farey's allegations of some "technological complacency" in the Lancashire entrepreneurs.

pressure engine so connected with a condensing engine as to enable the waste steam of the former to pass on to and work the latter. This system is in many cases very convenient (Marx, 1992, pp. 193-194).

The localized nature of technical progress can then account for the emergence of a persistent technology gap between Cornwall and Lancashire. It is clear that the explanation relies on the role of the barriers such as b and b' which constrain the search for technical improvements around specific techniques. In David's original interpretation these barriers are generated by the "technological interrelatedness" existing among the various components of the technology in question. Improvements in one component, frequently require or induce modifications in other components. Thus the initial combination of factor proportions is preserved over time (i.e., technical change is "locally" neutral). In our case, one could make the case that the adoption of higher and higher steam pressures in Cornwall demanded a proportionate strengthening of the pitwork, of the foundations of the engine house, etc. It is possible, however, also to give another interpretation of the localized nature of technical change which points to the role played by the *cognitive dimensions* of the inventive process.

In fact, the particular "topography" of technical change posited in David's contribution (which is alternative to the smooth movement of *all* the points of the unit isoquant assumed by the traditional neoclassical view of technical change) is fully consistent with Giovanni Dosi's paradigm/trajectory approach to technological evolution (Dosi, 1982, 1988). Dosi defines a technological paradigm as "'model' and a 'pattern' of solution of *selected* technological problems, based on *selected* principles derived from natural sciences and on *selected* material technologies" (Dosi, 1982, p 152, italics in the text). The term paradigm is borrowed from Thomas Kuhn's philosophy of science. In case of technologies, the concept of paradigm refers to a framework, jointly adhered by a significant group of innovators, guiding the search for technical advances in particular historical contexts. In this way, a technological paradigm defines the boundaries of the domain in which future technological developments will take place. Dosi suggests that it should be possible to "deconstruct" each technological paradigm in a set of "heuristics". These represent the prevailing accepted rules prescribing the procedures to be adopted in the search for innovations (i.e., "in order to develop a more efficient engine, try to increase the rate of expansion") and they act as the elastic barriers hypothesized by David. It is interesting to note that the notions of technological paradigms and heuristics are intended to be broader in their scope than mere sets of engineering prescriptions. In Dosi's view, technological heuristics are the product of the "amalgamation" of what might be termed the "autonomous drift" of a technology (i.e., the "compulsive sequences" of challenges and solutions individuated by Rosenberg (1976) which are insensitive to market signals) with "inducement factors" of a genuinely economic type (i.e., current and expected factor prices). This means that local circumstances can, to a certain extent, shape the pattern of technological development. In our example, both the early development of high pressure in Cornwall and the various attempts of upgrading the low pressure engine in Lancashire can be seen as a reflection of how the different economic needs of the various regions were incorporated in technical practices.

The heuristic search process practised by the inventors' community, by channelling inventive activities in specific and finalised directions, generates relatively ordered patterns of technical change, called "technological trajectories", which, at least in principle, can be mapped in both the space of input of coefficients and that of product characteristics (Dosi, 1997, p. 1533).

The paradigm/trajectory view of technological evolution points to three essential features of the process of technical change:

i) the *local* nature of technical progress: inventive activities are paradigm-bounded and, for this reason, they are highly selective and focussed in rather precise directions.
ii) along a specific technological trajectory, technical advances are strongly *cumulative*, that is to say, they are strongly related to previous attainments.
iii) finally, technological development is likely to display strong *irreversibility* features. This means that techniques developed along particular trajectories are likely to become superior to "old" ones at every relative factor price level (in terms of figure 6.6, they reach points below A'). This means that once the movement along a particular technological trajectory has gained momentum, it becomes relatively irresponsive to change in input prices. Note, for example, that the rapid improvement in fuel efficiency of the Cornish engines continued despite coal prices in Cornwall are clearly characterized by a *downward* trend (see figure 6.3).

To sum up, the basic argument put forward in this section is that the emergence of the two distinct technological practices characterizing steam engineering in Britain in the early nineteenth century requires to take into account not only the economic needs of the various regions and application sectors, but also the nature of the space of technological opportunities searched by the inventors. As we have shown, this involves the abandonment of the narrow boundaries of the neoclassical conceptualisation of technical change and the adoption of an interpretive framework in which the "specificities" of the technology in question are explicitly taken into account. As Dosi aptly puts it,

> ...[I]f one sticks to a general equilibrium framework and a representation of technology based on well-behaved production functions or convex production possibility sets, it is very difficult and often logically incoherent to attribute any observed bias in the rates and direction of technical change to particular biases in relative input prices. In the last instance, 'economic incentives' to reduce costs always exist in business operations, and precisely because such incentives are so diffuse and general, they do not explain very much in terms of the *particular sequence and timing of innovative activity*; however, specific incentives, *coupled with the paradigm bound, cumulative and local nature of technological learning*, can explain particular rates and directions of technological advance (Dosi, 1988, p. 1143, italics in the text).

Our suggested interpretation is that steam engineering practice in Britain during the early nineteenth century was characterized by the existence of two rival technological paradigms, the Cornish paradigm advocating high pressure used expansively and the Lancashire one, favouring low pressures (sanctioned by the authority of James Watt). The existence of two distinct technological paradigms accounts for the disbelief with which information on the superior efficiency of the Cornish high pressure engine was received outside Cornwall. Technological development within the high pressure paradigm, proceeded following two (to a limited extent) overlapping sets of heuristics (which over time consolidated themselves in two distinct design traditions): the first one prescribed procedures for innovation in single cylinder pumping engines adopting the irregular Cornish power cycle, whereas the second was concerned with the compound engine and its application to manufacturing purposes. Technological opportunities determined a more rapid progress along the technological trajectory generated by the single cylinder set of heuristics, than along the compound mill engine one. Furthermore, many inventions matured along the single cylinder trajectory could not be readily transferred to the compound trajectory.

All this leads us to consider the "entrepreneurial failure" of Lancashire entrepreneurs and their delay in shifting to high pressure steam in a rather different perspective. Clearly, the evidence presented above points to the technological conservatism of Lancashire industrialists. However, our interpretation stresses that the major stumbling block was represented by the lasting resilience of the low pressure paradigm in Lancashire. Hence, one could also note that influential contemporary advocates of the high pressure expansive engine such as John Farey and William Fairbairn were by and large ineffective in their timid efforts of instigating in the Lancashire engineering community the "revolutionary climate" needed for the successful and "timely" subversion of the low pressure paradigm and, precisely for this reason, indulge in the temptation of laying a non minor part of the responsibility at their doors.[20]

6.3. *Lean's Engine Reporter*: issues of coverage and reliability.

In what follows, we will make use of the data of *Lean's Reporter* to reconstruct the main patterns of innovation characterizing the development of the Cornish pumping engine. As mentioned in the previous chapter, various members of the Lean family were in charge of the publication over different periods of time. Here we will consider the period 1811-1876.

Our data-set is constructed simply by collating together the various "reports" concerning our period of interest.[21] In particular, for the period 1827-1831 when Thomas and John Lean issued separate editions of their reports we have simply assembled the engine data contained in the two reports. We will start our analysis by considering the issue of the overall reliability and coverage of the data reported. For each engine reported, the Leans published the following information:

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

[20] In analogy with political revolutions we may refer here to this passage by Trotsky: "Revolution posses a mighty power of improvisation, but it never improvizes anything good for fatalists, idlers or fools. Victory demands correct political orientation, organization and the will to deal the decisive blow" (Trotsky, 1924, p. 254).

[21] We have made use of an almost complete collection of *Lean's Engine Reporter* for the period 1811-1904 that is conserved in the Cornish Studies Library (Cornwall Centre), Redruth, UK. We have integrated some missing or unreadable pages retrieving the data from the collection of *Lean's Engine Reporter* conserved in the Science Museum Library of London.

xiii) the name of the engineer entrusted with the engine and eventual remarks on potentially interesting features of the engine and of its working behaviour. [22]

The main aim of the reporters was to ascertain the monthly duty performed by each engine. The duty was computed using the following formula:

$$D = \frac{L \times l \times s}{C} \qquad (1)$$

In the formula D indicates the duty performed by the engine (expressed in millions of lbs lifted one foot high by consuming a bushel of coal), L the load of the water contained in the pumps (expressed in lbs.), l the length of the stroke in the pump (expressed in feet), s the number of strokes performed by the engine during the month, C the monthly consumption of coal (in bushels). Clearly, the reliability of the duty estimated depended on the reliability of the four observations used in the computation. Let us consider each of them separately:

1) L (the weight of water in the pumps): this was not measured *directly* but estimated on the basis of the volume of the pumps. Thus, when the pumps were not completely filled with water, (the Cornish term for such a behaviour was “working in fork”: this could happen when the mine was well drained or in periods of low rainfall), duty tended to be overestimated. Additionally, one has to notice that leakages in the pumps led also to overestimate the weight of water actually lifted and, as a consequence, the duty performed. [23] On the other hand, the weight of water lifted was computed by multiplying the volume of pumps for a constant which represented the weight of a unit volume of spring water. Of course, the water pumped from Cornish mines, containing a non negligible amount of minerals in suspension, was in general heavier than pure spring water. This introduced an upward bias (going in the opposite directions of the foregoing downward biases) in the overall estimation of L. During the 1830s, various experiments were carried out in order to measure *directly* the weight of water lifted. William Henwood and John Rennie measured the actual weight of the water pumped by the Wheal Towan engine and found that it was about 7.6 per cent lower than the one calculated using the volume of the pumps (Henwood, 1838, p. 58). Thomas Wicksteed, during his experiment on the Holmbush engine, instead found a gap of about 13.5 per cent; finally, other experiments on the Eldon’s engine at United Mines found a gap of about 4 per cent (Pole, 1844, p.154). The conclusion that contemporaries such as William Pole and Thomas Wicksteed drawn from the results of these experiments was that the *Reporter* contained an inner tendency to *slightly* overestimate the water actually pumped by the engine. Overestimation could safely be considered to be between 4 and 10 per cent. Furthermore, no allowance was made for friction. The amount of friction to be overtaken depended on the specific circumstances of operation of each single engine (length of the pumps, their state, their inclination, etc.). This was an important factor to be taken into account when the performance of two engines was compared (Wicksteed, 1836, p. 121).

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[22] Over time, a number of minor changes were introduced in the tables of the *Reporter*. The most significant is perhaps the passage from the bushel to the imperial hundredweight (112 lbs.) to measure the coal input in the calculation of the duty in 1856.

[23] Some of the engines examined by Thomas Wicksteed delivered water to the surface. In these cases he observed that “there were no bubbles of air mixed with the water, proving that the pumps were lifting ‘solid’ water, (as it is termed in Cornwall) and not partly water, and partly air, as has been suggested by those who have no faith in the reports of the work done by the Cornish engine” (Wicksteed, 1836, p. 119).

2) l (the length of the stroke in the pumps): the length was calculated on the basis of the length of the piston stroke (multiplied by the proportion of the beam comprised between the pivot point and the attachment to the pump stroke, see von Tunzelmann, 1970, p. 81). Accordingly, when the engine performed a shorter stroke, this method led to an overestimation of duty. The length of the stroke performed by the engine could be regulated quite easily by the engineer by properly adjusting the tappets which controlled that descent of the piston. In fact, making the engine perform a shorter stroke was considered as the easiest possible way of "cheating" (in the sense of having an engine credited for a higher duty than the one actually performed). According to Farey (1971), the length of the stroke used in the reporter was the *full* length of the stroke in the cylinder. The actual stroke performed was about three of four inches shorter and this produced a difference between reported and actual length of about 1/25, as resulted from an experiment carried out in 1816. However, according to Pole (1844), the length of the stroke used in the reports was the *mean* length. This contrasting evidence probably indicates that some change occurred between 1816 and 1844 in the measurement of the stroke length. Pole also mentioned an experiment conducted on an engine at Consolidated Mines which showed that the difference between actual and reported stroke length did not exceed 1 per cent (Pole, 1844, p. 153).

3) s (the number of strokes performed): the number of strokes was registered by a special counter that was installed by the "reporter". The counter was protected by a Bramah's lock and the key were entrusted exclusively to the engine reporter.[24] An experiment of four months conducted in 1839 showed that the counter overestimated the number of strokes performed of about 2.5 per cent (von Tunzelmann, 1970, p. 81).

4) C (the bushels of coal consumed): this was measured on the basis of the coal purchased as resulting from the mining accounts. It is worth noting that bushel was a measure of volume, corresponding to a cylindrical vessel of 18.8 inches of diameter and 8 inches deep. This vessel was to be heaped up above the border to form a cone with the same base of the cylinder and at least 6 inches high (Farey, 1971, p. 181). Typically the weight of the coal bushel was reckoned to be 84 lbs. This was a fairly good estimate for Newcastle coal (Farey, 1827, p. 337). But, in Cornwall where Welsh coal was used, the weight of the bushel was normally higher. Rather surprisingly, early commentators of the Cornish engine reports such as Gilbert, Henwood and Taylor, did not take into account the greater weight of the Welsh coal compared to the Newcastle one and considered the bushel equal to 84 lbs., underestimating its actual weight (Howard, 2002b). In 1831, Thomas Lean measured the weight of a bushel in 31 Cornish mines and found out that the average weight was equal to 92.43 lbs. (the maximum observation being 98 and the minimum 88 lbs, see Farey, 1971, p. 232).[25] From 1835, in the engine reports the bushel was formally reckoned to be 94 lbs. Various criticisms were voiced against the use of a unit of volume rather than weight as a measure of the coal input. According to William Pole, these criticisms were wide off the mark. He noted that 1 bushel= 94 lbs could be used rather safely as a general conversion ratio, discrepancies from that value were likely to have only minor effects on the estimated duty. (Pole, 1844, p. 155). Additionally, one

[24] Joseph Bramah patented this lock in 1784. He exhibited the lock in his shop-window in Piccadlilly with the following notice: "The artist who can make an instrument that will pick or open this lock shall receive two hundred guineas the moment is produced". Notwithstanding many attempts, the prize was not won until 1851, when a mechanic opened the lock after 51 working hours, see Gilbert (1958), p. 423.

[25] In the same year William Henwood measured the weight of bushel at three mines and found an average of 93.6 lbs. The degree of wetness of the coal also influenced the weight of the bushel. When coals were dried the average weight of the bushel in the three mines was 87.1 lbs, see Farey (1971, p. 232-233).

has to note that in Cornwall, until the end of 1836, coal was sold by the bushel (more precisely by the wey, corresponding to 64 bushels). Hence, the duty calculated in terms of bushel provided a measure of engine efficiency, endowed with a direct *economic* significance (von Tunzelmann, 1970, p. 82).

The upshot of all this is that the duty figures reported are to be considered as an *approximate* estimation of the fuel efficiency of the engines reported. However, being most of the engines reported for a number of consecutive months, it is likely that the possible influence of special circumstances on the estimated could have been easily individuated. In fact, it was common practice to perform special trials lasting one or two days, on the best-duty engines or on dubious cases. In these trials a number of independent observers took care of ascertaining properly the four observations necessary for calculating the duty of the engine in question (see for some examples Lean, 1839). Furthermore, in some of the largest mining ventures, such as Consolidated Mines, the duty of the engines was calculated *daily* using another counter under the control of the mine captains. The average daily duty was compared with the one published in the monthly reporter when this was issued. According to John Taylor the two measures were in most cases found to correspond very closely (Taylor, 1831, pp. 54-55). [26]

John Taylor, one of the leading mining entrepreneurs in the Cornish district, published several papers with the aim of dispelling the scepticism with which the duty figures published in *Lean's Engine Reporter* had been received outside Cornwall. In one of these papers published in *Quarterly Mining Review*, Taylor provided a detailed account of the reporting procedures noticing that the there was very little room for fraud by the engineers and the workers entrusted with the engines. Furthermore, his position of mine entrepreneur gave him also the possibility of crosschecking the validity of the duty figures with the reduction of coal expenditure. He observed:

> The evidence of progressive improvement….which the periodical reports of duty have gone on to exhibit, is corroborated by the unerring testimony of the account books of mines; and those savings which in the one [the monthly duty papers] appear in somewhat theoretic form are in the other apparent in the solid condition of money saved, and so in fact gained (Taylor, 1831, p.51-52).

The overall conclusion of Taylor's paper was that "the application of steam has been improved so as to economize fuel in Cornwall, and that the rate of improvement has been fairly expressed by the printed reports" (Taylor, 1831, p. 57). Taylor was without doubt one of the most convinced advocates of the accuracy of *Lean's Reporter*. Other competent contemporary observers, such as Davies Gilbert, Thomas Wicksteed, John Farey, William Pole and William Henwood, who had first hand experience with the methods used to report the duty of the engines generally regarded the publication as providing reliable estimates. For our present purposes, it seems to us that the data

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[26] Charles Babbage also mentioned the system of daily assessment of the duty in his *On the Economy of Machinery and Manufacturing* (Babbage, 1835, pp. 284-285): "The advantage arising from registering the duty done by steam-engines in Cornwall has been so great that the proprietors of one of the largest mines, on which there are several engines, find it good economy to employ a man to measure the duty they perform every day. This daily report is fixed up at a particular hour, and the engine-men are always in waiting, anxious to know the state of their engines. As the general reports are made monthly, if accident should cause a partial stoppage in the flue of any of the boilers, it might without this daily check continue two or three weeks before it could be discovered by a falling off of the duty of the engine. In several of the mines a certain amount of duty is assigned to each engine; and if it does more, the proprietors give a premium to the engineers according to its amount. This is called million-money and is a great stimulus to the economy in working of the engine"

contained in *Lean's Engine Reporter* can provide a particularly useful picture of the development of steam power technology in Cornwall.

Figure 6.7 displays the number of engines reported each year. The number of engines reported went steadily up to about 60 until the mid 1840s and then it begun to decline steadily (with an interesting 'revitalization period' in the 1860s).

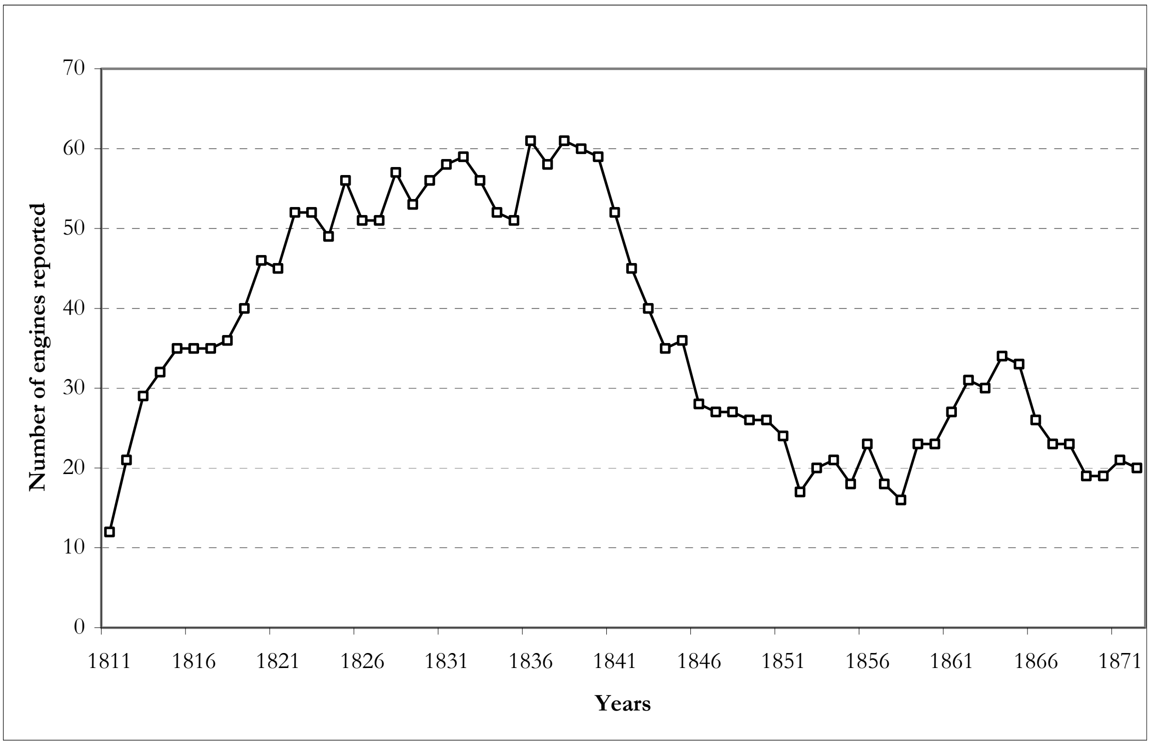

Figure 6.7: Number of engines reported

Source: Henwood (1870), p. lviii.

How representative was the sample of pumping engines reported? Unfortunately, we have little information on the total number of engines (and their relative size) at work in Cornish mines. At the end of 1834, Thomas Lean undertook a census of the pumping engines in operation in the Cornish mines (Lean, 1839). Admittedly his list was not complete, but, nevertheless, it can be considered as representative of the major bulk of steam power employed at the time in Cornish mines. Another, probably more exhaustive, engine census was undertaken at the end of the year 1838 by W.J. Henwood, with the help of Rev. John Buller (Henwood, 1843).

Collateral evidence indicates that about twenty engines (or little more) were missing from this list (Barton, 1965, p. 252). Finally, another list of pumping engines at work in Cornish mines was compiled in 1864 by Thomas Spargo (1865). Also this list cannot be considered complete, but just as representative of the major bulk of steam power employed in Cornwall (some of the smallest mines not being included). Table 6.2 summarizes the results of these engine censuses (ordering the engines by size) and compares them with the engines contained in *Lean's Reporter* in each corresponding year.

Table 6.2 clearly indicates that the practice of reporting engines declined over time. Thus from the late 1830s to the 1860s, not only the total number of engines reported declined, but also the share of engines reported in the total number of engines at work shrunk. In his *Treatise*, William Pole commented:

It will scarcely be credited that the proprietors of some mines have lately discontinued allowing the reports of the duty of their engines to be published, in order to save the small sum paid to the reporter for his trouble. That any parties could be found so wilfully and foolishly blind to their own interests is indeed astonishing, for a more obviously penny-wise and pound-foolish measure could scarcely be conceived. It is no reflection on the character of the engineers to say that, when the stimulus afforded by the publication is removed, the duty of the engines must of necessity, according to the nature of things, fall off; and of course further improvement is out of question, as no inducement is offered for it, and no means of ascertaining its amount and value when effected. (Pole, 1844, p.47)

Table 6.2: Engines in Operation in Cornwall (by size)

Cylinder size (diameter in inches)	1834	(%) reported	1838	(%) reported	1864	(%) reported
10-20	1	0	1	0	4	0
20-30	16	31.25	16	25	26	0
30-40	25	36.00	30	23.33	53	1.89
40-50	11	45.45	25	44.00	48	8.33
50-60	8	62.50	19	26.32	35	11.43
60-70	18	66.67	23	47.83	42	21.43
70-80	13	53.85	17	41.18	28	39.29
80-90	9	88.89	18	66.67	16	25.00
90-100	4	100	4	100	1	0
Total number of engines	105	52.38	153	39.87	253	13.04

Sources: for 1834, Lean (1839); for 1838, Henwood (1843); for 1864, Spargo (1865).

As we will see in the next section, Pole was indeed right: the decline of the practice of reporting coincided with a progressive deterioration of both best-practice and average duty.

Table 6.2 also shows that other types of biases affected the reporting procedure. It is quite clear that large engines were more likely to be reported than smaller ones. The economy of fuel of large engines could play a major role in determining the overall profitability of some mines (von Tunzelmann, 1970, pp. 83-85). For this reason, they tended to be reported *continuously*. Small engines had a much lower fuel consumption, so the gains from increasing their fuel efficiency were proportionally limited, and for this reason they were more likely not to be reported. Casual perusal of *Lean's Reporter* also suggests that small engines had a higher tendency to be reported *discontinuously*. Mine entrepreneurs could probably have small engines reported only once in a while to check their efficiency at particular "topical" moments of the engine lifetime (e.g., after erection, after a major reparation work or after the movement of the engine from one mine to another).

6.4. The contours of technical change in Cornish engines

Figure 6.8 displays the evolution of the duty (average and of the best engine) of the "reported" engine-park for the period 1811-1876. In our inquiry, we will mainly use observations for the month of April, which following von Tunzelmann (1970) was chosen as a reasonable compromise between the "wetter" winter and the "drier" summer months. In figure 6.8, however, we also show the corresponding series for the entire year as calculated by Thomas Lean II (Lean II, 1872).The behaviour of the two series is indeed very similar, which suggests that the use of the April observation can be taken as good approximation of the yearly series.

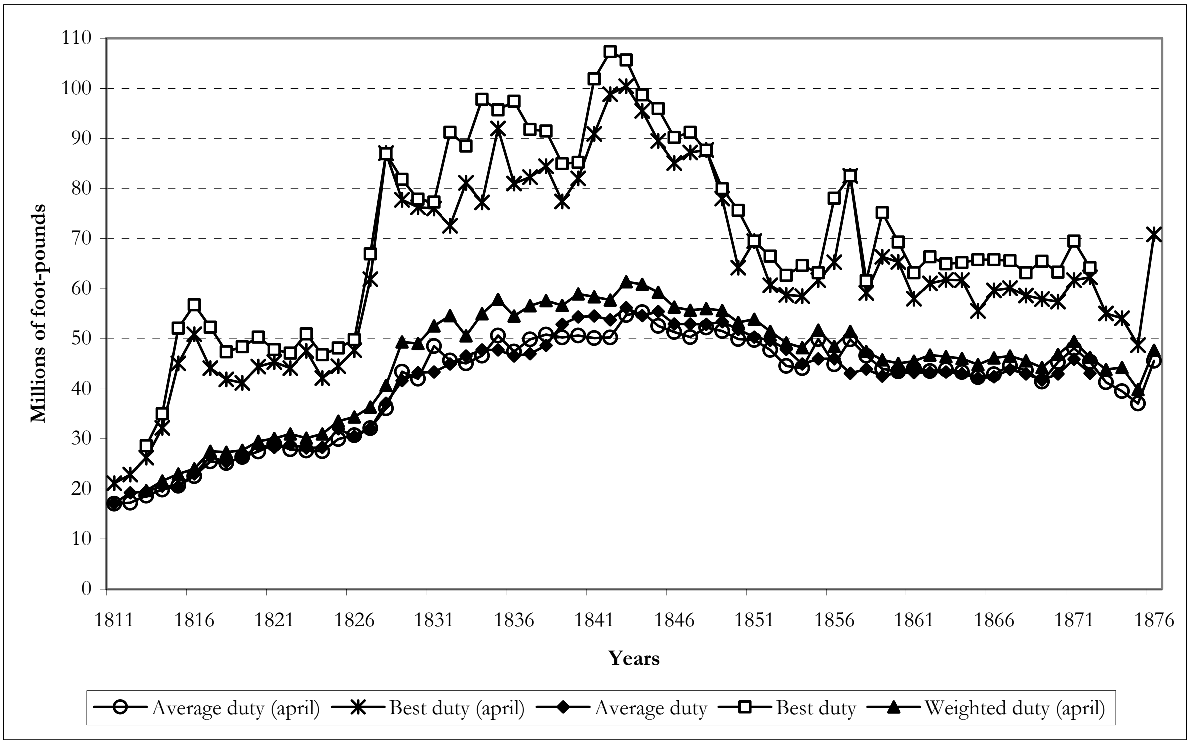

Figure 6.8.: Duty of Cornish engines, 1811-1876

Source: *Lean's Engine Reporter* (April); Lean II (1872) for the yearly series.

Figure 6.8 exhibits a steady increase both in best practice and in average duty until the early 1840s followed by a period of progressive deterioration. The series “weighted duty” represents the average duty weighted by the share of the engines in the total horsepower delivered by the “reported” engine park. This series mirrors closely the behaviour of average duty. The fact that the weighted average slightly outperforms the simple average indicates that more efficient engines also tended to deliver more horsepower.

The period of increasing duty figures coincided with the rapid expansion of the Cornish copper mining industry (period 1810-1840), vice versa the phase of recession, beginning in the late 1840s, is coupled with a decline of average duty and best duty. This is well illustrated by figure 6.9 which charts the average and best duty series together with the Cornish yearly production of copper ore. A possible explanation for this tight connection between the expansion of production and the growing efficiency of Cornish engines is that the installation of new productive capacity during the expansion phase permitted experimentation with design alterations prompting the discovery of new improvements. This link has also been pointed out by Allen (1983) in his study of the Cleveland iron industry.

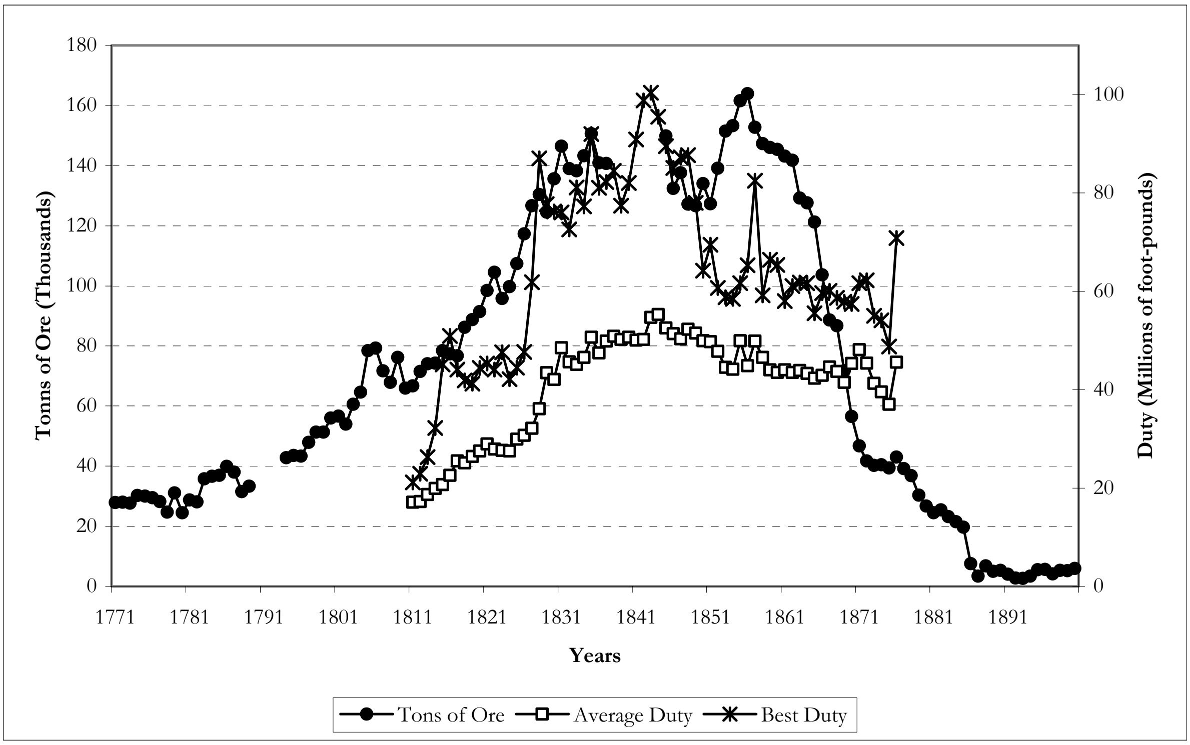

Figure 6.9: Cornish copper ore production and duty of Cornish engines, 1771-1900
Source: Copper production: Burt (1987); Duty: *Lean's Engine Reporter* (April).

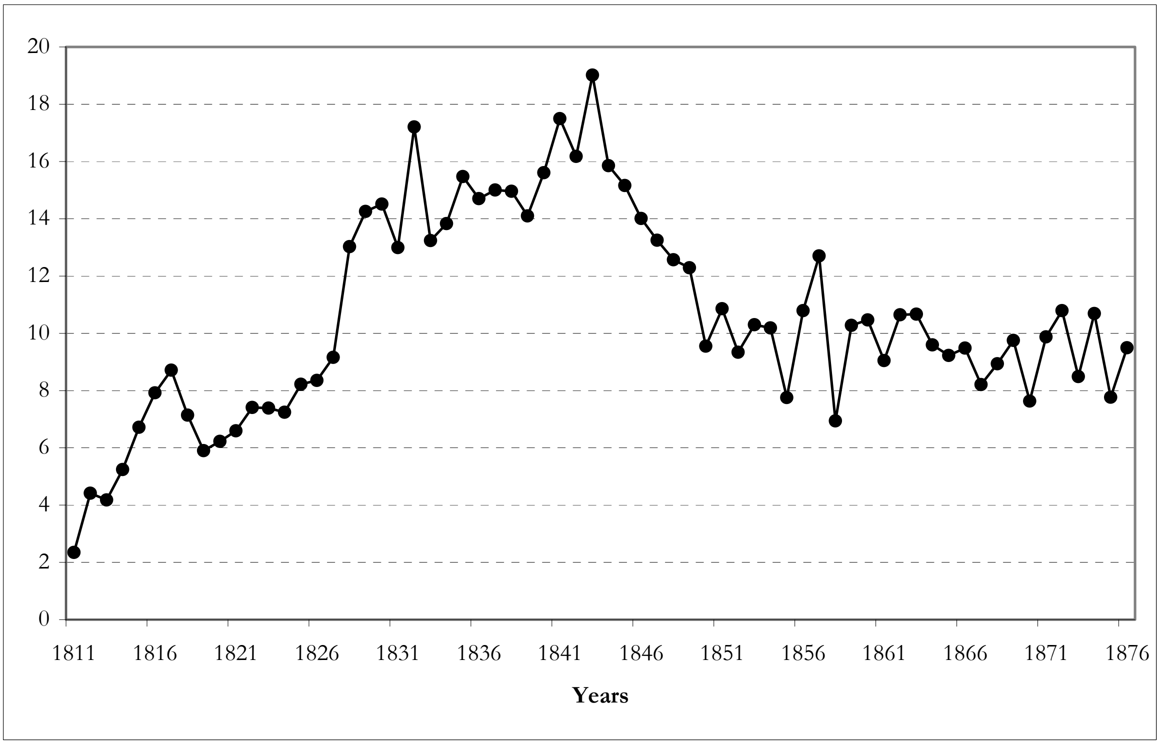

Figure 6.10.: Standard deviation of duty
Source: *Lean's Engine Reporter* (April)

Figure 6.10 reports the standard deviation of the average duty. As is apparent from the figure, dispersion around the mean increased more or less continuously until the 1840s and then began to decline steadily. Again, the pattern seems to reflect that of average duty. In this respect, it is important to note that by in the 1840s a typical design of the Cornish engine had emerged (this will be discusse in detail below). According to Barton:

> By mid-century, with [Cornish] engine design beginning to settle down to a comfortable pattern from which no major variations were made, the practice of building engines in duplicate, or even in small batches had become a feature of engine manufacture. This made use of existing founders' patterns and engineers' drawings as well as enabling foundries to offer quicker delivery (Barton, 1965, p. 98).

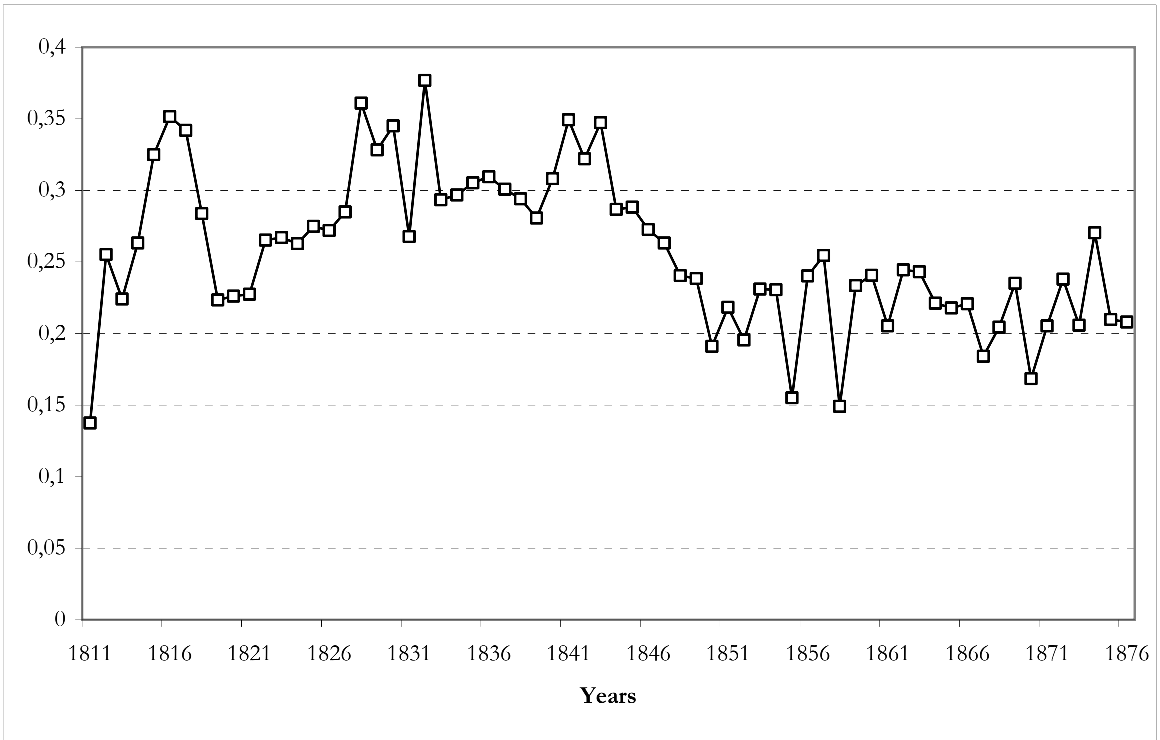

Figure 6.11: Coefficient of variation of duty

Source: *Lean's Engine Reporter* (April)

Figure 6.11 portrays the coefficient of variation of the duty, which we understand as an indicator of convergence among the engines in the reported engine-park. The figure shows three distinct 'epochs' (represented by peaks in the figure) of rapid technological change (when best-practice escapes away from average practice), broadly corresponding to the late 1810s, the late 1820s/ early 1830s and the early 1840s. These three rather sharp bursts are also visible in the series of best duty depicted in figure 6.8. Note that each phase is followed by a period of catching-up. After these three peaks, the coefficient of variation seems to level off until the end of the period we are considering.

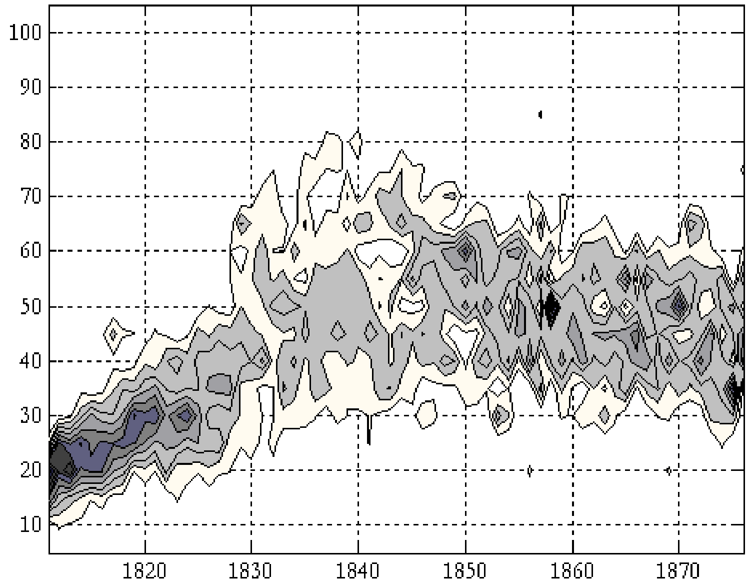

Figure 6.12: Distribution of the engines: duty on the vertical axis, time on the horizontal axis, darker shades indicate a higher percentage of the population
Source: *Lean's Engine Reporter* (April).

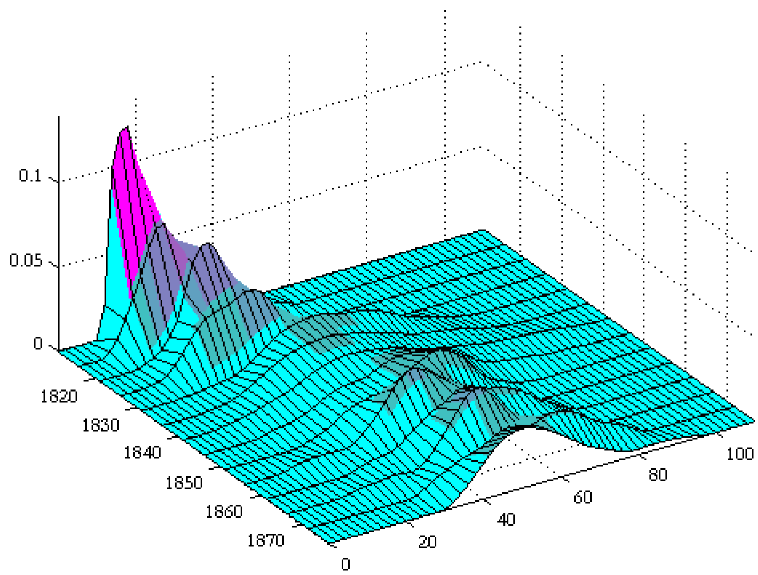

Figure 6.13: Kernel density of duty (years on X axis, duty on Y axis, density on Z axis)
Source: *Lean's Engine Reporter*

A snapshot on the dynamics of the duty distribution of the engine park reported is provided by figure 6.12 . The duty performed is indicated in the vertical axe. Darker (brighter) areas in the diagram indicate higher (lower) concentrations of engines. At the very beginning of the period we are considering here, the distribution appears to be quite narrowly concentrated (around a duty of 20 millions). Then, we can distinguish a prolonged phase of 'dispersion' of the engine distribution which is coupled with a growing average duty. From the late 1840s the distribution appear to narrow down and then remains stable.

Figure 6.13 (which is analogous to figure 6.12) shows the evolution of the distribution of the duty of the engines over time in a three dimensional space. In the figure the density of the engine distribution in a particular year has been estimated using an Epanenchinkov kernel (for a general introduction to kernel density estimation, see Silverman, 1986). Figure 6.13 shows that the growth of the mean of the duty in the period 1820-1840 is coupled with an increasing dispersion of the density. Correspondingly, the period 1850-1870 seems to be characterized by the a decrease in the mean of the duty and in a lower dispersion.

The three phases of rapid technological change which is possible to distinguish in figure 6.11 have a clear counterpart in more qualitative accounts of steam engineering in Cornwall. The first epoch of rapid technical change one can discern in figure 6.11 covers approximately the period 1811-1818. This period, which also corresponds to the start of *Lean's Engine Reporter*, can be seen as one of experimentation aimed at finding the best design for implementing the use of high-pressure steam in an expansive way. The two pioneers of the time were Richard Threvithick and Arthur Woolf. The idea behind the adoption of the principle of expansion was that of fuel economy (i.e., allowing the 'expansive force' of steam to perform some of the work necessary to push the piston). This was done by cutting off the steam when the piston was at the beginning of the stroke and letting the expansion of the steam inside the cylinder complete the stroke. This idea was originally expounded in a patent taken by James Watt in 1782. However, in order to achieve some gain in fuel efficiency using steam expansion, higher pressures than atmospheric ought to be employed (at low pressures, the gain in efficiency was very limited). After the expiration of Watt' s key patent in 1800, however, Cornish engineers were free to begin the exploration of the high-pressure *cum* expansion trajectory.

Two distinctive engine designs emerged in this period, one associated with Threvithick, the other one with Woolf. Threvithick adopted a single-cylinder condensing design, which later on would become the definitive layout of the 'Cornish engine'. Woolf, who had served as an apprentice under Jonathan Hornblower, instead preferred a compound double-cylinder layout. In the same period, another Cornish engineer, William Sims also introduced particular type of compound design. This consisted in the addition of a small high pressure cylinder to existing low pressure engines which could in this be operated using high pressure steam expansively. A sort of ultimate test between the Trevithick single cylinder and the Woolf compound design was carried out in 1825 with two new engines (of comparable size) at Wheal Alfred mine. The two engines performed the same duty (about 42 millions). This led to the abandonment of the Woolf design on grounds of his higher erection and maintenance costs (Hills, 1989, p.109).

In the early 1810s, Trevithick and Woolf also introduced two new type of high pressure boilers (necessary to generate steam of sufficiently high pressure to be worked expansively). These two type of boiler designs have been described in chapter 2. Like in the case of single cylinder engine design, Trevithick's boiler design became soon the one of most common use.

In terms of the paradigm/trajectories view of technological evolution, this first period corresponds to the emerging phase of a new technological paradigm. Accordingly, this phase is characterized by experimentation and competition between different designs, culminating in the test at Wheal Alfred. The Wheal Alfred test established a common design framework (the single cylinder engine) where a steady flow of incremental improvements could take place.

In the early 1820s there were very few "visible" technological developments. However, in this period, in many engines, the pitwork and other moving parts of the engines were considerably strenghtened so that they could withstand the use of high pressure steam. The familiarity acquired in this phase with the technical adjustments imposed by the use high pressure steam on the various components of the engine was of critical importance for the increasing use of expansion which characterizes the other two "spurts" of rapid technical change (von Tunzelmann, 1970, p. 90). This passage from a paper by James Sims describes the efforts made in 1820s to adapt the engines and the pitwork to the use of high pressure steam:

"[Woolf] having improved several Boulton and Watt engines, by causing them to work more expansively by using higher steam, awakened the whole of the Cornish engineers to a new era of steam power; and many sleepless night have I had with others in repairing the many breakages of engines and boilers, caused by the boilers being to weak for the steam attempted to be used, and the material of the engine not being strong enough for the concussion given by the sudden admission of much higher steam on the piston than was originally intended" (Sims, 1849, pp. 170-171).

The second epoch of rapid technological change comprises the years 1826-1834. Here the technological trajectory had already settled into the 'dominant' single cylinder design proposed by Threvithick. The flow of incremental innovation aimed at increasing the performance of this dominant design appears to begin in this period. By and large, the central focus of this flow of incremental innovations was the careful 'clothing' of cylinders (in some cases reviving Watt's steam jacket) and pipes (in order to conserve heat) - as originally done by Samuel Grose at Wheal Hope mine in 1825 - and in other incremental improvements of details of the engine such as the valves. Woolf's improved double beat valve was introduced in this period.

Finally, the third epoch (approximately the period 1838-42) witnessed a revival of the compounding principle by means of the engines designed by James Sims. These had to compete with engines erected by engineers Hocking and Loam according to the more traditional layout.

Note that the "convergence" phase in this final instance was probably due more to the deterioration of the best practice than from the "catching-up" of average practice. By the early 1840s the Cornish engine had probably reached its practical limits, so one can well speak of a maturity phase of the technological trajectory. Carried to the extreme with pressures reaching about 50 p.s.i., the expansion of steam produced an extremely powerful shock to the piston and to the pitwork at each opening of the steam valve. Such an operating cycle was likely to increase the probability of breakages in the pitwork and to accelerate the wear and tear of the engine (Barton 1965, pp. 57-58). The main motivation behind James Sims' elaboration of a new compound design was therefore not the search for further fuel economy, but the idea of finding a remedy for the strain that large engines were putting on the pitwork. Both Sims' design and the competing solution proposed by Hocking & Loam (a circular protuberance in the piston which was fitted in a corresponding cavity in the cylinder top) did not encounter much success (Pole, 1844).

It is not surprising then that from the late 1840s, Cornish engineers preferred to give something up in terms of engine efficiency to reap gains on the maintenance and duration side:

all the coal saved above 70 millions duty is paid for at too dear price in the racking of the engine and pump-work and the increased liability to breakage (*West Briton,* cited in Barton (1965), p. 59, no date specified).

One can therefore interpret this phase as one in which decreasing returns to development along the established trajectory began to set in (in innovation studies, the phenomenon of diminishing returns to innovative efforts along a specific technological trajectory has been frequently referred to as Wolff's law).[27] The single cylinder design had reached its practical limits, and in order to circumvent these, a new phase of experimentation was necessary. With hindsight, this phase appears largely unsuccessful, but this may be due as much to changing economic circumstances (falling ore prices and the general decline of the Cornish mining industry) than to technological factors.

Unfortunately, *Lean's Engine Reporter* does not cover a number of important technical characteristics and operating procedures that are intimately linked with the technological developments described above (e.g. steam pressure in boilers,[28] rate of expansion or cut-off point). In this respect, we should take into account that much more information besides the tables of the reporter was shared by Cornish engineers, by means of informal contacts, visits paid to particular interesting engines, etc. (Farey, 1971). [29]

After the crucial test in 1825 at Wheal Alfred between the Woolf and Threvithick engines, a major part of the energy of Cornish engineers was absorbed in the progressive exploration of the 'optimal' dimensions of the single cylinder design. In 1859, in a paper read to the South Wales Institution of Civil Engineers, James Sims presented a detailed description of dimensions, proportions, operating procedures of an 'ideal' Cornish engine (Sims, 1860). Note that the entire tone of the paper is such as if Sims was expounding what was to be considered fairly established common wisdom. In his paper he recommended 85" as the optimal size of cylinder diameter (if more power was needed, Sims suggested to install two engines, rather than erect one with larger diameter).

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27 "Wolff was a German economist who in 1912 published four 'laws of retardation of progress'. Essentially, he argued that the scope for improvement in any technology is limited and that the cost of incremental improvement increases as the technology approaches its long run performance level" (Freeman, 1982, p. 216). In the paradigm view of technological change, Wolff's law can be reinterpreted in terms of the progressive exhaustion of technological opportunities along a specific technological trajectory, see Dosi (1988), pp. 1137-1138.

28 Boiler steam pressures began to be reported by the Leans in the late 1840s.

29 This is also confirmed by the accounts of Thomas Wicksteed (1838) and William Pole (1844) who in their visit to Cornwall had the possibility of having access to all the installed engines.

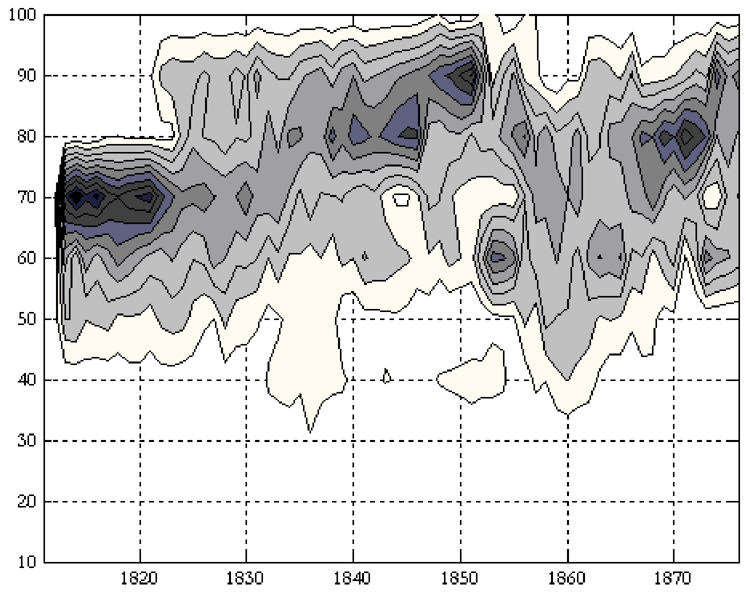

Figure 6.16: Distribution of the engines reported, cylinder size on the vertical axis, time on the horizontal axis, darker shades indicate a higher percentage of total HP delivered by the total population

Source: *Lean's Engine Reporter* (April)

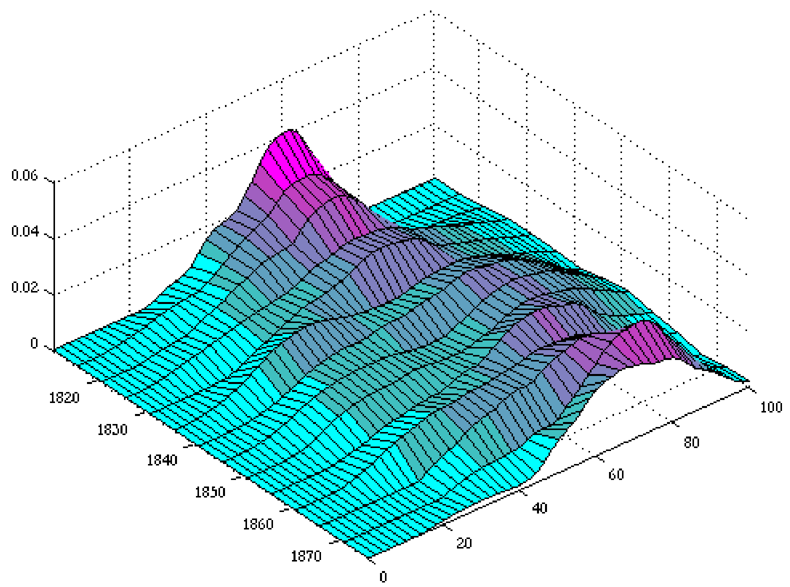

Figure 6.17: Kernel density of cylinder diameter (years on X axis, cyl. diameter on Y axis, density on Z axis)

Source: *Lean's Engine Reporter* (April)

We can have a quantitative glimpse on this exploration of the technological trajectory laid out by the dominant design, by looking at the evolution of the cylinder diameters of the reported engine park. In figure 6.16, 6.17 and 6.18 we have ordered the engines by cylinder diameter on the vertical axis, and we have charted the evolution of the shares in the total horsepower delivered each year (as in the foregoing diagrams, darker areas indicate higher levels of concentration). Figure 6.16 shows that, in the 1810s, the major bulk of the horsepower was delivered by engines with diameters around 60"-70" (this was the typical size of the Boulton & Watt pumping engines). The 'average engine' in this period can be found inside the narrow black rim around 70". After the emergence of the dominant design, i.e., the 1820s and 1830s, this 'steady state' dissipates, only to settle down at the higher level of 80" in the late 1830s and early 1840s. In the late 1840s and early 1850s we have a further movement upwards and we see another concentration peak around 90".

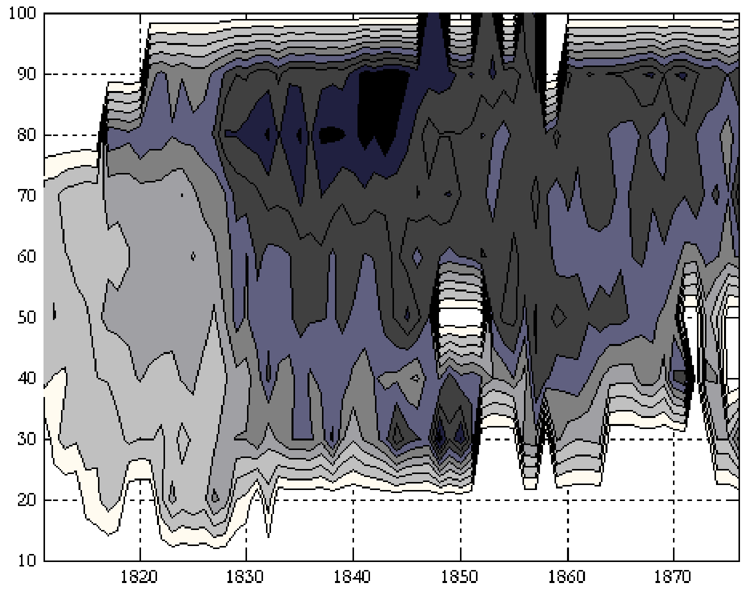

Figure 6.18: Distribution of the engines, cylinder size on the vertical axis, time on the horizontal axis, darker shades indicate a higher duty

Source: *Lean's Engine Reporter* (April).

Figure 6.17 shows the evolution of the (kernel) density of cylinder diameters in a three dimensional space. Also this figure shows a progressive shift from densities centered around values of 60" to densities centered around values of 80" – 85". Note, however, that in the later period the shape of the density function seems to change and to assume a bimodal behaviour. This is probably to be explained by the general expansion of mining activities which made it necessary in a growing number of cases the adoption of "sub-optimal" small engines.

Figure 6.18 shows the average duty delivered by classes of engines of given size. Interestingly the figure seems to indicate, for the period of the 1830s and early 1840s, the existence of scale economies in duty up to approximately 80"-85" cylinder size, with diseconomies taking place after that threshold. Contemporary engineers also noted this fact. The Leans contended that this behaviour ought to be regarded as a robust regularity:

[W]e are struck with the fact, that the duty performed advances with the size of the engine, till it reaches a certain point, (namely, 80" cylinder) and then recedes. (Lean, 1839, p.139).

Farey also made analogous remarks (Farey, 1971, p. 243). This case illustrates quite well how Lean's *Reporter* data were used to continuously refine the design of the Cornish engine (in this case the data permitted the identification of the "optimal" cylinder size of the engine).

To recapitulate, the technological development of the Cornish pumping engine can be divided into three distinct phases. The first period represents the emerging phase of the new technological paradigm of high pressure steam used expansively. The Cornish mining district in the early nineteenth century constituted a very favourable environment for the new paradigm to take firm root. Economic circumstances ensured that search for innovations was rather systematically committed towards improvements in the fuel efficiency of the steam engine. Furthermore, due to the 1790s patent conflict, the Cornish engineering community was less conditioned by James Watt's disapproval of the use of high pressure steam. In this first phase various engine layouts were explored, until the establishment around the mid 1820s of the canonical design of a single cylinder engine. The second phase and third phases are constituted by a steady flow of incremental innovations which brought about a continuous refinement of this design. The piecemeal nature of these innovations (von Tunzelmann, 1970), defies attempts of detailed compilation. Furthermore, it makes extremely difficult to single out the individual contribution of particular inventions to duty growth.

Cardwell (1971, pp. 180-181) has suggested a back of envelope computation which would permit a rough evaluation of the role played by increasing steam pressure in determining the growing efficiency of Cornish steam engines. Cardwell considers the case of the Fowey Consols engine designed by William West which in a famous trial in 1835 performed the staggering duty of 125 millions. The maximum steam pressure in the boiler during the trial was about 59 psi (which correspond to a temperature of about 148 C). Assuming that the temperature of the cold water in the condenser is equal to 15 C, the formula for the efficiency of a perfect heat engine: $\frac{T_1 - T_2}{T_1}$ (where T_1 is the temperature of the heat source and T_2 is the temperature of the sink measured in Kelvin degrees) tells us that a perfect thermodynamic engine operating between those two temperatures would have an efficiency of 31.5 per cent. On the other hand, the efficiency of perfect engine operating between temperatures of 100C and 15C such as the Watt low pressure engine would be 22.8 per cent. Hence, the wider temperature range of the Cornish engine, therefore, can account for an increase of fuel efficiency of about 40%. The performance of the Fowey Consols, instead, was more than four times the fuel efficiency of the best Watt engine (125 millions versus 30 millions duty). In Cardwell's interpretation, the example suggests that increasing steam pressures must have played a relative minor role in the growth of the duty. Overall, the major contribution to duty growth probably came from the cumulative accretion of incremental innovations. One can indeed suggest that increasing steam pressures probably exerted their impact mainly in the growth of the duty in the early nineteenth century (i.e., the first phase that we have individuated). After that (i.e. in the second and third phase), the main source of improvements in engine performance was constituted by the incorporation of minor improvements into the established design.

Figure 6.19 displays the average, maximum and minimum steam pressures in the boilers (probably figures are above atmosphere) for the period 1848-1876. This is the period during which *Lean's Engine Reporter* published steam pressure. It is interesting to note that the average steam pressure in this phase is still around 40 psi (which is the steam pressure which had emerged as typical during the 1830s).[30]

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[30] Note that these value are fully in line with that of the Fowey Consols engine used in Cardwell's example. To express the value in comparable unit, it is necessary to add 14 psi (atmospheric pressure).

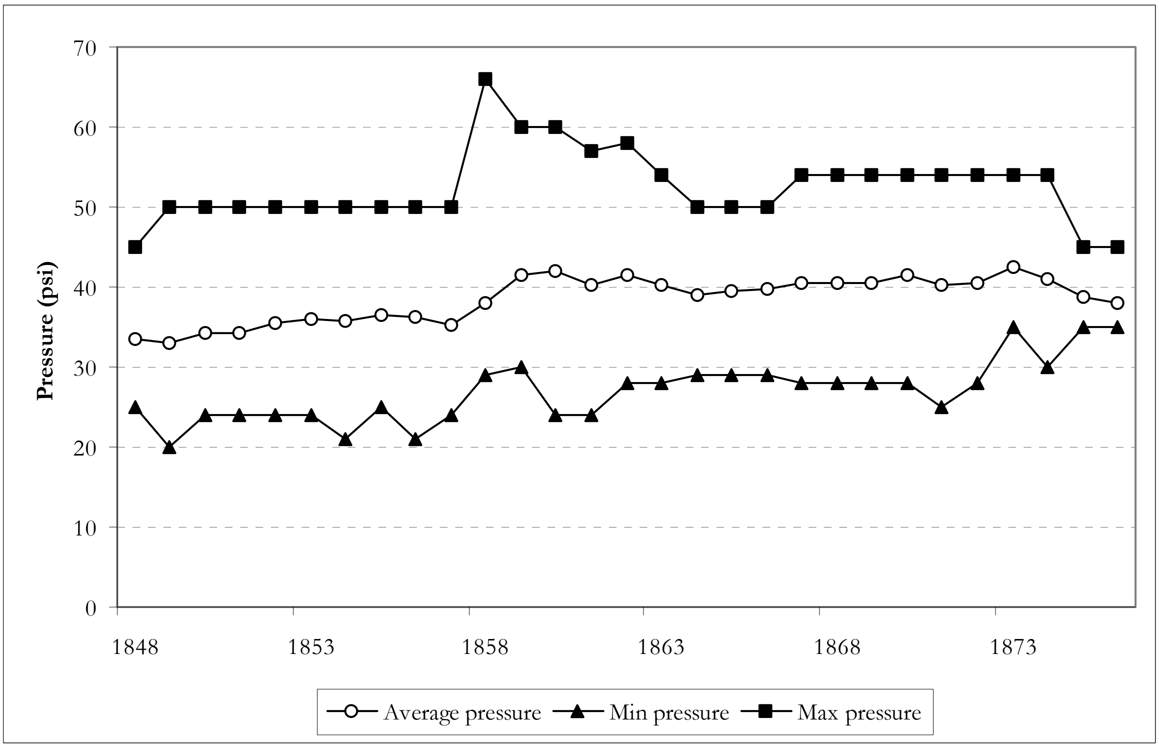

Figure 6.19: Steam pressure in boiler of Cornish engines, 1848-1876
Source: *Lean's Engine Reporter* (April)

Remarkably, figure 6.8 indicates that after what the maturity phase (early 1840s), the duty of Cornish engines began to decline, rather than to stagnate. This is quite startling because, at first sight, it might be interpreted as a curious form of "technological retrogression". Contemporaries long debated on the possible factors accounting for the decline of the duty. One suggested explanation held that as mine went deeper, the engines were required to pump more water. Figure 6.20 shows the average load per square inch in the cylinder. The series is clearly characterized by an upward trend, which can provide some indication of an increasing load for the pumping engines at work in Cornwall. Consistent with this explanation, some observers noted that, over time, the number of diagonal, rather than perpendicular, pumping shafts increased. This meant that an increase amount of work was consumed by friction, possibly determining a deterioration of the duty. Table 6.3 shows that since the 1850s the share of the engines working "diagonal" shafts begun to increase steadily. These two bits of evidence taken together suggests that it might well be the case that over time the increasing amount of work which Cornish engines were called to perform did not allow anymore an effective use of steam expansion, causing a decline in the duty.

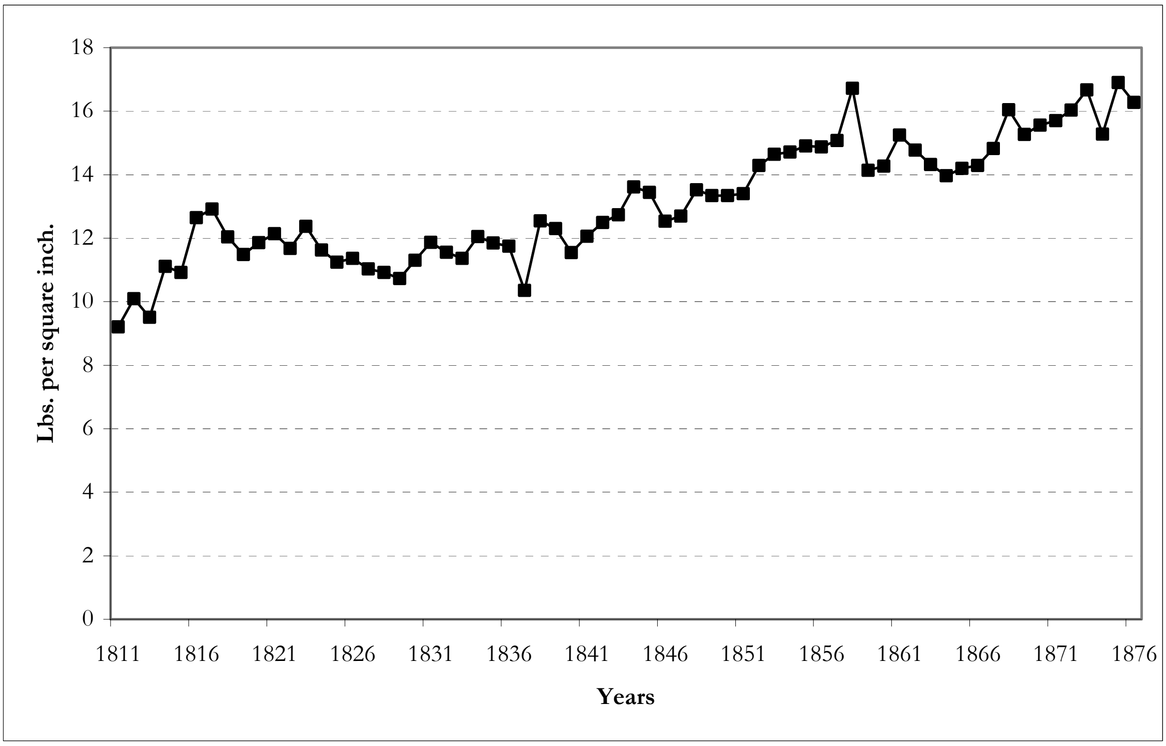

Figure 6.20: Average load per square inch on cylinder, 1811-1876
Source: *Lean's Engine Reporter* (April)

However, it is interesting to consider the behaviour of the average strokes per minute series which is represented in figure 6.21.

Table 6.3: Pitwork of the engines

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

Source: *Lean's Engine Reporter* (April).

This series seems to be characterized by a downward trend. As we have already mentioned, the slow piston speed was the main feature of the Cornish cycle (see also von Tunzelmann, 1978, pp. 80-81). The slow motion of the piston permitted to maximize the rate of expansion. Figure 6.21 then suggests that, although deeper draining determined an increase in the pump load, it did not cause an increase in the strokes per minute. Note that the decline in the number of strokes per minute could also somewhat alleviate the problem of growing friction (less strokes meant the less work was lost in friction per a unit of time).

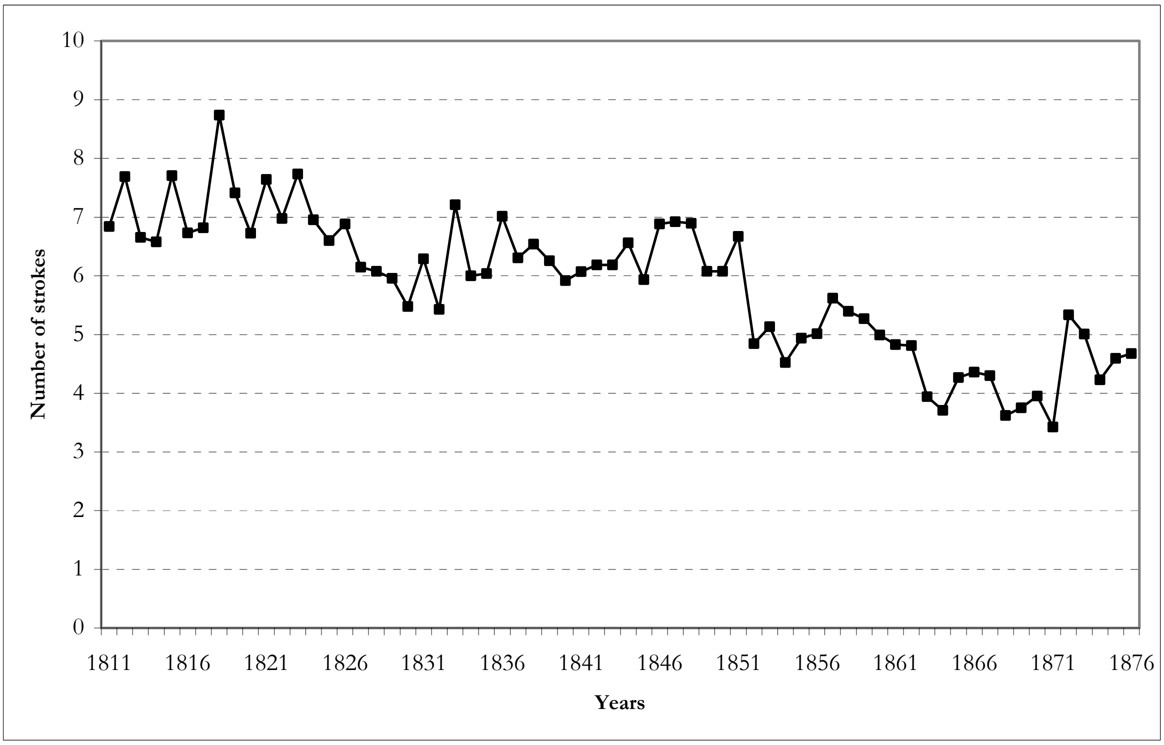

Figure 6.21: Average number of strokes per minute

Source: *Lean's Engine Reporter* (April)

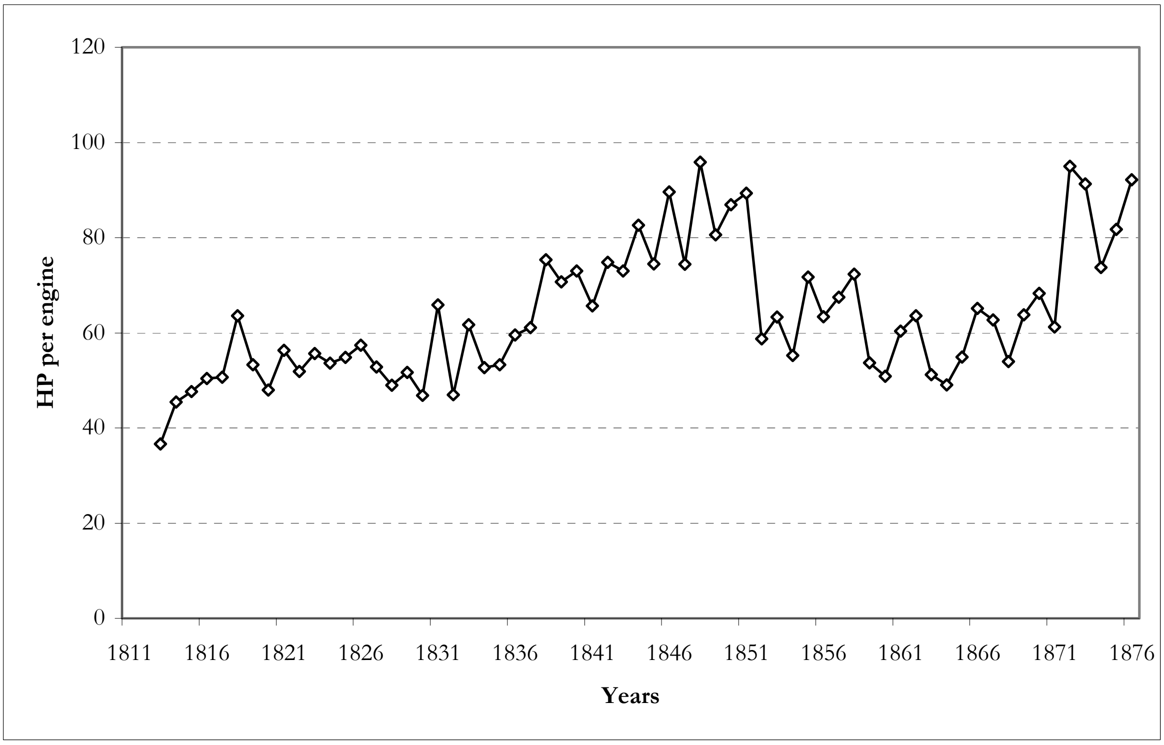

Figure 6.22.: Horsepower delivered per engine, 1811-1876

Source: *Lean's Engine Reporter* (April)

Figure 6.22 shows the number of horsepower delivered per engine. The series is characterized by some wide fluctuations, but does not exhibit any increasing trend. This means that the work (not counting the possible increase of friction due to diagonal shafts) delivered by each engine did not tend to grow over time. Hence, explanations of the deterioration of the duty based on difficulties related with changing draining conditions, which were frequently put forward in the contemporary engineering literature, can probably account only partially for the decline in the duty.

An additional factor that probably contributed to a deterioration of duty was the lower quality of the coal employed in Cornwall since the early 1840s. This interpretation was indeed sketched in a number contemporary accounts (Farey, 1971; Sims; 1860).

Overall, it is clear that from the early 1840s the development of the Cornish pumping engine had reached its maturity stage. Concerning the deterioration of the duty of the engine park which took place from the late 1840s, although it is not possible to assess in a precise way the impact of the various potential factors, the foregoing discussion suggests that it is likely that the increasing use of lower quality coals combined with the draining of a growing number of diagonal shafts ought be considered the main responsible.

6.5. Concluding remarks

One of the most notable features of the analysis contained in the previous section is that a proper understanding of the dynamics of technical progress in Cornish steam engineering requires to take explicitly into account that, at each moment in time, the industry was characterized by a population of engines with varying levels of efficiency. In particular, the evolution of the Cornish pumping engine is best understood taking into account the overall "population dynamics", rather than just focussing on the movement of what was considered as "best-practice" technology at any moment of time. In this respect, we would contend that the broad features of the process of technical change that we have outlined in the previous section are consistent with an analytical model of technical change proposed by Conlisk (1989).

Conlisk's model considers an economy in which production takes place in a number of "plants", each characterized by a given level of productivity. In each period a number of new plants is constructed (using current savings). The productivity of each new plant is generated by a random distribution. Conlisk assumes that the productivity of a new plant is a normally distributed variable with a positive mean. The mean of the random variable is assumed to be equal to the mean of the k best plants in operation in the current period. Hence, the k best plants define what might be called the performance level of "best practice" technology. Future technological developments are built on this "best practice". Note that a lower value of the parameter k implies faster diffusion of technological knowledge. In other words, k is "a rough measure of the efficiency with which new plant designers learn the lessons of the past" (Conlisk, 1989, p. 795). In the Cornish case, *Lean's Engine Reporter* can be seen as a mean to reduce the value of k, in order to enhance the efficiency of the learning process.

Given this simple set of assumptions, Conlisk shows that the aggregate rate of productivity growth (or, if we want to transpose the model explicitly to the Cornish case, the growth of average duty) is a positive function of three parameters: i) the standard error of the productivity distribution of new plants (engines), ii) the savings rate (which determines the number of new plants installed in each period), iii) the speed of diffusion of new technical knowledge which is defined by the parameter k explained above.

The distinguishing feature of Conlisk's model is the link between the standard error of the productivities of new plants and the rate of growth of aggregate productivity. The intuition behind this result is very simple. A greater variance in the productivity of new plants clearly increases the possibility of discovering a major innovation (a plant exhibiting a big productivity jump). Since further draws will be extracted from a distribution having as a mean the productivity of the k best plants, the drastic innovation will be gradually incorporated into average practice plants. As noticed by Conlisk, the aim of this specification is to capture the idea of "cumulative technology" suggested in Nelson and Winter (1982, p. 294).

In other words, in Conlisk's model the dispersion of the probability distribution of the productivity of new plants is an indicator of the width of the space of technological opportunities explored by the engineers. A higher dispersion indicates that a higher number of options is available to engineers engaged in the design of new plants. This also means a higher possibility of elaborating a design which can attain a drastic performance improvement. Vice versa, a narrow dispersion means that engineers are facing a restricted number of design options. In the evolution of actual technologies, the variance of the probability distribution is clearly not constant over time. When a technological paradigm is in its emerging phase, engineers are clearly considering a wider range of design options than when the paradigm is relatively established. This explain the progressive setting in of diminishing returns to innovative efforts within a specific technological paradigm (Wolff's law).

The patterns of technical change that we have reconstructed in the previous sections appears to be broadly consistent with the operation of Conlisk' s model. The period of average duty growth is a period in which the dispersion of the duty distribution also increases (see figure 6.10 and figure 6.12 and 6.13). The behaviour of the coefficient of variation (figure 6.11) also suggests the existence of a dynamic interaction between the movement of best practice engines followed by the "catching up" of average practice engines as the one described in the model. Additionally, the positive link between the installation of new plants and average productivity growth existing in Conlisk's model (the intuition behind this result is relatively straightforward: the installation of a higher number of plants will improve the age distribution of the plants bringing average practice closer to best practice; furthermore, if more new plants are installed there is a higher probability of a positive innovation which will improve the performance of the best practice plants) seems also to be a feature of the pattern of technical change in Cornish steam engines. As we have seen (figure 6.9), the phase of rapid growth coincided with the expansion of the Cornish mining industry and the installation of new productive capacity (new engines). In addition, our interpretive account of the difference in the rates of technical progress between Lancashire and Cornwall can be also related to two of the parameters that in Conlisk' s model affect the growth rate of the system: the standard error of the productivity distribution of new plants (a coefficient that is plausible to assume higher in Cornwall than in Lancashire, reflecting the higher degree of technological opportunities in the use of high pressure steam in mining than in manufacturing in the early nineteenth century) and the speed of diffusion of new technical knowledge (that in Cornwall was spurred by *Lean's Engine Reporter*). In this respect, Conlisk model can be seen as providing a description of the micro-dynamics of technological progress underlying the two "aggregate" paths of technical change that we have outlined in section 6.2 (see again figure 6.6)

Conlisk's model represents technical change as an endogenous (in the sense, that it is the outcome of investment decisions), uncertain and cumulative process. The mechanics of the model is rather simple. However, the model displays properties which appear rather appealing because of their empirical plausibility. As we have shown, the mechanics of the model, notwithstanding its extremely stylised character, seems able to capture the salient features of the patterns of technical progress in Cornish steam engines.

Finally, one of the most intriguing aspects of Conlisk's model is that the it considers a conceptualisation of technical progress which is in stark contrast with the one prevailing in the neoclassical growth literature (Conlisk, 1989, p. 810). The neoclassical growth literature (both in the old "Solowian" version and in the new "endogenous" form) assumes the existence of a production function and considers technical change as (exogenous or endogenous) shift of this production function. In Conlisk's model, technical change is represented by a series of random draws from a probability distribution which are progressively incorporated into productive capacity. In this way the model avoids the use of the "problematic" notion of production function (and the related artificial distinction between technical progress and factor substitution), providing a more realistic representation of the dynamics of technical change.

7. The Drivers of Technical Progress in Cornish Steam Engines

7.1. Introduction

In the previous chapter, we have outlined the patterns of technical progress characterizing the development of the "high pressure" technological paradigm in Cornwall. This chapter is concerned with the factors driving technical progress along what may be called the Cornish technological trajectory. In particular, we will try to assess the various processes of technological learning underlying the development of the Cornish pumping engine. We will begin by looking at the role played by individual engineers and by considering how the interplay between "innovative" and "imitative" behaviours affected the collective patterns of knowledge accumulation. Then we will turn our attention to the life history of individual engines, in order to shed some light on the process of learning by using stemming from the actual operation of the engines. Finally we will carry out a rather simple accounting exercise which tries to assess the relative contributions of the what may be called the "proximate" sources of duty growth.

7.2. The role of the engineers

As we have seen in chapter 5, Cornish pumping engines were designed by independent consulting engineers, who typically provided their services to different mines for an annual fee. The tasks of the engineer were to provide the drawings of the engine (including the engine house) to the selected foundry[1] and to the other manufacturers involved in the construction of the various components, to supervise the installation of the engine and to pay occasional visits to the mine in order to give directions concerning the operation and maintenance of the engine (once this was installed).[2] The profession of engineer was typically a family vocation, with sons usually learning the "secrets of the trade" from their fathers. [3]

For the period 1811-1876 about 60 different names of engineers or engineering partnerships appear on the pages of *Lean's Engine Reporter*. Figure 7.1 and 7.2 give the share of engineers in the total number engines reported in each year (as in the previous chapter we are considering here the month of April). In using the number of engines reported to evaluate the "market shares" of individual engineers, we must also take into account the remarks made in the previous chapter about the incomplete coverage of *Lean's Reporter*.

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[1] "With the sole exception of Woolf, who was connected with Harvey & Co. as founders, the Cornish engineers appear to have been quite independent of any particular foundry, a system that undoubtedly assisted the free development of the Cornish engine and engineering during their heyday" (Barton, 1965, pp. 147-148).

[2] According to Barton (1965, p. 147) the typical fee for a new engine was one guinea per inch of cylinder diameter.

[3] Useful biographical information on a number of Cornish engineers is provided in Harris (1977).

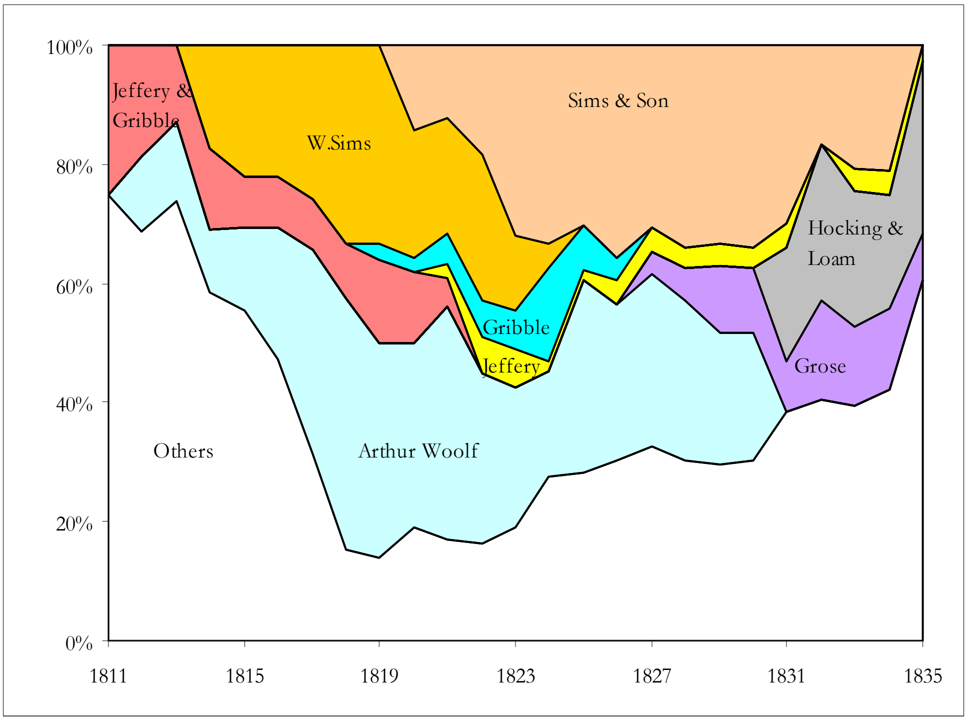

Figure 7.1: Share of engineers in *Lean's Reporter*, 1811-1835
Source: *Lean's Engine Reporter* (April)

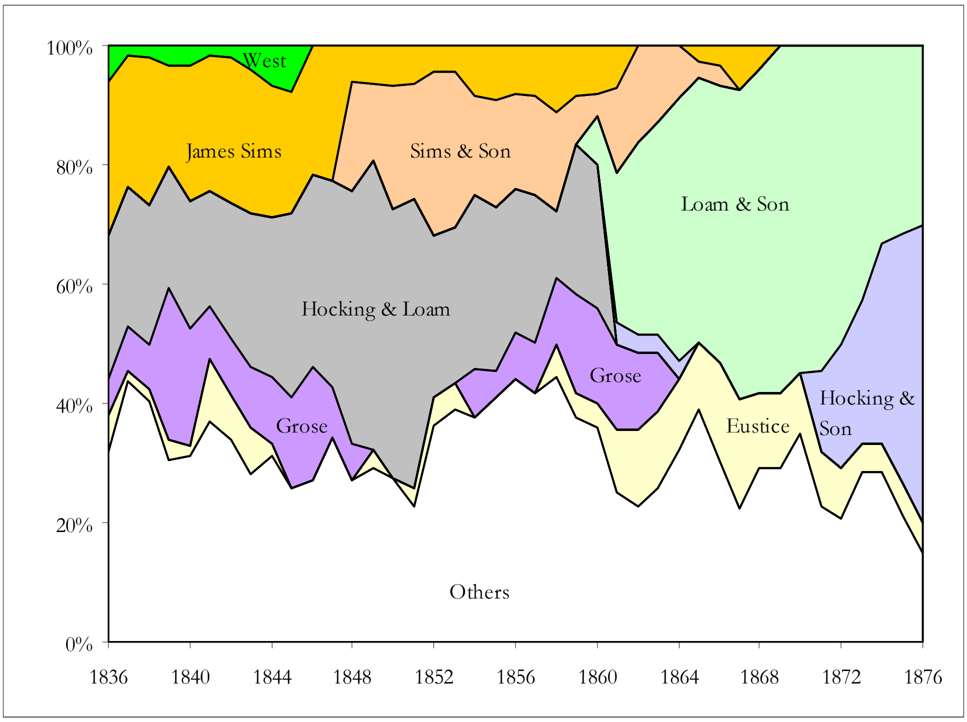

Figure 7.2: Share of engineers in *Lean's Reporter,* 1836-1876
Source: *Lean's Engine Reporter* (April)

The available evidence (see chapter 6, table 6.2) suggests than in the mid 1830s approximately half of the engines at work in Cornwall appeared in the pages of *Lean's Engine Reporter*. This percentage declined in the following years. Accordingly, it is plausible to assume that the shares in the number of engines calculated using *Lean' s Engine Reporter*, at least up to the late 1830s, broadly reflected the respective "market shares" (and the reputation) of the various engineers.

Considered together, figure 7.1 and figure 7.2 show that throughout the period 1811-1876 the bulk of the engines reported was highly concentrated on a restricted number of engineers.

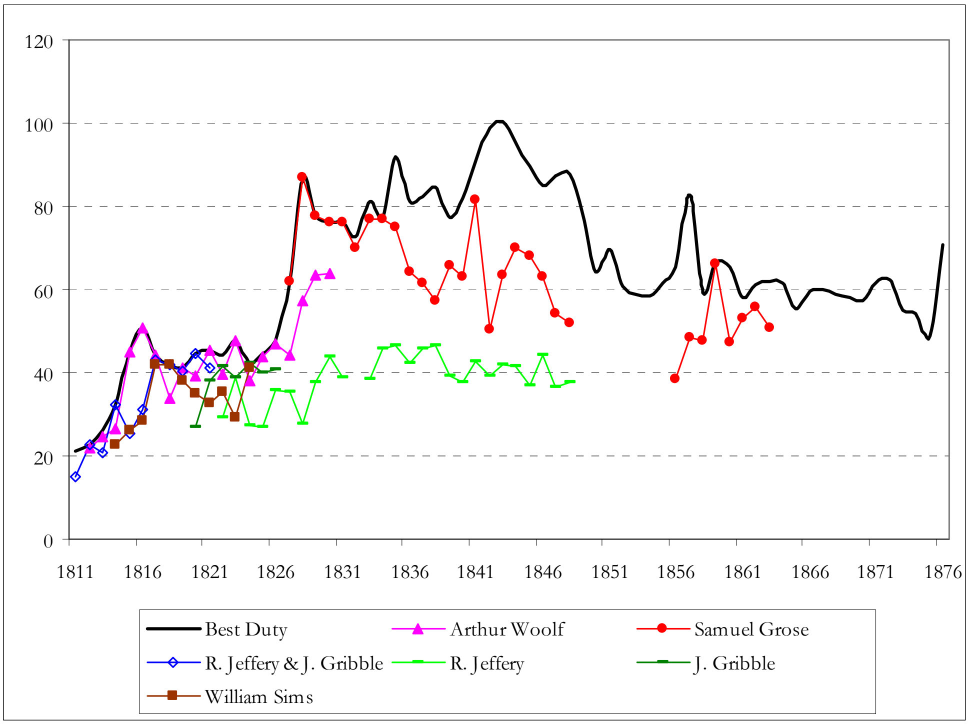

Figure 7.3: Best duty of Cornish engineers: Woolf, W.Sims, Grose, Jeffery and Gribble.

Source: *Lean's Engine Reporter* (April)

Figures 7.3 and 7.4 give, for the month of April, the best duty for the engines of some of the most "famous" Cornish engineers (these are engineers whose names are mentioned frequently in contemporary engineering publications). Note that to a major degree these are also the engineers that detained a sizable share in the engines reported. The figures also show the best duty in the engine population which is indicated by the thick black line without markers.

Figures 7.3 and 7.4 show that the competition for the best duty reported was restricted to no more than a handful of engineers. Up to 1826, Arthur Woolf appears to dominate the duty race, challenged by William Sims and Jeffery and Gribble. Grose has consistently the best duty engine from the mid 1820s till the mid 1830s. From the mid 1830s, Hocking and Loam (initially challenged by James Sims and William West) maintain the lead position. Finally, from the late 1850s Loam and son detain the lead.

Figure 7.5 and 7.6 display the average duty of the engines entrusted to each engineer in our selected group. As in the previous case the figures also display the average duty of the entire engine population by means of a thick black line without markers.

Interestingly enough, with the exceptions of Samuel Grose in the mid 1820s and William West in the 1840s, the average duty of individual engineers is not sizably higher than the average duty of the entire engine population. In some periods, the average duty for some our selected engineers appear even to be appreciably worse than the average duty of the overall engine population. Thus, as far as average duties are concerned, the group of the most famous Cornish engineers does not appear to significantly outperform the rest.

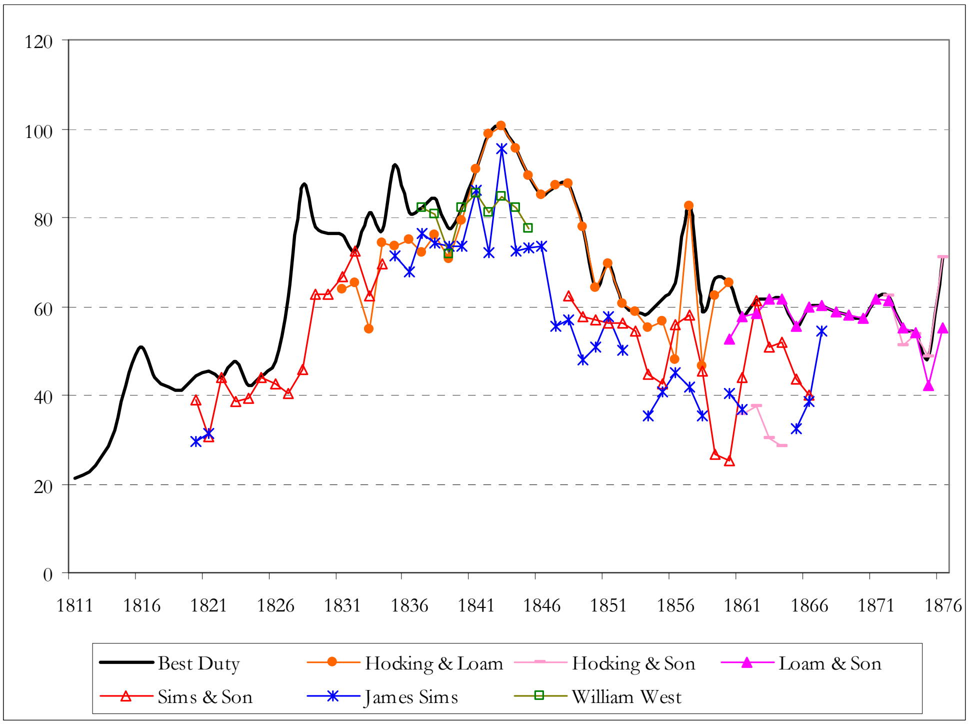

Figure 7.4: Best duty of Cornish engineers: J. Sims,Hocking, Loam, West
Source: *Lean's Engine Reporter* (April)

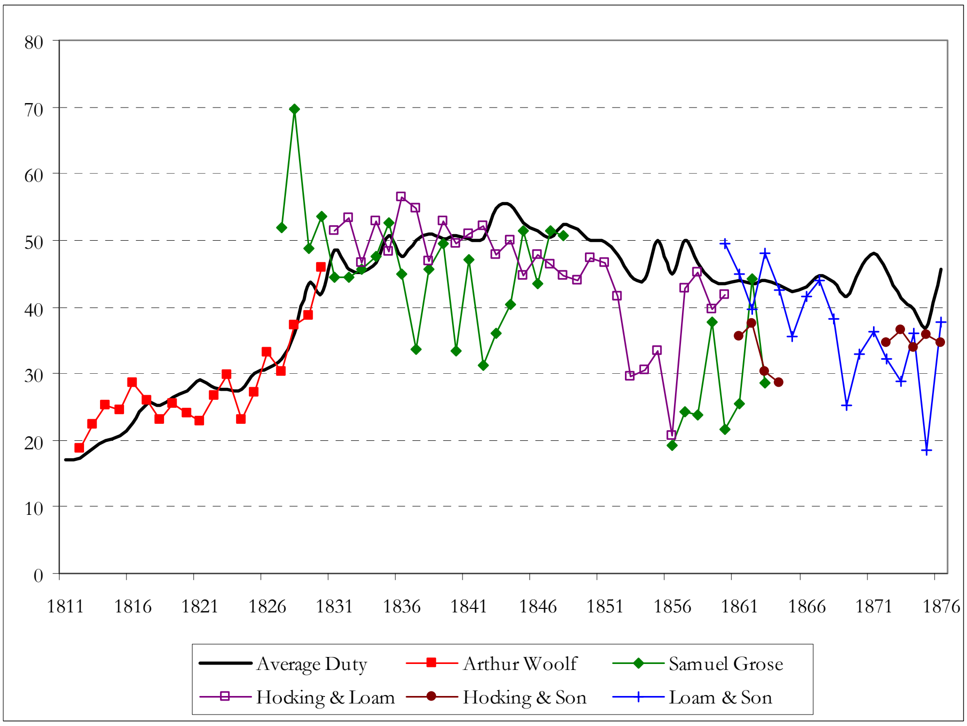

Figure 7.5: Average duty of Cornish engineers: Woolf, Grose, Hocking and Loam.
Source: *Lean's Engine Reporter* (April)

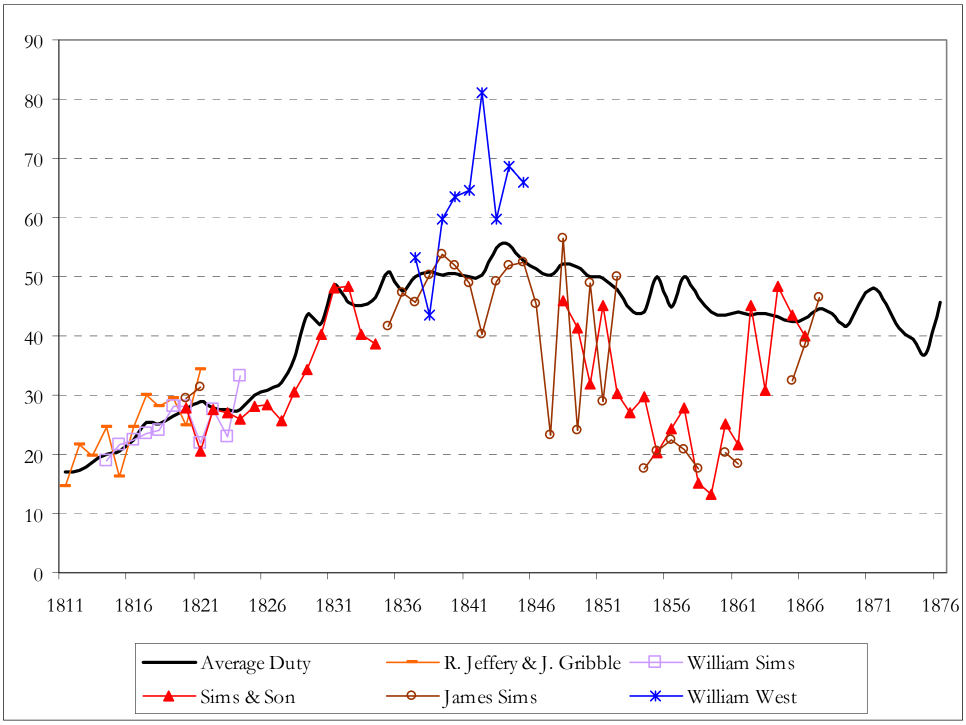

Figure 7.6: Average duty of Cornish engineers: Jeffery, Gribble, West, William and James Sims

Source: *Lean's Engine Reporter* (April)

Figure 7.7 and 7.8 give the linear coefficient of correlation between engineer's average (figure 7.8) and best (figure 7.8) and the number of engines reported (observations significant at a level of 10% are marked by circles).

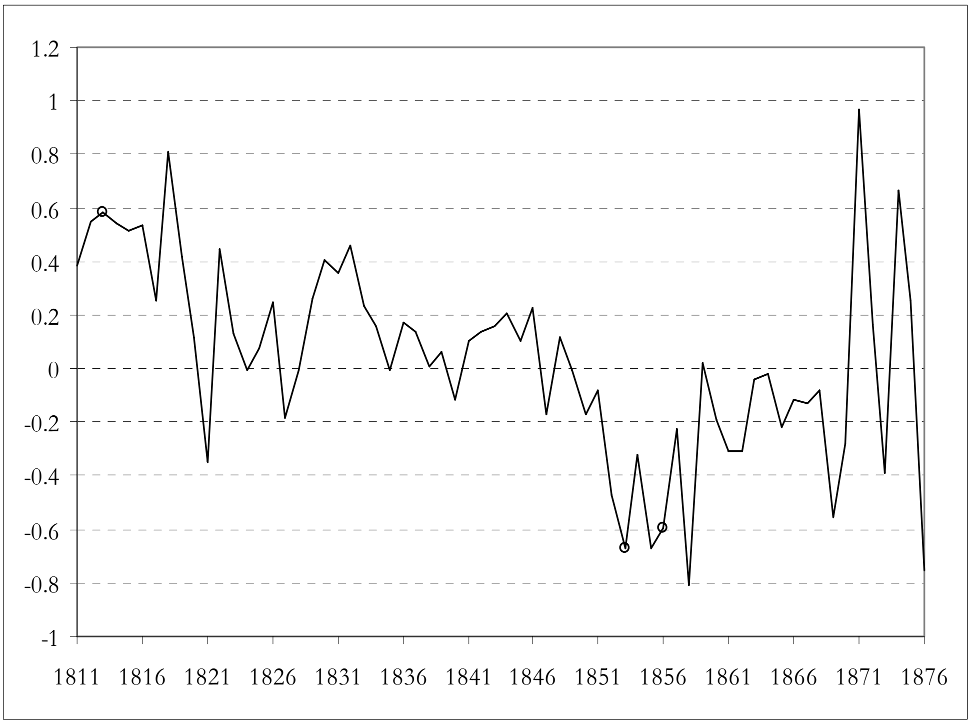

Figure 7.7: Coefficient of correlation between number of engines and average duty

Whilst there is no significant correlation between the number of engines and the average duty "scored" by individual engineers, there is a significant positive correlation between the best duty and the number of engines for the period 1811-1848.

One would clearly expect that engineers scoring high duties will be commissioned a higher number of engines. Of course, the relationship is likely to work with some unknown delay. However, since most engines tend stay in the engine park reported, we might reasonably expect to capture at least partially this effect also by looking at contemporaneous correlations.[4]

Figure 7.7 and figure 7.8. therefore seems to suggest that the reputation of individual engineers was more tightly related with single achievements (that is to the remarkable performance of particular engines) than to the average duty that each engineer was able to score in each period.

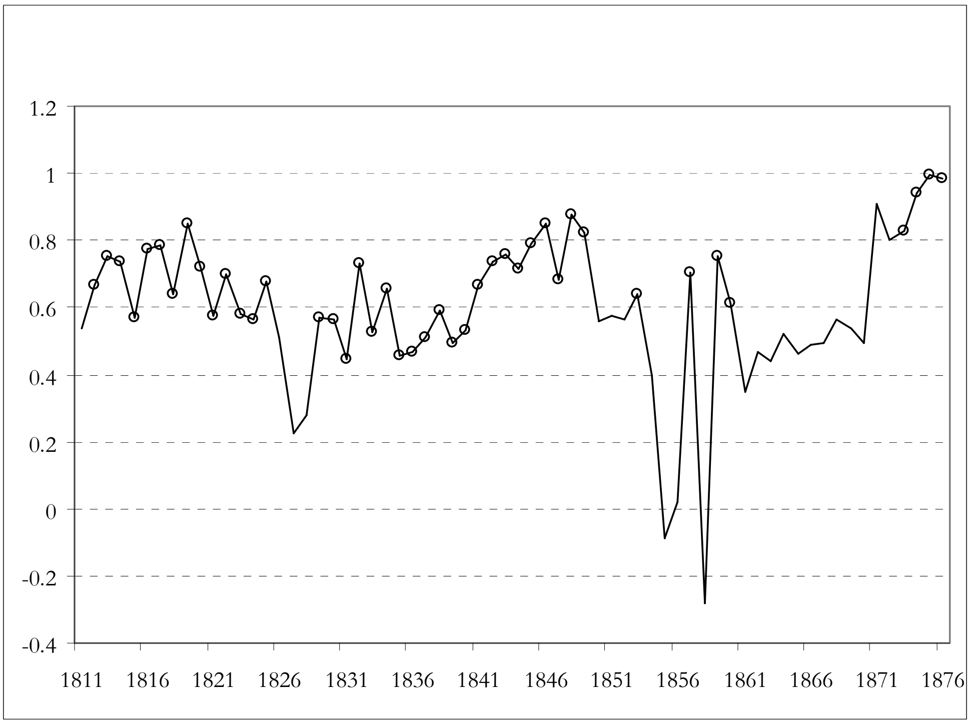

Figure: 7.8: Coefficient of correlation between number of engines and best duty

A possible interpretation of these findings might be as follows. The Cornish engineering community was comprised of two different types of agents. On the one hand, we have what we might call the 'inventors', that is to say, engineers who were willing to assume the risks of introducing modifications into existing designs. Engineers such as Richard Trevithick, Arthur Woolf, William Sims, James Sims, Hocking and Loam can be considered as typical representatives of this part of the Cornish engineering community. As shown in figures 7.1 and 7.2, this group of engineers controls the large bulk of the engines reported by the Leans. The engines designed by these group of engineers typically incorporated a certain degree of "design novelty" and this made of particular interest the monitoring of their performance (for the engineers that had designed them, but also for the wider community constituted by the other engineers and mine

[4] In this respect, it should be pointed out that, once installed, engines were usually supervised by the same engineer for rather large "chunks" of their life-cycle.

entrepreneurs). On the other hand, we have other engineers who were more cautious and less willing, in the design of their engines, to depart from what was considered the accepted 'best practice'. This group can by and large be considered as composed by "prudent imitators": their general attitude was to adopt novel design features only when these had proven their potentialities.[5] The names of these engineers tend to appear in the reporter only sporadically.

Taking into account the overall pattern of technical progress analysed in the previous chapter, this particular feature of the structure of the Cornish engineering community can be considered as a good illustration of the essential role played by "anomalous", or "non conformist" behaviours (i.e., departures from what is considered as consolidated best practice) in the exploration of the space of technological opportunities. This shows that (somewhat paradoxically) even in collective invention settings individual inventors still represent a fundamental "source" of technical progress.[6] In this perspective, the rise of aggregate duty in over the period 1811-1841 can be seen as a series of waves of discovery-imitation between innovating and imitating engineers.[7]

7.3. The behaviour of individual engines

Further insights concerning the nature of the process of technological learning in Cornish steam engineering may be gleaned by examining the behaviour of the duty at the level of individual engines.

Figure 7.9 shows the monthly times series of the duty of two engines which are characteristic of the emerging phase of the high pressure paradigm in Cornwall. As is apparent the duty of Cornish engines exhibits a short term fluctuating behaviour. This was due to the fact that operating conditions (amount of water to be pumped, quality of coal, etc.) were subjected to variation from one month to the other. In order to identify the "trend behaviour" of the duty series, we have filtered the series using the Hodrick-

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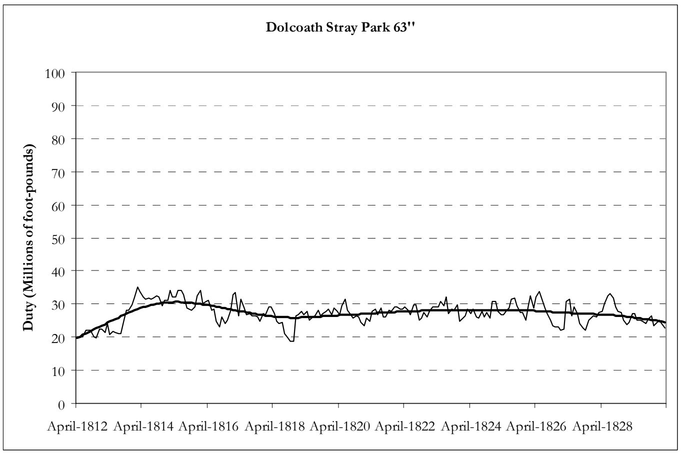
[5] Notably, in his case study of collective invention in the Cleveland blast industry, Allen also points to the existence of two attitudes towards the risks related with the introduction of new designs: "Suppose a firm had decided that the construction of a new blast furnace was commercially justified and was considering building it a bit taller or hotter than the existing least cost design. As long as the furnace would have been built anyway, the cost of experimenting was the possibility that the production costs in the new design would exceed costs in the old design. Correspondingly, the benefit was the possibility that unit cost would be lower. *Firms varied in their willingness to gamble.* When it was realized in the Cleveland district that increasing height lowered fuel consumption, no firm was so risk prone as to build a ninety foot furnace. However, since height and temperature vary continuously, the increments in height and temperature could be made sufficiently small so that some firms found the gamble worthwhile. *Those firms constituted the group of pioneers that leapfrogged each other increasing height and temperature. More risk averse firms copied the best existing design.*" (Allen, 1983, pp. 11-12, italics added). Allen and McGlade (1986) describe a similar interaction between "innovators" and "imitators" in the case of Nova Scotian fishing fleets.

[6] For a thorough and provocative discussion of the critical function of individual inventors in the innovation process, see Jewkes, Sawes and Stillerman (1969), especially pp. 96-103.

[7] Allen (1988) and Dosi and Fagiolo (1998) have proposed two evolutionary models in which the interplay between the two class of agents ("innovators" and "imitators") generates self-sustained growth in the overall performance of the system. One very interesting result emerging from these models is that a population composed only by "imitators" will perform poorly, exploring only a very limited part of the system's evolutionary potential. On the other hand, a population composed exclusively by "innovators" will display the tendency to remain too dispersed and to jump too quickly on the space of technological opportunities, preventing a thorough exploitation of the discoveries they have made. The evolutionary potential of the system is best exploited by a mixed population of "innovators" and "imitators" *with information flowing among the two classes*, so that "imitators" can refine and fully exploit the potential of the discoveries accomplished by the "innovators".

Prescott filter (see Appendix 7.A.1). The filtered series are represented by thick lines, whilst the original series incorporating short run fluctuations are represented by thin lines.



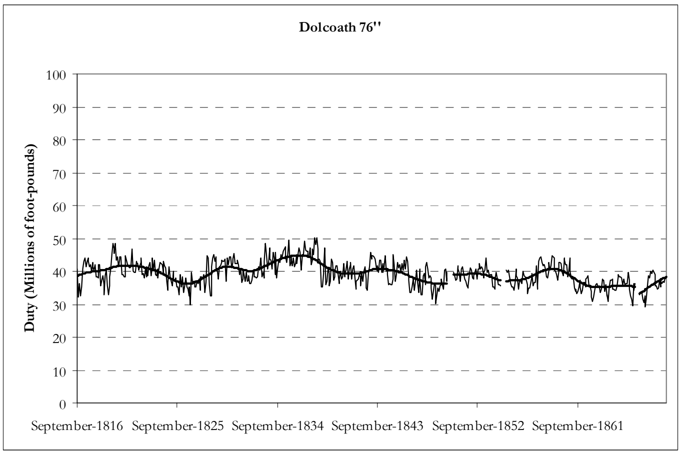


Figure 7.9: Duty of Cornish engines (the emergence of the high pressure paradigm)

Source: *Lean's Engine Reporter*

Dolcoath Stray Park 63" was one of the best low pressure engines erected in Cornwall by Boulton and Watt and it can be used as a useful yardstick to evaluate successive improvements in fuel efficiency attained by Cornish engineers in the early nineteenth century.[8] The best duty delivered by this engine was a little above 30 millions in the period 1814-1815.

Dolcoath 76" erected by Jeffery and Gribble in September 1816 was one the first steam engines, embodying what would become that typical design for Cornish engine. It was a single cylinder engine, working expansively with steam generated by Trevithick boilers. This engine was able to deliver consistently duties above 40 millions, clearly outperforming the Watt low pressure engine. Hence figure 7.9 might provide an indication of the advantages of using high pressure steam as they were apparent to Cornish engineers during the 1810s Dolcoath 76" is also of particular interest because it was reported without major interruptions for almost 50 years.

Figure 7.10 shows the behaviour of some of the early compound engines designed by Arthur Woolf after his return from London. Wheal Abraham Woolf 45" was the first compound engine (cylinders 24" and 45") erected by Arthur Woolf in Cornwall. After its installation, the engine scored a duty above 40 millions and then above 50 millions. In August 1818 the cylinders of the engine were refitted (Farey, 1971, p. 96). As is apparent from the figure, these repairs halted the declining trend which was setting in, making possible a new phase of duty growth. In a trial of three days performed in August 1818 to which John Farey personally attended, the engine supplied by "the best Welsh coals" scored the unprecedented duty of 65.21 millions. Farey noted that during the trial steam pressure in the boiler was 65 psi. However, such steam pressure was not deemed to be sustainable for long periods of working and steam pressure in normal operating conditions was usually set between 40 and 45 psi (Farey, 1971, p.123). The engine was re-erected at Wheal Wentworth mine in 1824 (Harris, 1966, p.88). After the transfer the performance deteriorated remarkably.

[8] In November 1818 the cylinder of this engine was substituted by a new one, Farey (1971, p. 200).

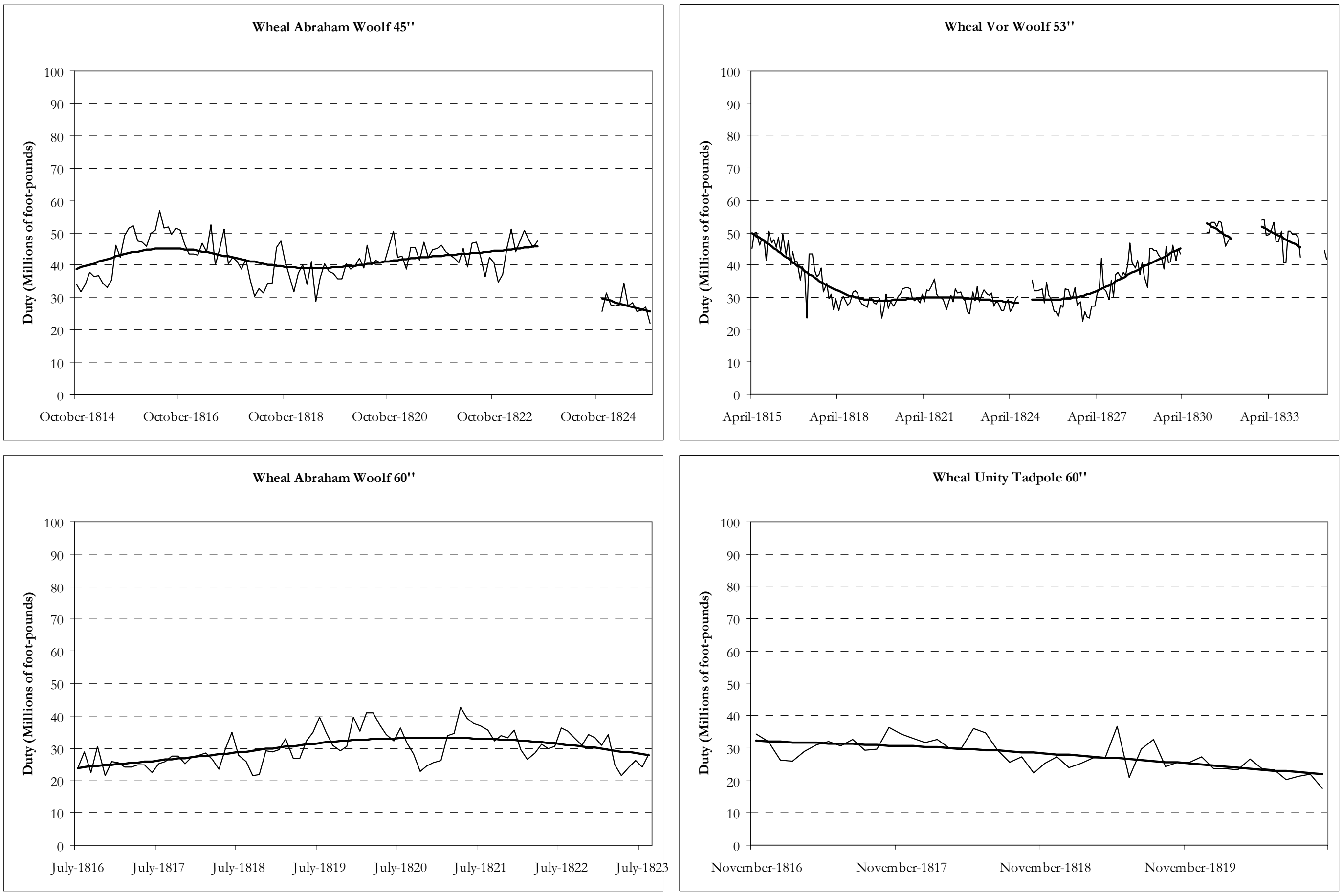


Figure 7.10: Duty of Cornish engines (early compound engines designed by Arthur Woolf)

Source: *Lean's Engine Reporter*

Wheal Vor 53" was the second compound engine (cylinders 28" and 53") erected by Woolf in Cornwall. The engine scored duties above 40 millions in the first two years of its life history, however in the subsequent periods the performance deteriorated rapidly. The engine was reverted to single cylinder by Sims and Richards in March 1824. Also in this case, the modification seems to determine a new phase of increasing duty.

Wheal Abraham 60" was the third Woolf compound engine (cylinders 33" and 60"). The engine did not deliver a particularly remarkable duty.

In 1816, with the Wheal Unity Tadpole 60" engine, Woolf made an attempt of improving the performance of an existing Watt engine, converting it to his compound design (cylinders 34" and 60"), by means of the addition of a small cylinder and replacing the boiler with an high pressure one. As shown by figure 7.10 the result was not particularly satisfactory in terms of duty improvement.

Figure 7.10 clearly shows that the performance of Woolf compound engines after a period of operation tended to deteriorate. In this respect, it is enlightening to compare the behaviour of Dolcoath 76" with that of Woolf compounds. Dolcoath 76" exhibits a rather stable performance around 40 millions, Woolf compounds instead (with the partial exception of Wheal Abraham 45"), although capable of scoring duties above 40 millions, do not seem capable of sustaining such performances for long periods of time. There were two main reasons for the quick deterioration of performance in Woolf compounds:

i) the difficulties in keeping the two cylinders steam tight; ii) the cast iron water-tube boilers were prone to rapid obsolescence. The water used for generating steam in Cornish mines typically contained a good deal of residual minerals. Hence, incrustations developed quickly inside the boiler, in particular in the small tubes that, consequently, tended to burn out. Furthermore, the repeated heating and cooling of cast iron[9] made the boiler susceptible of cracking. For these reasons, Woolf water tube boilers after a period of use had to be operated at lower pressures than those needed for fully reaping the advantages of expansive action (Harris, 1966, pp. 59-60).

Besides introducing the compound engine and the water-tube boiler, Arthur Woolf exerted a major impact in raising the general standard of Cornish engineering workmanship.[10] Farey gives a detailed description of the role played by Woolf's example on Cornish engineering practices:

> In the construction of these two engines [Wheal Abraham 45" and Wheal Vor 53"], Mr. Woolf introduced a perfection of execution that was quite unknown in Cornwall at that time, and which had never before extended to such large engines in any other district. Mr. Woolf, in his previous practice in London, had taken an active part in extending and applying all those improvements in means of executing steam engines with superior workmanship and durable materials, that were brought into use after Mr. Watt's retirement, at the expiration of his patent in 1800: these improvements were introduced partly by Mr. Watt's successors in the Soho manufactory, and by their early competitors, who made great exertions to excel them in style of workmanship; Mr. Woolf adopted all these improvements and added others of his own, whereby he gave to his new engines all the stability and certainty of action that could be derived from the most accurate and durable manner of putting their parts together…….The improvements in execution that Mr. Woolf thus introduced into Cornwall were found so advantageous, that they have been adopted in all the engines that have since been erected in that district. (Farey, 1971, p. 102).

William Sims was more successful than Woolf in upgrading existing engines to high pressure steam (Farey, 1971, pp. 186-189 and Barton 1969, pp. 39-40). In his compound design the cylinder of the existing Watt engine acted as low pressure cylinder. To this, Sims, added a small high pressure cylinder in which a pole, performed the function of the piston. (Sims had bought Trevithick's plunger-pole patent before the latter left for Peru in 1816). High pressure steam was generated by Trevithick wrought iron boilers. Figure 7.11 shows the duty behaviour of some of these "upgraded" engines.

United Mines Poldorey 63" was altered to compound in 1818. Wheal Chance Sims 45" in 1816 (later on, it was reverted to single cylinder again). In June 1817 United Mines Williams 65" was converted to the plunger pole design. Also this engine was later on reverted to single cylinder (May 1821). Finally, in November 1817 Sims converted to his compound design the Treskerby 58" engine. This engine was considered by William Pole as the best engine erected according to the compound design conceived by Sims. As shown by figure 7.11 these modifications can be considered rather successful as they enable old Watt engines to deliver duties between 30 and 40 millions. It is also interesting to note that most of these engines were reverted again to single cylinder design, when, in the early 1820s, in the Cornish engineering community grew the belief that compound engines did not provide sizable advantages in terms of duty, and that the experienced improvements in fuel efficiency were likely to be much more related to the use of higher steam pressure rather than to the double cylinder design.

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[9] "In fact, cast iron was not a suitable material for boilers where it could be subjected to unequal heating and at this period there was no way of discovering whether there were any flaws in the castings which might fatally weaken them" (Hills, 1989, p. 131)

[10] During the years spent in London, Woolf was trained as a millwright in the famous engineering works of Joseph Bramah in Pimlico, see Barton (1965, p. 142).

In his book Pole gave a detailed description of the introduction of William Sims' compound engines:

In 1816, when Trevithick left England for South America, Mr. William Sims, an engineer of considerable reputation in Cornwall agreed with him for the patent right of the pole for the purpose of attaching it to Boulton and Watt 's , and so forming an expanding engine. This was done by allowing steam to enter first at high pressure under the pole or plunger, and partially to expand in that cylinder, by being cut off at a certain fraction of the stroke. It was then permitted to pass into the cylinder of a Boulton and Watt engine, where expansion was further extended, and afterwards the condensation took place as usual. The plunger was attached to the same beam as the piston of the great cylinder, and the engine was similar in action to those erected by Woolf. Mr. Sims and his son...., being in partnership at the time, immediately altered five engines to this plan......, and in all these cases Trevithick's cylindrical boilers were substituted for the original waggon-shaped ones, the steam being worked at 4-0 lbs. per square inch above the atmosphere. The best engine of this construction was the one at Treskerby, and the application generally effected considerable improvement on the Boulton and Watt engines. The duty of the Wheal Chance engine for one month, in 1817, reached very nearly 50 millions, but afterwards fell off, from the engine and boilers being allowed to get in bad order. Some of the engines were in use for many years, and were formidable rivals to Woolf's engines, but were, with them, equally put aside by the introduction of high pressure steam into the single cylinder. (Pole, 1844, pp. 58-59).

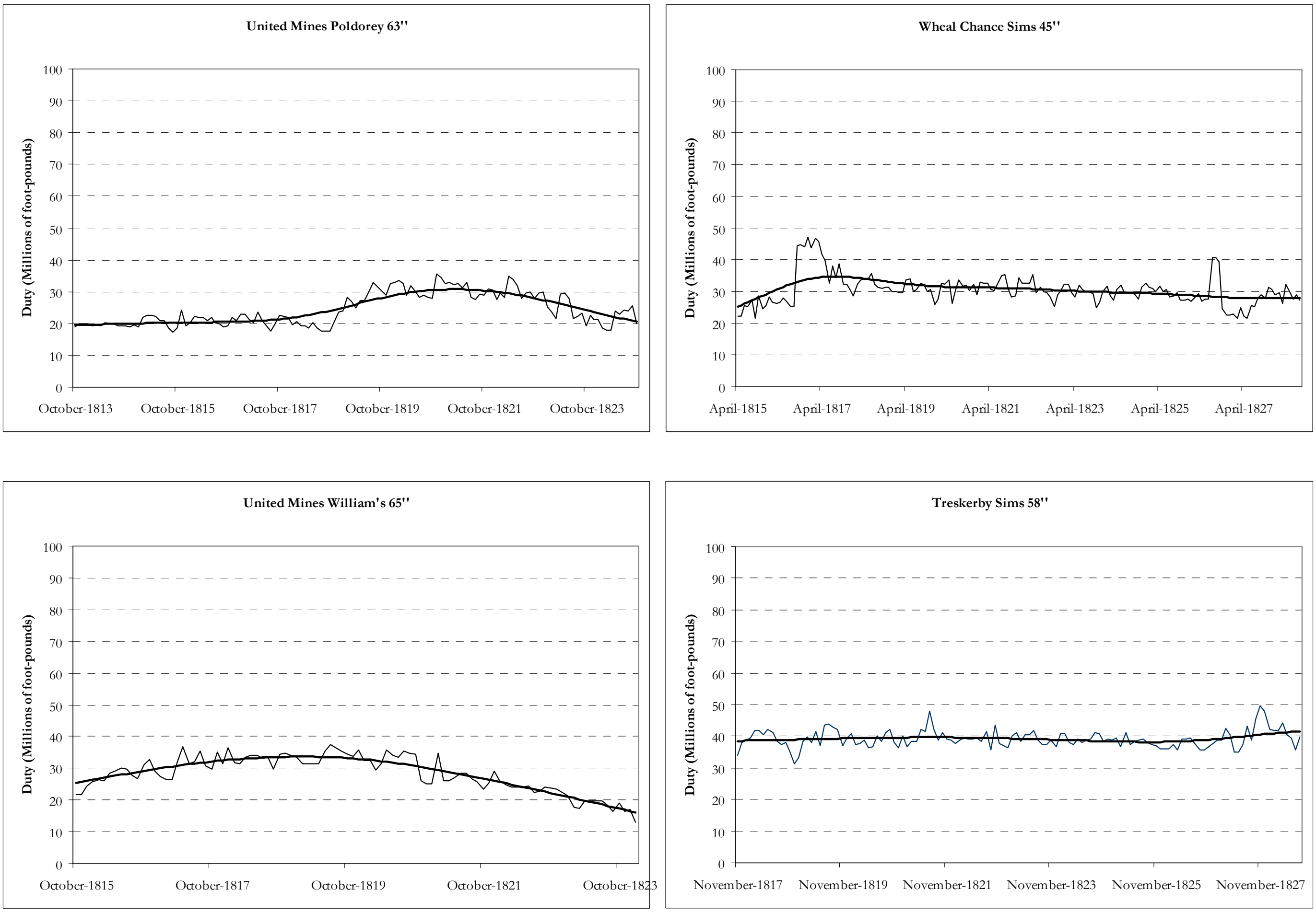

Figure 7.11: Duty of Cornish engines (William Sims compound design)

Source: *Lean's Engine Reporter*

As mentioned in the previous chapter, during the emerging phase of the new "high pressure" paradigm it was not clear which design between the single cylinder and the compound was to be preferred. In 1825 a critical test was carried out at Wheal Alfred mine where two new and fully comparable engines were installed by Arthur Woolf. The duty of the two engines (Wheal Alfred Woolf 70” (compound 40” and 70”) and Wheal Alfred Taylor 90”) is given in figure 7.12. As is apparent, during the year 1825, the two engines scored a similar duty (slightly above 40 millions). On the grounds of its reduced cost and easier of maintenance the single cylinder was favoured, becoming the predominant design in Cornwall.

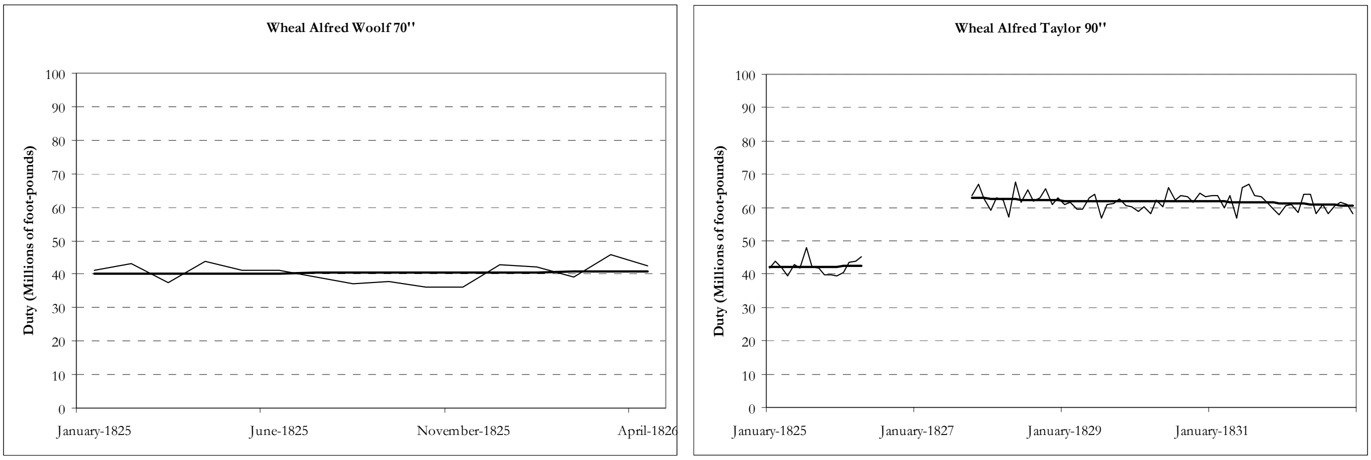

Figure 7.12: Duty of Cornish engines (the test at Wheal Alfred mine)
Source: *Lean’s Engine Reporter*

The single cylinder design was further improved in the mid 1820s by Samuel Grose who took care of carefully “clothing” steam pipes, cylinders and boilers in order to avoid all possible heat losses. Figure 7.13 shows the duty of two engines designed by Grose and incorporating the new clothing system.

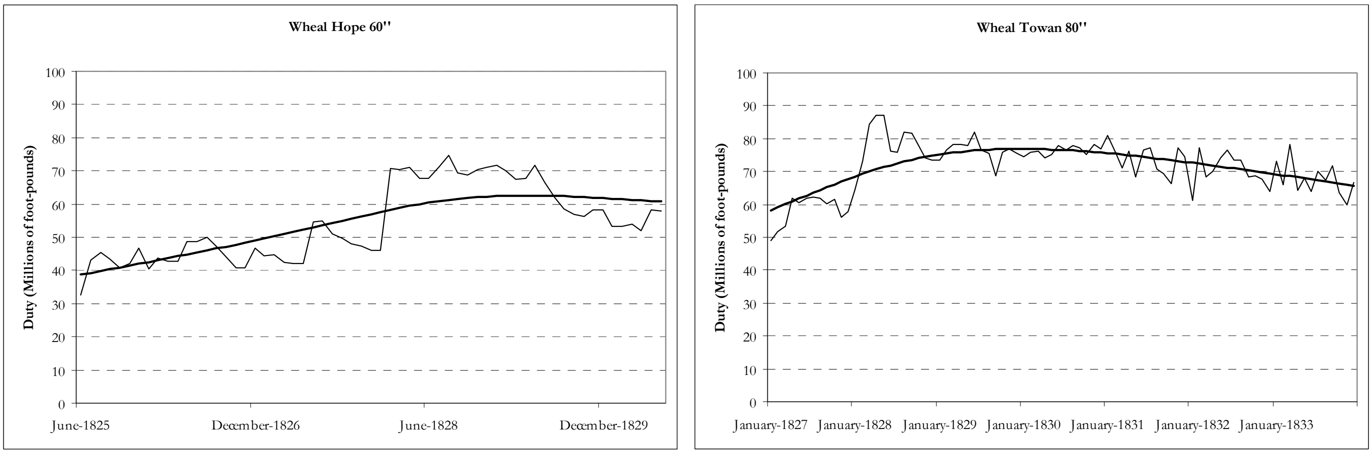

Figure 7.13: Duty of Cornish engines (engines designed by Samuel Grose)
Source: *Lean’s Engine Reporter*

Wheal Hope 60” was the first engine embodying these relatively minor modifications, which nevertheless, determined a drastic improvement in the duty (above 60 millions). Encouraged by the performance delivered by Wheal Hope 60”, Grose adopted similar practices of heat conservation in Wheal Towan 80” engine, achieving further gains in duty (above 80 millions).

In this respect, it is interesting to note the behaviour of Wheal Alfred Taylor 90” displayed in figure 7.12. This engine was originally installed at the Wheal Alfred (it was the single cylinder engine used in the test between the single and compound design). In October it was transferred at Consolidated Mines where it was renamed as “Woolf”.

Woolf took the opportunity of the reinstallation of the engine for incorporating the clothing system ideated by Samuel Grose (Barton, 1965, pp. 46-47). This accounts for the sharp performance jump exhibited by the time series. This example also well illustrates the role played by *Lean's Engine Reporter* in permitting the prompt identification of the most fruitful pathways of technical advance. This example also shows that, at least to some extent, a number of innovations could be "retrofitted" into existing engines. Thus, operations of maintenance or the transfer of a steam engine from one mine to another were occurrences that the engineers could exploit for "upgrading" existing machines.

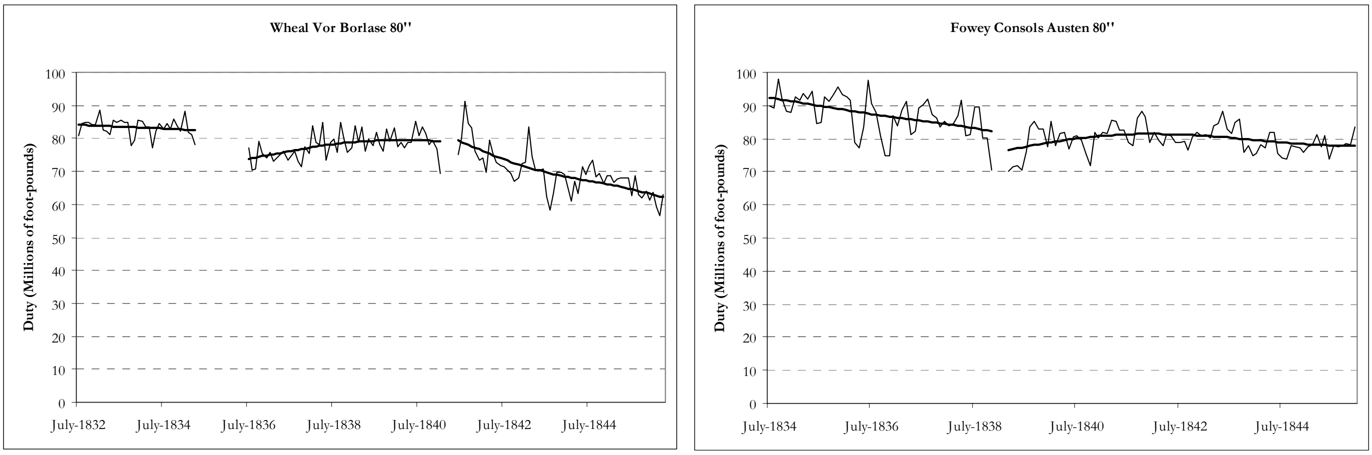

Figure 7.14: Duty of Cornish engines (the 1830s)
Source: *Lean's Engine Reporter*

Grose's practices were quickly and widely adopted. Additionally, from the early 1830s, Cornsih engineers also increased the ratio of expansion further. This led to a additional "spurt" in duty growth, so that, in this phase, it was not uncommon for engines newly erected to score duty above 80 millions. Fowey Consols Austen 80" erected by William West in a trial in 1835 reached the record duty of 125 millions (Lean, 1839, p. 100). Wheal Vor Borlase 80", another engine designed by Thomas Richards can also be considered as an engine typical of this period (Barton, 1965, p. 49).

In the late 1830s James Sims attempted to revive the compound principle. [11] The Carn Brea 90" (cylinders 50" and 90") displayed in figure 7.15 was the most successful engine on Sims' compound design. In this phase, the main competitors of James Sims were Hocking and Loam (the successors of Woolf in the mines managed by JohnTaylor). Figure 7.15 gives also the duty series of United Mines Taylor 85" the most successful engine designed by Hocking and Loam and the only one to score duties above 100 millions in *Lean's Engine Reporter*. By the early 1840s the Cornish engine had probably reached its practical limits, so one can consider this period as the maturity phase of the technological trajectory. Carried to the extreme, the principle of expansion produced an extremely powerful shock to the piston and to pitwork at each opening of the steam valve. Such an operating cycle was likely to increase the probability of breakages in the pumps and their supports and to accelerate the wear and tear of the engine (Barton 1969, pp. 57-58). In fact, the main motivation behind James Sims' elaboration of a new compound design was not the search for further fuel economies, but the need of finding a remedy to the strain that large engines were putting on the pitwork. Both Sims' design and the competing solution proposed by Hocking & Loam (a circular protuberance in

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[11] James Sims was the son of William Sims. In his compound design the small high-pressure cylinders was put above the low pressure one. In the Woolf design the two cylinders instead were put side by side.

the piston which was fitted in a corresponding cavity in the cylinder top) did not encounter much success (Pole, 1844). The series reported in figure 7.14 seem indeed to suggest the occurrence of a number of breakdowns both for the Carn Brea and for the United Mines Taylor engine.

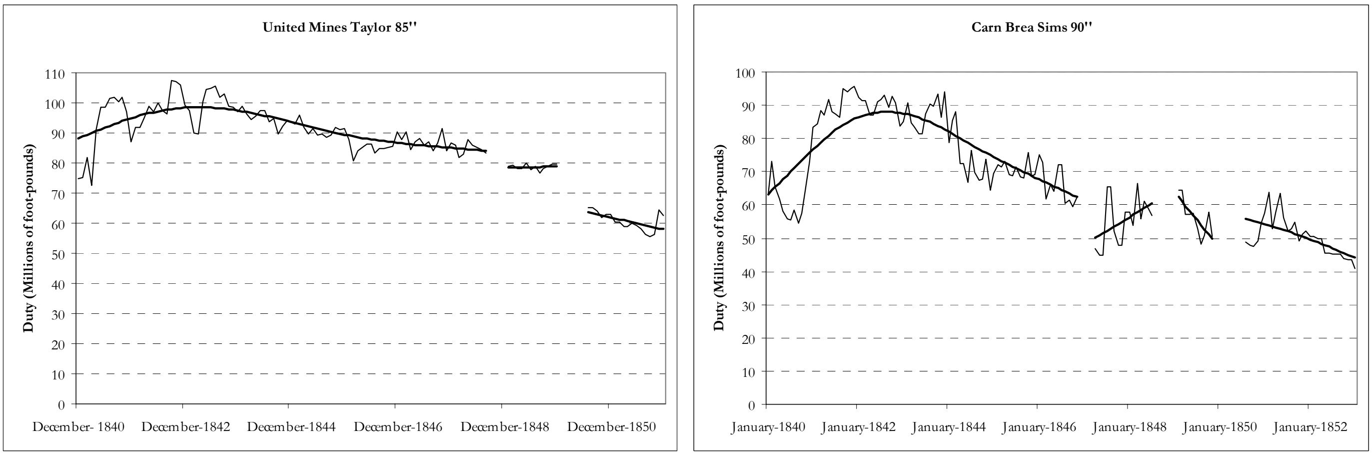

Figure 7.15: Duty of Cornish engines (the maturity phase)
Source: *Lean's Engine Reporter*

Figures 7.9-7.15 allows us to shed some light on some features on the process of learning by using arising from the actual operation of each engine. According to John Farey (1971, p. 211; see also von Tunzelmann, 1970, pp.85-86) the typical life cycle of the duty of a Cornish engine, in general could be seen as characterized by an inverted U shape pattern. In the first period of operation the duty of the engine tended to rise steadily. This was due to the fact that this period was a phase of particularly intensive learning by using. A good deal of this accumulated experience was idiosyncratic (i.e., engine-specific), essentially amounting to find the optimal way of dealing with the specific "quirks" of each engine. In particular, Farey (1971, p. 85) individuated two factors accounting for initial duty rise:

1) some time of actual operation was necessary in order to individuate and remedy to leaks in the engine and in the boilers and/or to correct other eventual deficiencies arisen in the construction and erection of the engine.[12]
2) improved operation of the engine stemming from learning by using process: in particular, it was necessary to accumulate experience concerning:
    i) the managing of the fires and dampers;
    ii) the size of the fire grates and the number of boilers to be worked at once;
    iii) the regulation of the feeding of the boilers;
    iv) the best management of the cleaning of the boilers;
    v) the best level of steam pressure in the boiler;
    vi) the best ratio of expansion (determined by the cut-off point) at which the engine (given a particular load in the pumps) was to be operated.

The increase of duty by means of this process of learning by using at the engine level progressively run into diminishing returns and it was finally offset by physical wear and

[12] Von Tunzelmann (1970, p. 85) also suggests that "in this period of rather primitive lubricants" an initial phase of operation was necessary in order to permit to irregular rubbing surfaces to wear themselves smooth.

tear, producing an inverted U shape pattern of duty evolution. The main sources of physical deterioration identified by Farey (1971, p.85) were:

1) the wearing out of pumps, engine and pitwork causing "derangements" which negatively affected the performance delivered by the engine. [13]
2) leaks in boilers.
3) wearing out of boilers plates which meant that steam pressure had to be reduced for safe operation.

Additionally, as the mine deepened, an increasing load was charged on the engine and this was likely to force the engine to operate at a sub-optimal rate of expansion.

In general terms, inspecting figures 7.9-7.15, one does not find generally a clear corroboration for the inverted U shape pattern hypothesized by Farey (although some of the engines may be said to fit that pattern). In our interpretation, the inverted U shape pattern is to be understood as a "notional" pattern of duty evolution. In particular, one has to take into account that during the life time an engine was subjected to a series of repairs and others modifications, which could affect its performance. Hence, most engines exhibit a wave-like behaviour. Repairs and modification determined alternating phases of duty increases and declines.

7.4. Accounting for duty growth

It is possible to employ the data contained in *Lean's Engine Reporter* to try to assess the relative importance of the various "proximate" factors responsible for duty growth. The term "proximate" is used here to indicate that the we are concerned with the *direct* sources of average duty growth. In case of Cornish engines, average duty growth may be considered as an indicator of the overall rate of technical progress in Cornish steam engineering. As discussed at length in Soete and Turner (1984), the rate of technical progress may be considered as composed by two main components: the first one is the rate of improvement of already installed pieces of capital equipment (disembodied technical change), whereas the second component is the rate of "embodied" technical change. This consists in the introduction of new pieces of equipment embodying the latest technological developments.

In this spirit, the accounting exercise carried out here examines the behaviour of different segments of the engine population (more specifically we distinguish between existing and new engines) and estimates their relative contribution of each segment to average duty growth. As we have seen in the previous section, technical innovations could, to some extent, be retrofitted into existing engines.

In his study of the Cornish pumping engine von Tunzelmann has emphasized the role played by the continuous upgrading of installed capacity:

> It would be incorrect to suppose that because the steam engine was a large fixed item of capital investment, technical progress could be achieved only by being incorporated in new engines. Practically all the advances mentioned required at most the replacement of a small portion of the engine. For instance, Watt engines could be converted to high-pressure engines by strengthening the steam case and boilers and modifying the

[13] Leaks in the pumps, amounting to a reduced load could, at least, potentially also have a positive effect on duty. However, in most cases, the deterioration of the pitwork also meant that steam pressure had to be reduced to avoid the risks of breakdowns.

valves. This phenomenon is still more marked for the later improvements – lagging the pipes, etc. involved non necessary interference with the machinery…..[T]he relatively inconspicuous nature or even disembodiment of the technical changes accounts for their diffusion being unduly rapid…In the case of engines on the Cornish plan, there is little doubt that the adoption of greater expansion, superheating, and the like, proceeded at a rate relatively unhindered by the weight of equipment operating under the previous technology with lower fuel economy. (von Tunzelmann, 1970, pp. 93-95).

The analytical tool to be used for the identification of the proximate sources of duty growth resembles the decomposition exercises which, in the industrial economics literature, are used to single out the contributing factors of productivity growth in "longitidunal" data sets (see Bartelsman and Doms, 2000 for an overview).

In our case, the weighted average duty in a given year is given by:

$$(1) \qquad \overline{D}_t = \sum_{i=1}^{N} S_{i,t} D_{i,t}$$

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

Using the following decomposition formula[14] it is possible identify the main contributing factors underlying the rate of aggregate duty growth:

$$(2) \qquad \frac{\Delta \overline{D}_t}{\overline{D}_{t-1}} = \frac{\sum_{i \in C} (D_{it} - D_{it-1}) S_{it-1}}{\overline{D}_{t-1}} + \frac{\sum_{i \in C} (S_{it} - S_{it-1})(D_{it-1} - \overline{D}_{t-1})}{\overline{D}_{t-1}} +$$

$$+ \frac{\sum_{i \in C} (S_{it} - S_{it-1})(D_{it} - D_{it-1})}{\overline{D}_{t-1}} + \frac{\sum_{i \in N} (D_{it} - \overline{D}_{t-1}) S_{it}}{\overline{D}_{t-1}} - \frac{\sum_{i \in X} (D_{it} - \overline{D}_{t-1}) S_{it}}{\overline{D}_{t-1}}$$

In the formula C represents the set of "continuing" engines, N the set of new engines (i.e., engines installed in year t) and X the set of "exiting" engines (i.e. engines active in year $t-1$ that were scrapped in year t).

The first term on the right hand side represents a "within" engine component weighted for the initial share. The term captures the more efficient operation of installed productive capacity (arising from learning by using or from technical improvements that were retrofitted to existing engines, etc.). In other words, this term measures the change of performance of the "continuing" engines. So whenever the physical deterioration of the engines is not counterbalanced by maintenance and repairs and by the "disembodied" component of technical change, the term will assume a negative value.

The second term on the right hand side represents a "between" engine component (also called "static shift" effect). This term reflects the increase of the average duty due to the

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[14] The formula we have adopted here is the "preferred" decomposition employed by Foster, Haltiwanger and Krizan (1998). Other decompositions can be envisaged, but, as we shall see, in the present context, the formula proposed by Foster, Haltiwanger and Krizan seems to be particularly indicated.

reallocation of the installed capacity from worse to better engines (or vice versa). Note that the term is expressed as deviation from the mean. Overall, this term can be considered to reflect the degree of efficiency in the management of the existing engine park (an effective management of installed productive capacity would require to the most efficient engines to deliver more horsepower).

The third term on the right hand side represents what might be called a "dynamic" shift effect and it captures the growth of the average duty determined by the reallocation of productive capacity towards more "dynamic" engines, that is engines endowed higher duty growth rates (note that the "between" engine component reflects the reallocation of capacity towards engines with higher duty *levels*). Also this term can be seen as representing a technology management aspect.

The fourth term on the right hand side measures the improvement of the average duty due to the installation of new capacity (introduction of new engines). Note that the term is expressed as a deviation from the mean, so, to give a positive contribution to average duty growth, a "new" engine should perform a higher duty than the average duty of the previous period. It should be noted that, because engines were often moved from one mine to another, in some cases, it is difficult to identify whether an engine that appears in the columns of the *Reporter* is new or an existing engine transferred from another mine. This can bias the results of the decomposition exercise, introducing an overestimation of the "entry effect" and an underestimation of the "within" effect.

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

Figure 7.16 reports the results of the decomposition exercise. We have considered seven years intervals. In the figure the histograms indicate the magnitude of the various contributing factors in each interval. The total effect (equal to the rate of growth of average duty) is indicated by the thick black line.

The first three intervals 1814-1821, 1821-1828, 1828-1835 represent the phase of duty growth. In this phase the predominant contribution to duty growth is given by the "entry" effect (installation of new engines). The "within" engine effect is also positive, indicating the existence of possibilities for improving ("upgrading") existing engines.

In fact, our results indicate that - although the "upgrading" of installed engines, throughout the years 1814-1835 gave a positive contribution to duty growth - the *major* driving factor accounting for duty growth was represented by the installation of new engines.[15]

[15] As noted above, our estimation of the "entry" effect can contain some upwards bias to the detriment of the "within" effect. However, for each of the three periods 1814-1821, 1821-1828, 1828-1835, the estimated magnitude of the "entry" effect is more than two times the "within" effect, leading us to conclude that, notwithstanding some possible overestimation, our decomposition is probably correct in the determining the relative contribution of the two effects. This result is indeed consistent with the considerations contained in Soete and Turner (1984) which hold that when there is a large variation in performance across technologies, the contribution stemming from the installation of new pieces of capital equipment is likely to represent the major component of the overall rate of technical progress. As we have seen in the previous chapter, over the period 1810-1840 the development of the Cornish engine was characterized by three "big" spurts in which the distance between best practice and average practice grew

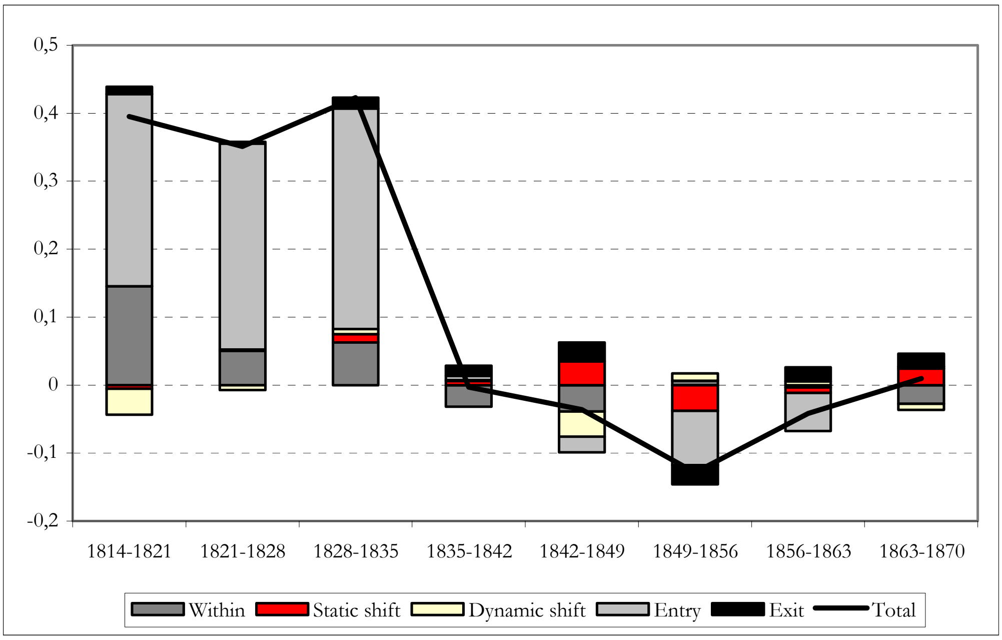

Figure 7.16: Decomposition of average duty growth

It also should be noted that the within effect is particularly strong in the years 1814-1821, which is the period when William Sims converted to compounds a number of existing Watt engines. However Farey noted that the comparisons of the performance of new engines with the upgraded low pressure ones made during the 1810s induced most mine entrepreneurs to favour the installation of new engines:

The results of all altered engines, compared with those of the new engines at Wheal Abraham and at Dolcoath showed the miners that there would be far more advantage in having entire new engines, than in making any considerable alterations in their old engines (Farey, 1971, p. 188).

The static and dynamic shift effect, through out all the period 1814-1870, appear to affect duty growth in a relatively minor way. This can be perhaps accounted for by the existence of "rigidities". That is to say, there was rather narrow scope for adjusting the horsepower delivered by the engine, once this was installed.

The period 1835-1870 is the phase of "climacteric" in the historical evolution of the duty. Again, the major contributing factors to (negative) duty growth are the "within engine" effect, which shows a deterioration of installed capacity (this may well be a consequence both of the decline in the quality of coal used and of a diminished rate of expansion) and the "entry" effect. Note that since the entry effect is taken in deviation from the mean, this means that new engines tended to have *lower* duty than the average of the installed capacity.

7.5. Conclusions

As stressed in the previous two chapters, the process of "learning from others" among engineers represented a powerful driver of technical progress in Cornish steam engineering. In this chapter we have examined in detail in this aspect of the process of technical change and we have argued that is possible to consider the Cornish engineering

considerably leading to a high dispersion of the performance across the installed pieces of capital equipment.

community as composed by two groups of agents, the "innovators" and the "imitators". Innovators were engaged in the exploration of new areas of the space of technological opportunities. In a second phase, these discoveries were integrated into average practice engines by the group of "imitators".

The innovations discovered in this search process could have either a disembodied or an embodied character, although as remarked by von Tunzelmann (1970) the distinction between the two types of technical change was actually rather blurred. Many components of installed during the lifetime of an engines were replaced or upgraded (especially when the engines was moved from one mine to another)

In the previous section we have carried out a decomposition exercise with the aim of assessing the relative contribution of disembodied and embodied technical change to overall duty growth. The decomposition exercise has revealed that although sizable the contribution of the disembodied component technical progress was relatively minor when compared with the installation of new engines. The major driver of increased performance was instead constituted by embodied technical progress. New engines (in the period 1814-1835) were consistently characterized by higher duty than existing capacity.

The available evidence also suggests that design modifications were *first* experimented on new engines and, when crowned with success incorporated into existing equipment. Thus, in the 1810s Woolf's compound arrangement was retrofitted into existing engines by William Sims. Similarly, the "clothing system" introduced by Samuel Grose in the new engines of Wheal Hope and Wheal Towan were progressively adopted into existing engines. Note, that, in principle, also the opposite behaviour would have been possible namely, first experimenting design modifications on existing machines and then erecting new engines embodying those changes that had proven successful. However, the installation of a new engine probably represented a more suitable occurrence for the introduction of innovations than the operations of maintenance of an existing engine. In the latter case, the pumping necessities of an operating mine made prolonged stoppages of the engine a particularly undesired option, highly restricting the scope for experimenting innovations in existing machinery. Hence, the installation of new engines incorporating innovations was somewhat a prerequisite for triggering a positive contribution to duty growth from the "within" effect.

Although they can be easily distinguish at a conceptual level, it is clear that the learning by processes described in this chapter ("learning from others", "learning by using" and "innovative investment") overlapped and fed back upon each other. Indeed, a key aspect of innovative aspects in Cornish steam engineering was the *complementarity* between the three learning processes described in this chapter. In other words, the development of the Cornish pumping engine appears to have been characterized by a rather complex type of innovation process, stretching for about thirty years (from 1812 to the early 1840s), and propelled by the mutual interaction between the driving forces individuated in this chapter.

7.A.1 The Hodrick-Prescott filter

The Hodrick-Prescott (or Whittaker) filter is a smoothing method which provides an estimation of the long term component of a series.[16] Assume that x_t (with $t = 1,2.......T$) is the original time series. The estimation of the long-term trend ($\bar{x}_t$) is obtained by minimizing the following function

(A.1) $$\sum_{t=1}^{T}(x_t - \bar{x}_t)^2 + \lambda \sum_{t=2}^{T}[(\bar{x}_{t+1} - \bar{x}_t) - (\bar{x}_t - \bar{x}_{t-1})]^2$$

The function minimizes the variance of x_t around $\bar{x}_t$ (first term) subjected to the constraint that the estimated value should not be too "distant" from the rest of the trend (second term). The parameter λ controls the "curvature" of the trend (as $\lambda \longrightarrow \infty$, $\bar{x}_t$ approaches a linear trend). In our estimation we have used $\lambda = 14400$ as is conventional for monthly economic series. The estimates shown in figures 7.9-7.15 were robust to variations of the parameter over the range 14000-16000.

[16] Hodrick and Prescott (1980) is the original reference.

PART IV. CONCLUSIONS

8. The Making of Steam Power Technology in Retrospect

8.1. Introduction

So far we have considered a number of issues related with the "making" of steam power into a major industrial technology in the eighteenth century and early nineteenth century. In particular, the history of steam engine technology has been examined at two different levels of aggregation. In part II (chapter 3 and chapter 4) we have adopted a broad perspective considering the whole range of innovative activities in steam engineering during the eighteenth century. In part III (chapter 5, 6 and 7) we have narrowed down our focus and considered in detail the application of steam power technology in the Cornish mining district. The aim of part III was to provide a historically "contextualized" interpretation of steam engineering activities in the early nineteenth century.

This concluding chapter has a twofold purpose. First, we will provide a concise summary of the main research findings of our inquiry and point to possible directions where further research seems to be needed. Second, we will put forward some (admittedly highly conjectural) hypothesis concerning the wider economic impact of steam engine technology. In the first chapter we have noted that economic historians have frequently emphasized that the development of steam power technology was at the root of major economic and social transformations of modern industrial economies. Thus, it seems appropriate in the conclusion, to go back, at least briefly, to the "grand theme" of the economy-wide repercussions of steam technology and to consider what implications the findings our research bear upon this question. Before doing that however, it seems appropriate to highlight some methodological issues surfacing from the present study.

One characteristic which is common to all the previous chapters is their use of quantitative evidence. The findings presented in part II are based on the examination of a data-set containing information on the steam engines erected in Britain during the eighteenth century originally collected by Kanefsky and Robey (1980). The results in Part III rest on the analysis of the data contained in a contemporary steam engineering publication, *Lean's Engine Reporter*.

Indeed, at a methodological level, the main ambition of this work has been to demonstrate the fruitful combination of what might be called the "traditional" approach to economic history and history of technology (retrieval and careful investigation of contemporary sources) with the methods characteristic of the so-called "new economy history". Broadly speaking, the "new economic history" revolution was based on two main methodological prescriptions (McCloskey, 1978). The first one was the emphasis on the systematic collection of quantitative data that could capture various dimensions of the phenomenon investigated, whereas the second was the interpretation of the historical evidence by means of the formal testing of hypothesis and models. Concerning this latter feature, one may note that, in the most "extreme" formulations (McCloskey, 1978 can be taken as representative of this point of view), the distinguishing feature of the "new economic history" was the systematic use of mainstream neoclassical economics for the explanation of the economic record of the past.

As technological change typically takes place in what we may call structurally uncertain environments, we would maintain that the reliance on the neoclassical framework has severely restrained both the scope and the depth of the contributions that the new economic history could offer to the history of technology.[1] Over the last twenty years a growing number of studies has argued that the use of models based on the assumptions of agents engaged in the solution of optimisation problems over a well-defined choice-sets will *per force* generate results with very restricted interpretative power when applied to the study of technology and innovation. Furthermore, at a more fundamental level, it is possible to argue that the concern of neoclassical models with timeless "equilibrium positions" (or "steady states" type of outcomes) favours the production of results that are *inherently* endowed with a profound *a-historical* character. As was cogently pointed out by Joan Robinson (1974, 1980), the "comparative statics" type of exercises carried out in neoclassical models pertain to *reversible* processes taking place in logical time and not in history.[2] Historical processes will typically display irreducible irreversibility features. Over the last twenty years, following the seminal contributions of Arthur and David, there has been a growing appreciation of the path-dependent nature of economic evolution[3] and recently one has begun increasingly to see examples of models representing various aspects of economic change in terms of dynamic irreversible processes (for a recent overview of these contributions, see Castaldi and Dosi, 2004). In this respect, one particularly challenging research direction in the field of the economic history of technical change that is possible to envisage, is the adoption of models characterized by a genuinely historical type of dynamics.[4] This is indeed a major research undertaking that will probably require the same amount of energy and creativity that the first generation of "new economic historians" put in their contributions.

This work can be seen as moving some exploratory steps in this direction. We have sketched an historical reconstruction of some critical moments of the development of steam power technology. With respect to the existing historical literature on steam technology, we have paid a great deal of attention to the microeconomics of the innovation processes. In particular, in our interpretative efforts, we have tried to suggest some possible links between our findings and the sets of hypotheses adopted in various evolutionary models of technical change.

As it happens, in this work, we have refuted the methodological recommendation of the "new economic history" invoking the adoption of mainstream neoclassical economics as interpretative framework; but, on the other hand, we have accepted the prescription concerning the importance of "quantification". As McCloskey (1978, p. 18) puts it,

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[1] This may sound as a particularly harsh judgement considering that some of the most influential works of the new economic history were expressly devoted to the analysis of nineteenth century episodes of technological change (e.g. Fogel and Fishlow on the economic impact of American railways, Harley on the diffusion of the steamboats, McCloskey on the choice of technology in the British iron and steel industry, David on the diffusion of the reaper and on the processes learning by doing in the American cotton industry). In this respect, the analysis of the limitations of the neoclassical analytical framework contained in David (1975, pp. 1-16) constitutes a particularly revealing "soul-searching" reflection.

[2] For a thorough discussion of Joan Robinson's views on this fundamental issue, see Harris (2004).

[3] A lucid discussion of the various path-dependent features of technological learning is contained in Rosenberg (1994, pp. 9-23).

[4] A similar point is suggested in von Tunzelmann (1990). The potentialities of an evolutionary approach for the (economic) history of technology are thoroughly discussed in Mokyr (1990, ch. 11) and Mokyr (1996).

"counting" is indeed indispensable if one aims to give meaningful answers to critical historical questions such as "how large ? how long ? how often ? how representative ?".[5]

It must be recognized that, in the field of the history of technology, the use of quantitative evidence is of vital importance if one aims at attaining an accurate historical reconstruction of the pattern of technical progress. In particular, since - in most historical cases - more technological options were, at least conceivably, feasible, the historian is often puzzled with questions concerning the relative merits and shortcomings of alternative technological solutions. This should lead to consider with particular attention engineering publications and other contemporary sources dealing with the assessment of technological performance in various circumstances. Of course, this also raises interesting issues concerning the social character of the "construction" of these performance indicators adopted by the relevant community of technological practitioners. Another dimension of technological evolution, in which the use of quantitative data is clearly indispensable, is the study of technology diffusion. Traditionally, historians of technology have paid most of their attention to the process of "invention". In this respect, the existing literature on steam technology with no more than a handful of contributions[6] aimed at documenting and describing the precise pattern of diffusion of the technology represents a typical case. The case of steam technology, also shows clearly that the neglect of diffusion can lead to major misjudgments (as the case of Rostow's analysis of the British industrial revolution discussed in chapter 1) when one is called to formulate periodizations dealing with the historical transformation of the production systems (see Rosenberg 1976, pp. 189-191; for discussions of this issue in the context of the development of steam technology, see Hunter, 1975 and Greenberg, 1982).

However, the research compass in the economic history of technical change must go beyond the retrieval of quantitative data and their analysis. As agents engaged in inventive activities rarely fully comprehend the set of alternatives they are confronted with, in the formulation of historical explanations it is necessary to reconstruct both the *context* and the *perspectives* of the various individuals and groups involved in the process of technical change. Of course, this exercise calls for a careful examination of primary sources (not only those of quantitative nature) and contemporary commentaries. In the light of what we have said so far, this exercise (which, in certain cases, we are more than happy to admit, may indeed require virtues of historical "empathy") is of critical importance for the proper characterization of the micro-behaviours of the different actors underlying the process of technical change.

[5] This set of questions was originally formulated by Sir John Clapham: "…every historian should have acquired…the habit of asking in relation to any institution, policy, group or movement the questions: how large ? how long ? how often ? how representative ?" (cited in Coleman (1987), pp. 77-78).

[6] Here one can mention the works of Hunter (1985) dealing with the US, Kanefsky (1979) and von Tunzelmann (1978) with Great Britain, Van Neck (1979) with Belgium and Bardini (1998) with Italy. All these works have produced conjectural estimates of the extent of usage of steam power in various periods, but much remains to be done. Concerning the British case, one might observe that, notwithstanding the painstaking efforts of Kanefsky (1979), the precise contours of the diffusion process of steam technology in various application sectors during the first half of the nineteenth century are still uncertain. Correspondingly, much work is still to be done on the identification of the driving forces underlying the process of technological diffusion.

8.2. Technological revolutions and economic growth

On reflection, the current understanding of the relationship between technical change and economic growth appears to have been profoundly influenced by the model of economic development that Schumpeter presented in *Business Cycles*. As is well known, Schumpeter proposed that the economic history of capitalist economies was characterized by long (Kondratiev) waves of development, that is to say by historical phases in which economic growth is rather robust and sustained, intertwined with periods in which the growth process is relatively sluggish and the overall economic performance (in terms of productivity growth, unemployment, etc.) of the system is far from satisfactory. In Schumpeter's view, this cyclical pattern of development was due to the clustering of basic innovations at particular moments of time. In his book, Schumpeter illustrated how the uneven appearance of the clusters of basic innovations (reinforced by a bandwagon effect of minor collateral innovations) could generate upswings which became progressively exhausted producing a wave-like pattern of economic growth.

Few exceptions aside, from the 1950s to the mid of the 1970s, Schumpeter's view of economic development was neglected in the mainstream economic literature. Not surprisingly, the long-lasting economic performance of the post war period led most economists to consider a rather different perspective for the study of economic growth.
In the orthodox view of the time (epitomized in the Solow model), the process of economic growth proceeded smoothly at a stable growth rate. Also in the Solow model, technical change was reckoned as the key driver of economic growth, but it was considered to be the outcome of autonomous developments in science and technology and, accordingly, treated as an exogenous factor. Interestingly enough, in stark contrast with the Schumpeterian view, it was posited that technological progress was characterized by a constant time-drift. In a nutshell, the Solow model illustrated how the constant rate technical progress produced a stable and constant rate of economic growth.

In the second half of the 1970s, Schumpeter's perspective on economic development was revived in several contributions (for a review of this literature, see Silverberg and Verspagen, 2003). Mensch (1979) suggested, on the basis of the examination of new empirical evidence of time series of major industrial innovations, that major innovations exhibited a tendency to cluster in the depression phase of the long waves of economic growth (i.e., the 1830s, the 1880s and the 1930s). It was the progressive exploitation of this bunching of innovations to trigger a new economic upswing. According to Mensch, in the downswing of the long wave, firms, faced with dismal economic prospects, were more inclined to bear the high risks related with the introduction of major industrial innovations. In the long wave literature this will become known as "depression-trigger hypothesis". Kleinknecht (1987) further contributed to this line of research by producing further empirical evidence in support the depression-trigger hypothesis.

These research findings were criticised by Freeman, Clark and Soete (1982). Although, these scholars were highly sympathetic towards the Schumpeterian theory of long waves, they argued that the purported link between the temporal clustering of basic innovations and the long wave of economic development was highly questionable. In their view, when the historical record is carefully examined, it appears that the period of rapid economic growth of the long wave is not driven by innovations introduced in the previous downswing. Rather, Freeman, Clark and Soete (1982) contended that, if they display some clustering tendency at all, major innovations tended to concentrate in the upswing peak of the long wave.

According to Freeman, Clark and Soete (1982), the connection on which it was necessary to focus the attention was not the one between the dates of individual major inventions and the downswing or upswings of the long wave, but the one linking the *diffusion* of major innovations to the overall pattern of economic growth. Since the diffusion of major innovations suffered from prolonged and variable delays, the empirical identification of clustering of innovations in time series of major innovations could not be considered as a sound foundation for a technology-based long wave theory of economic development. Further support for this view of the spurious role of the temporal clustering of innovations for the formulation of a long wave theory of economic change was provided by Silverberg and Lehnert (1993). Silverberg and Lehnert (1993), by means of a simple dynamic model of capital accumulation, demonstrated that a long wave like pattern of economic growth could emerge even if the generation of new technologies had been characterized by a time homogeneous Poisson arrival process.

Over the last twenty years, Chris Freeman, in a number of contributions, written in collaboration with various co-authors such as Luc Soete, Carlota Perez and Francisco Louca, has proposed a new theory of long waves fuelled by technical change. The fundamental building block of Freeman's theory is the notion of technological system or techno-economic paradigm. With this term, Freeman indicates a "constellation" of innovations characterized by strong technological and economic linkages (mainly between materials, machinery, power systems and final products). One can think as a possible example to the interdependencies and complementarities between machine-tool technology, steam engine and iron and iron producing techniques during the British industrial revolution). These "technological systems" are endowed with a high degree of *pervasiveness* in the sense that they can be applied in a wide range of industrial activities. The long term evolution of capitalist economies, according to Freeman, has been characterized by the implementation of a succession of these pervasive technological systems. Furthermore, the implementation of each "new technological system" triggers deep changes in the organization of production, determining a fundamental restructuring at the level of the whole production system:

> Such discontinuities have long been familiar to archaeologists with their taxonomies of 'Stone Age', 'Bronze Age', 'Iron Age'. We shall argue here that there is justification for a similar approach to the far more rapidly changing and complex technologies of industrial societies…[Accordingly], it has been common parlance for a long time among historians to use such expressions as the 'age of steam' or the 'age of electricity', even only for convenient descriptive periodization…..[In our view] this type of taxonomy is needed not just for convenience, but because it enables us to develop a better understanding of the successive patterns of change in technology, in industrial structure, and, indeed, in the wider economic and social system (Freeman and Louca, 2001, p. 142).

In other words, Freeman puts forward a theory of long waves of economic development formulated in terms of large-scale technological transitions between different technological systems. This framework of analysis is employed by Freeman in an account of the economic development of capitalist economies since the British industrial revolution (see Freeman and Louca, 2001).

Remarkably, one of the most recent developments in neoclassical theorizing on economic growth (see the essays collected in Helpman, 1998) has been the attempt of formulating models which incorporate some key-ideas of the view of the process of economic growth originally proposed by Freeman and his associates.

This family of new neoclassical models has introduced the notion of "general purpose technology" (GPT), which is, in many respects, analogous to Freeman's concept of "technological system". In the original formulation proposed by Bresnahan and Trajtenberg (1995), GPT are defined as technologies with three salient characteristics:

i) they perform some general function, so they can be employed in a wide range of possible application sectors,
ii) they have a high technological dynamism, so that the efficiency with which they perform their function is susceptible of being continuously improved,
iii) they generate "innovation complementarities", that is to say that their adoption stimulates further rapid technical progress in the application sectors.

Steam power, electricity and information and communication technologies are most frequently put forward as clear-cut examples of GPTs. It is worth noting that GPT growth models retain the traditional neoclassical micro-foundations based on perfectly rational agents and equilibrium interactions. [7]

A particularly interesting aspect of this class of endogenous growth models is that they generate patterns of growth that are characterized by episodes of acceleration and deceleration determined by the implementation of successive GPTs, producing on a long time scale a wave-like profile. More specifically, these models assume that a new GPT requires a rather long period of "acclimatization". Hence, the initial impact of GPT on productivity growth is typically rather "small". This phase of sluggish dynamic of productivity concludes when the GPT is finally fully "acclimatized" in the economic system. Then, the rapid rate of technological change in the GPT and in the application sectors (due to the innovational complementarities of the GPT) produces an increase in the rate of overall productivity growth. Finally, as the scope for further improvements in the GPT is progressively exhausted, this phase of rapid productivity growth will gradually peter out.

Borrowing the expression from Harberger (1998), David and Wright (1999) have suggested that the progressive penetration of a GPT in the economic system triggers a dynamics of productivity growth that is 'yeast-like', in the sense that, spurred by the GPT, productivity tends to grow at the same, uniform and relatively rapid rate in a wide range of application sectors. Vice versa, before the phase of penetration, the dynamics of productivity is instead 'mushroom-like', this means that productivity growth rates tend to be highly idiosyncratic without much correlation across industries. In their paper, David and Wright analyse the development and diffusion of electricity in this perspective, linking the yeast-like behaviour of early twentieth century productivity of US manufacturing with the progressive penetration of the "dynamo" in the economy.

Given the significance of these recent developments in the theory of economic growth, it seems useful, while summarizing the main findings of our inquiry, to devote some space to briefly discuss the implications that they bear upon the conceptualisations of the economic growth process discussed in this section.

[7] In what follows we will consider the two models proposed by Helpman and Trajtenberg (contained in Helpman, 1998) as representative examples of the neoclassical literature on general purpose technologies.

8.3. The economic history of steam power technology

The perspective that we have suggested in this work maintains that the evolution of steam power technology over the period 1700-1850 was characterized by two distinct technological paradigms. The first one can be labelled as the "low-pressure" paradigm. This paradigm was established by Newcomen and Watt's inventions. The layout of Newcomen's engine (piston/cylinder apparatus coupled with the rocking beam) became almost immediately the "dominant design" in steam power technology. Watt's invention of the separate condenser (and closed cylinder) opened up the possibility of effectively using steam as the driving agent of the engine. In addition, Watt's experiments consolidated the "knowledge base" of the technology providing a number of effective rule of thumbs for the designing of engines of different sizes and for evaluating their performance.

At the beginning of the nineteenth century, it is possible to identify a marked discontinuity in the procedures of innovation in steam engineering. This rupture can be related to the emergence of the high-pressure paradigm. Note that the discontinuity is not so much related to the material characteristics of the artefact (as we have seen, the design layout of the low pressure and the high pressure steam engine is indeed very similar), but to the body of knowledge (both in terms of "understanding" and in terms of "practice") underlying the artefact. The fact that the discontinuity was related to the cognitive dimensions of the technology was confirmed by our analysis of the delay in the adoption of the high pressure engine which has stressed the "intellectual resistance" in the various engineering communities to the very idea of employing high pressure steam, rather than genuine technical difficulties (see chapter 6, section 6.2).

Concerning the differences between scientific and technological paradigms, Clark (1987) has argued that the latter are *intrinsically* more vulnerable, and for this reason much more unstable than scientific paradigms, as the competition between alternative technological solutions involves a series of continuous tests (validation) for the prevailing paradigm compared with possible alternatives. The competition between the high pressure and low pressure paradigms, which we have examined in chapter 6, instead suggests that social persuasion and legitimisation play a critical role *also* in the competition between rival technological paradigms, so that the emergence of new technological paradigm might also involve a particularly prolonged and delayed process.

The fact that the development of steam power technology was punctuated by paradigmatic discontinuities makes the task of assessing the precise impact of this technology on economic growth particularly difficult. Endogenous growth models such as those proposed by Helpman and Trajtenberg (Helpman, 1998, ch. 3 and 4) consider the emergence of a *single* GPT which is progressively refined and incorporated in user sectors producing an acceleration of the rate of economic growth. If the development of the GPT is characterized by major discontinuities, we should actually consider the possibility of a much more complex dynamics relating the evolution of the GPT to spurts of economic growth. This limitation of the model is explicitly acknowledged by Helpman and Trajtenberg (Helpman, 1998, p. 110) . Of course, one could suggest that the high pressure steam engine ought to be considered as a "new" GPT replacing old GPTs (be this water power or low pressure engines).This is indeed the perspective that Rosenberg and Trajtenberg (2004) seems to suggest when they consider the "Corliss" engine as the only form of steam engine which can qualify as GPT for the long term growth of US manufacturing.

However, this focus on a specific "generation" of steam engine technology seems to be a much too narrow perspective for the study of the connection between the long term evolution of technology and economic growth. In fact, economic historians have emphasized that steam technology was the backbone of a new system of production characterizing a prolonged phase of development of capitalist economies. The formation of this system of production was stretched over a long period of time clearly actually covering the implementation and successive dismantling of different "vintages" of steam engine technology (Von Tunzelmann, 1995). In this respect, Freeman's notion of "technological system" which has seemingly a broader "coverage" - both longitudinally (as it includes a number of interlinked technologies) and temporally - than the one of GPTs seems more appealing and more in tune with received historical accounts of the long term development of industrialized economies.

Yet, even considering the broad concept of "technological system", it must be recognized that the task of thoroughly tracing a connection between the emergence of particular technological systems in the sense of Freeman and Kondratiev waves of economic growth is still largely unfulfilled. Freeman and his associates (see, in particular, Freeman and Louca, 2001) have assembled some highly suggestive evidence, but it is fair to say that they have not provided any detailed analysis of the large-scale diffusion of the various technological systems in relation with the process of economic growth. In their historical account, they have also suggested the existence of a number of mechanisms such as backward and forward linkages, technological spillovers, investment multipliers of particular technologies, etc., that might indeed account for the economy-wide repercussions of the diffusion of these technological systems. However, in their contributions, the actual workings of such mechanisms are never rigorously assessed.

To date, the only attempts to assess the contribution of steam power technology to economic growth (in Britain) are represented by von Tunzelmann (1978) and Crafts (2004). Their findings indicate that steam technology gave a sizable contribution to economic growth only from the 1840s onwards. In this respect, we are bound to note that the measurement of the contribution of specific technologies to economic growth still remains one of the most problematic areas of research in economics. Given the importance of this theme, it is to be hoped that, in the next future, a renewed research effort will be devoted to this daunting task. Additionally, when the notion of "technological system" is used in such a way to encompass the entire life-cycle of steam power technology, the long term evolution of capitalist economies seems to be better captured by a different chronological scheme, based on the more traditional distinction between the "first industrial revolution", "second industrial revloution" and "third industrial revolution", than by the one based on Kondratiev waves (von Tunzelmann, 1995, pp 97-100). Note this scheme, in which the impact of technological transformations stretches over very protracted time spans is consistent with the Cipolla-Wrigley interpretation of the British industrial revolution that we have discussed in chapter 1.

As we have noted in the previous section, despite its historical importance, we still lack an accurate knowledge of the precise pattern of diffusion of steam engine technology. In chapter 3, we have provided a reconstruction of the historical patterns of diffusion of steam engine technology during the eighteenth century. Our analysis has revealed that, in the course of the eighteenth century, steam engine technology was gradually integrated in different regional production systems each of them characterized by distinctive techno-economic requirements. From this point of view, the versatility of the steam engine technology in its early development was nothing short of remarkable, so that by the end of the eighteenth century, steam technology had been successfully introduced into a wide range of industrial applications. Our analysis has also shown that the diffusion of steam technology in various areas proceeded at an uneven pace, reflecting the influence of a number of local conditions (price of coal, the local endowment of specialist engineering skills, the sectoral structure of production). Concerning the economic history of steam technology, another rather obvious research avenue that lays ahead is the improvement of our very rudimentary knowledge of the diffusion process both from a spatial and from a sectoral perspective (as we have already noted, in the British case this holds true especially for the first half of the nineteenth century).

The spatial or geographical dimension of technology diffusion is a feature of the long term evolution of technology which so far as received little attention both in the GPT-based growth models and in Freeman's narrative, which have mostly concentrated on the diffusion of the technology across different industrial sectors. In this respect, it is important to note that the geographical and sectoral dimensions of the diffusion process are actually intimately related and that, for this reason, an enhanced understanding of the process of economic growth will probably require a combined consideration of these two aspects. Rosenberg and Trajtenberg (2004), on the basis of their study of the adoption of the Corliss engine in the US economy, go so far as to suggest that relocation of production activities ought to be regarded as the most important channel through which GPTs display their function of "engines of growth" .

Chapter 4 has been devoted to an analysis of the nature of inventive activities in steam engineering in the second half of the nineteenth century. We have represented inventive activities as a search process unfolding in a design space, which can be considered as defined by Newcomen and Watt's inventions. In this way, we have suggested a broad analogy between design activities undertaken within the boundaries of a specific technological paradigm and the exploration of a rugged fitness landscape, which can be represented using Kauffman's NK model. This perspective on the search process can actually be considered as a way to formalise Vincenti (1990)'s view of engineering design activities as processes of blind variation and selective retention.

The analysis of chapter 4 has revealed that a good deal of inventive activities in steam engineering in the second half of the eighteenth century were actually aimed at adapting the technology to the diversity of needs of various user sectors. In other words, our analysis has revealed the formation of a number of "technological niches" characterized by distinct set of user requirements. In this respect, our analysis is broadly consistent with the contribution of Halsey (1981) who has identified four main design families in steam engineering at the beginning of the nineteenth century namely, the Newcomen engine, the Watt engine, the Cornish engine and the high pressure non condensing engine. The first two designs (Newcomen and Watt) are rooted in the low pressure paradigm, whereas the second two in the high pressure paradigm. All these designs can be seen as the results of the process of niche formation described in chapter 4.

"Sectoral" circumstances seem to have dictated to engineers different goals (fuel efficiency in Cornwall, speed and smoothness of motion in the manufacturing districts of the North, increases in the power/weight ratio for steam engine of locomotives, etc.), prompting the search for innovations in different directions. In fact, technological advances aimed at improving the effectiveness with which steam engine technology could cater specific sets of user requirements were indeed one of the main leitmotivs of the development of steam power technology during the entire nineteenth century. The emergence of these application specific knowledge bases (defined as the bodies of both "understanding" and "practice" underlying the material technologies) made difficult the transfer of innovations from one application to the other. In other words, the accumulation of technical knowledge tended to be extremely specific, being tailored to particular products and processes in which steam power technology was adopted. Due to the essentially idiosyncratic nature of these innovative activities, the evolution of the 'engineering knowledge bases' underpinning the various applications of the steam engine proceeded along rather differentiated directions. Accordingly, in each application domain, stable sets of engineering heuristics emerged from the combination of sector specific economic and technical circumstances with what might be called the more "general" internal logic of steam technology. This determined a highly uneven rate of technological progress among various application domains. Using the David and Wright (1999) terminology, the dynamics of technical progress across applications was not "yeast-like", but "mushroom-like". In fact, on the basis of the available evidence on the development of steam power technology during the nineteenth century (Hills, 1989), it would seem that the rate of technical progress across the various applications of steam power technology was highly uneven. We have briefly touched upon this issue in chapter 6 (section 6.2) while discussing the delayed adoption of high pressure steam in manufacturing.

In our view, future research should be aimed at reconstructing and comparing the various sets of heuristics guiding inventive activities for the diverse applications of steam engine technology. Such research endeavour appear to be feasible both in terms of availability of contemporary engineering sources and of background material discussing the connection between scientific developments and technical advances (Cardwell, 1971).

Within the GPT literature the theoretical implications of varying degrees of "localness"[8] of technological knowledge for the division of inventive labour, the configuration of industrial structures and the overall rate of technical change have been examined by Bresnahan and Gambardella (1998). In this respect, given the important role that "local" component of technological knowledge which seems to have played in the development of steam engine technology, one could suggest that the historical case of steam engineering represents a particularly suited example for probing further into the issue of the tensions between the "general" and "local" components of technological knowledge

The chapters of Part III have examined the application of steam power technology in the Cornish mining district. Chapter 5 has examined the institutional setting supporting inventive activities in the Cornish steam engineering community. In particular, our case study of the development of the Cornish steam engine has shown that the creation of a regime of "collective invention" represented a highly favourable for the improvement of the performance of steam technology. In this respect, it is interesting to note that recent research efforts in the mainstream economic literature have been influenced by the extremely abstract industrial organization literature (patent races models) and have displayed the tendency to concentrate in a rather exclusive fashion on the conditions of appropriability of the economic returns of innovations. Historical studies like Allen (1983) and the one contained in chapter 5 suggest the need of taking a broader perspective and of devoting attention not only at the institutional mechanisms that ensure the possible privatisation and commercialisation of technological knowledge, but

[8] The adjective "local" here is employed with the meaning of specific to particular applications

also at those that protect its public character. In addition, it must be recalled that much of the contemporary research on productivity growth at industry level considers knowledge spillovers as an important source of productivity growth. Therefore, it would seem natural to follow up this empirical finding by devoting research efforts to explore the possible role played by specific institutional structures in enhancing the proliferation of knowledge spillovers (see Nelson, 1992 for a discussion of some of these fundamental policy issues).

Chapter 6 and chapter 7 have considered in some detail the dynamics of knowledge accumulation in Cornish steam engineering. Interestingly enough, the process of knowledge accumulation seems to be characterized by what Allen (1988) has defined as "evolutionary drift". In general terms, the system, at least from the 1810s to the late 1840s seems to have an in-built tendency to generate novelties. If these novelties were proved to be performance-enhancing they became gradually incorporated in the average practice of the system. Notably, this is pretty much at variance with the process of knowledge accumulation that is described in "new" neoclassical growth models. In these models, new technological knowledge is the product of the investment of agents endowed with perfect foresight. In this framework, uncertainty concerning new technological developments is modelled in terms of a known probability density, so that the agents can still formulate optimal plans of R&D investments. On the basis of these basic assumptions, it is possible to solve the model by identifying a moving growth path where the representative agent is in equilibrium. All this represses the heterogeneity of behaviours among the agents engaged in inventive activities, which appears to have been the critical source of dynamism in the accumulation of technological knowledge in Cornish steam engineering.

Given these considerations, one can suggest that, in order to deepen our understanding of the process of economic growth it would be necessary to develop growth models which incorporate a less stylised and more realistic dynamics of knowledge accumulation. Dosi and Fagiolo (1998) represents a particularly stimulating exploratory attempt in this research direction.

This last section has probably left the reader with the impression that our theoretical tools for understanding the complex role of technological change in the process of economic growth are still rudimentary. In fact, notwithstanding the most recent developments, we are still short of a framework of analysis capable of fully coming to grips with the multifaceted economic ramifications of technological progress.

Thus, notwithstanding GPT growth models have been able to incorporate the distinction between "incremental" and "drastic" innovations, it seems to us that fundamental features of the process of technical change, such as the radical uncertainty (not reducible to calculable risk) surrounding the search for innovations and the heterogeneity of the agents involved in the process of technical change, are still repressed in the neoclassical framework. This is due to the fact that these growth models retain the ambition of adhering as closely as possible to the canons of general equilibrium theory (Nelson, 1998). In GPT growth models, technical change is essentially incorporated as a "complication" to the basic general equilibrium model. In this respect, we would maintain that further advance in our understanding of the process of economic growth requires the adoption of a more "phenomenological" approach to the analysis of technology in modelling exercises. This means that, rather than attempting of incorporating technical progress in a pre-ordained explanatory framework, the characteristics and the historical specificities of technical change ought to be taken as the starting point of the modelling exercises.

For this ambitious endeavour, the history of technology has much to offer. A satisfactory understanding of the process of economic growth will emerge only from unravelling the sources and procedures of technical change in different historical circumstances. This calls for a re-approaching between two disciplines, economics and history, that have been for long time looked at each other somewhat suspiciously, because characterized by seemingly incompatible research traditions. [9] Nowadays, the recent progresses attained in the study of complex evolutionary systems allows the formulation of frameworks of analysis *genuinely open to history*, making the trespassing of disciplinary boundaries a particularly rewarding research direction

[9] Interestingly enough, this point was keenly advocated by Zvi Griliches in one of his last contributions (Griliches, 2000, pp. 89-90): "Real explanations [of productivity growth] will come from understanding the sources of scientific and technological advances and from identifying the incentives and circumstances that brought them about and that facilitated their implementation and diffusion. Explanation must come from comprehending the historical detail, from finding ways of generalizing (modeling ?) the patterns that might be discernible in the welter of it. This leads us back to the study of the history of science and technology and the diffusion of their products, a topic that we have left largely to others. But if we want to understand better what we are talking about, where technical change is actually coming from, we will need to study history. There is no free lunch in economic research either.".

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Samenvatting (Summary in Dutch)[1]

Het hoofdthema van dit proefschrift is het ontstaansproces van stoomkracht en zijn ontwikkeling naar een belangrijke industriële technologie gedurende de periode van ongeveer het begin van de achttiende eeuw tot het midden van de negentiende eeuw. Het reconstrueren van de geschiedenis van de stoommachine is uitgevoerd met analysemethoden die de recente ontwikkelingen op het gebied van de economie van technologische verandering weergeven.

Het eerste gedeelte van het proefschrift (hoofdstuk 2) geeft een globaal overzicht van de historische ontwikkeling van de stoommachine gedurende de periode 1700-1840. Dit gedeelte beschrijft de geschiedenis van de belangrijkste doorbraken in de ontwikkeling van de technologie van de stoommachine en geeft daarmee de noodzakelijke achtergrond voor het volgend gedeelte van de studie. Het is belangrijk op te merken dat de geschiedenis van de technologie van de stoommachine in dit hoofdstuk wordt beschreven op een nogal traditionele manier welke ook wel de 'internalistische' benadering wordt genoemd door technologiehistorici. Dit wil zeggen dat de focus op het artefact zelf is gericht en niet zozeer op de relatie tussen het artefact en zijn wijdere historische omgeving. In de rest van het proefschrift zal dit worden uitgewerkt door het beschouwen van de invloed van de economische en institutionele context op de evolutie van de technologie.

Het tweede gedeelte van het proefschrift (hoofdstuk 3 en hoofdstuk 4) onderzoekt de opkomst van de technologie van de stooommachine gedurende de achttiende eeuw. Beide hoofdstukken zijn gebaseerd op een analyse van een dataset betreffende Britse stoommachines die in de loop van de achttiende eeuw zijn geïnstalleerd; deze dataset is oorspronkelijk opgezet door Kanefsky en Robey (1980).

Hoofdstuk 3 onderzoekt het diffusieproces van de technologie van de stoommachine in Groot-Brittannië in de achttiende eeuw. Het hoofdstuk geeft nieuwe schattingen voor regionale variaties in de timing, tempo en mate van gebruik van stoommachines. Daarnaast wordt er in het hoofdstuk een poging gedaan tot het identificeren van de factoren die bepalend zijn voor de diffusie van stoomkracht in verschillende geografische gebieden. Onze bevindingen wijzen uit dat de steenkoolprijs een van de belangrijkste bepalende factoren was voor de onderscheiden adoptiepatronen van Newcomen en Watt machines, hiermee eerdere studies van Tunzelmann (1978) en Kanefsky (1979) onderbouwend. Onze analyse duidt er voorts op dat de adoptie van stoomkrachttechnologie ook werd beïnvloed door de productiestructuur (sectorale compositie) van de verschillende gewesten. In dit verband kan ook opgemerkt worden dat onze data lijken te wijzen op significante crosssectionele heterogeniteit. Met andere woorden, adoptiepatronen lijken niet te worden gekenmerkt door een stochastisch proces dat in alle gewesten hetzelfde is maar juist worden beïnvloed door individuele gewest-specifieke factoren. Deze bevinding bevestigt dat regionale verschillen in acht

[1] I am grateful to Michiel van Dijk and Ted Clarkson for their assistance in the translation of the summary in Dutch.

dienen te worden genomen indien onderzoek wordt gedaan naar het proces van technologische verandering gedurende de Britse industriële revolutie.

Hoofdstuk 4 is gewijd aan een analyse van het karakter van inventieve activiteiten op het gebied van de stoomtechniek in de tweede helft van de negentiende eeuw. Wij hebben inventieve activiteiten weergegeven als een zoekproces dat zich ontvouwt in een 'design space', zoals deze bepaald wordt door uitvindingen van Newcomen en Watt. Op deze manier hebben we willen wijzen op een brede analogie tussen ontwerpactiviteiten die ondernomen worden binnen de grenzen van een specifiek technologisch paradigma, en het verkennen van een gezond geschikt landschap dat weergegeven kan worden met gebruikmaking van Kauffmans NK model. Deze visie op het zoekproces kan beschouwd worden als een manier om Vincenti (1990)'s kijk op technologische ontwerpactiviteiten te formaliseren als een proces van 'blind variation' en 'selective retention'.

De analyse in hoofdstuk 4 wijst uit dat een groot gedeelte van de inventieve activiteiten op het gebied van de stoomtechnologie in de tweede helft van de achttiende eeuw gericht was op het aanpassen van deze technologie op de diverse behoeften van verschillende gebruikerssectoren. Anders gezegd, onze analyse heeft het vormen van niches, gekenmerkt door typische gebruikersbehoeften blootgelegd. Tegen het einde van de achttiende eeuw waren ingenieurs in staat om specifieke ontwerpen te identificeren, die op een effectieve manier aan deze verschillende behoeften tegemoet konden komen.

Het derde gedeelte van het boek (de hoofdstukken 5, 6 en 7) is gewijd aan de ontwikkeling van de Cornwall stoommachine. De Cornwall stoommachine geeft het hoogtepunt van de stoomtechnologie weer, aan het begin van de negentiende eeuw. Dit [onder]deel onderzoekt in detail de historische context waarin deze specifieke versie van de stoommachine tot ontwikkeling en tot wasdom kwam.

Hoofdstuk 5 houdt zich voornamelijk bezig met de rol van het institutionele kader waarbinnen de innovatieve activiteiten op het gebied van Cornische stoomtechnologie plaatsvonden. Hoofdstuk 5 maakt aannemelijk dat de ontwikkeling van Cornische stoomtechnologie [werd] ondersteund werd door de opkomst van een 'collective invention' regime (een regime waarin concurrerende bedrijven systematisch nieuwe technologische kennis delen). Het hoofdstuk stelt dat het 'collective invention' regime een zeer gunstige omgeving vormde voor het verbeteren van de prestatie van de stoommachine in het begin van de negentiende eeuw.

In hoofdstuk 6 worden de patronen van technologische verandering in de Cornische stoomtechnologie geanalyseerd. Het hoofdstuk identificeert drie historische kernperiodes in de ontwikkeling van de Cornwall stoommachine. Voorts wordt in dit hoofdstuk de adoptie van de hogedruk stoommachine in Cornwall vergeleken met andere regio's in Groot-Brittannië.

Hoofdstuk 7 onderzoekt het technologische leerproces dat ten grondslag ligt aan het Cornische traject van technologische verandering. Het hoofdstuk beargumenteert dat het mogelijk is om de Cornische ingenieursgemeenschap op te splitsen in twee groepen, de 'innovators' en de 'imitators'. De innovators waren bezig met het verkennen van de technologische mogelijkheden. In een volgend stadium werden deze ontdekkingen door de groep van 'imitators' toegepast in algemeen gebruikte machines.

Tot slot bevat het vierde gedeelte (hoofdstuk 8) een korte en bondige samenvatting van de belangrijkste bevindingen van het onderzoek en een bespreking van hun verdere implicaties.

About the Author

Alessandro Nuvolari was born in Mantova, Italy. He studied Economics and Social Sciences at Universita' Commerciale "Luigi Bocconi" in Milan where he graduated ("cum laude") in 1996 with a thesis on "Growth and Crises in Italian Economic Development, c. 1860-1990". After graduating, he specialized in the economics of technical change at the Maastricht Economic Research Institute on Innovation and Technology (MERIT). In 1999 he started a PhD project on the historical evolution of steam power technology at the Eindhoven Centre for Innovation Studies (ECIS), Eindhoven University of Technology. The research findings of the project are reported in the present dissertation. He is currently working at the Technology and Policy Department of the Eindhoven University of Technology as Assistant Professor of Economics of Science and Technology. His research interests are fairly broad and include the economics of technical change, evolutionary economics, economic history (in particular the British Industrial Revolution) and the history of technology.

At a profound psychological level Alessandro's emotional ups and downs are deeply affected by the variegated performances of F. C. Internazionale.

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