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'GLORIOUS TIMES': THE EMERGENCE OF MECHANICAL ENGINEERING IN EARLY INDUSTRIAL BRITAIN, C. 1700-1850

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ABSTRACT:

The primary aim of this paper is to explore the significance of the emergence and growth of mechanical engineering as a distinct industrial activity in early industrial Britain. The paper provides a survey of the most important interpretations put forward concerning the role of mechanical engineering in the early phases of industrialization. These interpretations are then confronted with data on the growth of the sector and with an analysis of the patterns of innovation carried out by means of a study of patent data. Our results broadly confirm the role of the sector as the main engine of technical progress in this historical phase.

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KEYWORDS: mechanical engineering, machine making, innovation, patents, industrial revolution.

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THE EMERGENCE OF MECHANICAL ENGINEERING IN EARLY INDUSTRIAL BRITAIN, C. 1700-1850

"These are indeed glorious times for the engineers"
James Nasmyth, 11 July 1836

INTRODUCTION

One of the salient features of the industrial revolution was the mechanization of production processes in a wide range of industries: first and foremost cotton and other textiles, but also food processing, paper making, printing and many others (Landes, 1969; Mathias, 1983). Economic historians have long studied (and debated) the impact that varying degrees of mechanization exerted on the dynamics of productivity in various industries as well as at the more macro level (the new orthodoxy on productivity growth is represented by Crafts and Harley, 1992). In a broader perspective, they have also analysed how mechanization affected the organization of work and production and its impact on the standard of living of various segments of the workforce (see, among others, Berg, 1994 and Randall, 1991).

Given the critical role played by mechanization, one might have expected the historical evolution of the mechanical engineering industry (in particular the very formation of "machine making" into a distinct industrial activity) to have been the subject of intensive study. Yet, virtually all accounts of early industrialisation assign to the mechanical engineering industry a rather shadowy role. The supply of machinery and improved power sources to the various user industries is regarded as the outcome of an almost automatic process. In the field of history of technology, more attention has been devoted to the invention of various machines (some of these accounts are still framed in rather narrow narratives dominated by the figure of the heroic inventor). However, most of these studies conclude with the first implementations of the invention under scrutiny, and so the ensuing role of the mechanical engineering industry in facilitating the supply of the new machines is scarcely noticed. Against this background, the contributions of Nathan Rosenberg (1963a; 1963b) - whose analysis, in turn, echoes some pioneering insights of Marx (1990, chap. 15; see also Rosenberg, 1976) - represent a remarkable exception. Rosenberg noted that the creation of an "upstream" specialist machinery sector was a key driver of the widespread dissemination of new technologies in user industries. Additionally, the emergence of "machine making" as an autonomous industrial sector, by means of enhanced specialization and division of labour, enabled the progressive consolidation of relatively coherent bodies of technological knowledge which, in turn, permitted the continuous improvement of the design of various machines.

The primary aim of this paper is to explore the significance of the emergence and early growth of mechanical engineering as a distinct industrial activity in early industrial Britain.
Roughly speaking, the bulk of the existing literature on the subject falls into two broad categories: business histories focussed on particular firms (or entrepreneurs) or dealing with particular towns or regions, and histories of technology examining in detail the evolution of specific technological artefacts. Of course, since many

leading machine-making firms were created by inventors attempting to commercially exploit their inventions, there is also a good deal of overlap between the two categories. Another valuable source of information is constituted by the writings of informed contemporaries (entrepreneurs or engineers) such as Baines, Ure, Nasmyth, Babbage, and Fairbairn (Berg, 1980, pp. 346-57).

However, we still lack a systematic reconstruction of the overall evolution of the industry in its early stages of development. The time seems ripe then for a recognition of the existing fragmented literature on the subject, with the aim of distilling the main "stylized facts" that characterize the "making" of this industry, and of formulating a preliminary set of interpretive hypotheses that can act as a springboard for future research.

1. THE EMERGENCE OF MECHANICAL ENGINEERING: SOME PRELIMINARY INTERPRETIVE HYPOTHESES

As already mentioned, virtually all accounts of the British industrial revolution recognize the central role played by the expansion of mechanization. Indeed, a number of authors (see among others, Paulinyi, 1986; von Tunzelmann, 1995, pp. 104-22) consider "mechanization" and the related rise of a technological system capable of producing "machines to make machines" as the *key technological element of the early phases of industrialization*. Other contemporaneous radical innovations, such as transformations in power technologies (in particular, the steam engine), although of fundamental economic importance in the very long run, produced sizable economy-wide repercussions only from the mid-nineteenth century onwards (von Tunzelmann, 1978). [1]

This view of the role of technical change in the British industrial revolution owes much to discussion contained in Chapter XV of the first volume of Marx's *Capital* (Rosenberg, 1974, 1976). In this chapter Marx, emphasized that the distinctive technological feature of modern industry was the "mechanization" of production. When production becomes performed by means of "systems of machinery", Marx noted, production processes are susceptible to self-sustained and continuous improvement. This is because the adoption of "systems of machinery" and the ensuing reconfiguration of production processes that are increasingly independent of human intervention open the door to the systematic application of the principles of science and engineering to the sphere of production.[2]

[1] Paulinyi notices the dependence of the transformation of power systems on previous advances in mechanization: "If we confuse the causal links and in common with many authors, describe the new power technology (that is, steam engine) as the driving force, we confuse at least cause and consequence because….demand for energy independent of human muscle power, increases to the extent that hand-tool processes dependent on muscle-power can be replaced by working machines" (Paulinyi, 1986, p. 283).

[2] "In manufacture, it is the workers who, either singly or in groups, must carry on each particular process with their manual implements. The worker has been appropriated by the process; but the process had previously to be adapted to the worker. This subjective principle of the division of labour no longer exists in production by machinery. Here the total process is examined objectively, viewed in and for itself, and analysed into its constitutive phases. The problem of how to execute each particular process and to bind the differential partial processes together into a whole, is solved by the aid of machines, chemistry, etc." (Marx, 1990, pp. 501-502).

It is worth noting that Marx felt the need to ground his historical analysis in a rigorous definition of a "machine". Marx defined the "machine" as an artefact that "after being set in motion, performs with its tools the same operations as the worker formerly did with similar tools" (Marx, 1990, p. 495). It is important to remark that the distinction is not based on the source of power used by the artefact: "whether the motive power is derived from man, or in turn from a machine makes no difference here" (Marx, 1990, p. 495). As a matter of fact, the first expansion of mechanization was based on traditional power sources (human, animal and water power). As we have already mentioned, the widespread adoption of steam power as a prime mover in manufacturing properly belongs to the second half of the nineteenth century. In this way, Marx could draw a clear analytical distinction between the historical phases of "manufacture" and "modern industry". In manufacture the workers are grouped together in the same plant and carry out the production process according to an elaborate division of labour, but they still retain control of the actions of their tools, whereas in modern industry the output is produced by means of machines or systems of machinery and the workers perform ancillary tasks with respect to the actions of the machine.

Marx remarks that the expansion of mechanization determined the emergence of an independent machine-making industry.[3] Initially, in this sector, machines were produced by means of traditional handicraft methods. However, in the course of time, machines were applied to the construction of machine themselves. When this stage is reached, the realization of the full productive possibilities of modern industry finally becomes possible, and a process of self-sustained economic growth is irreversibly triggered. [4] In Marx's view, the beginnings of this historical phase can be dated to the early 1850s.[5] Marx's outline of the expansion of mechanization and of the related emergence of autonomous machine-making industries may be regarded as broadly accurate. However, as it stands, the account is nothing more than a brief sketch, which is evidently in need of further development.[6]

So far, the most noteworthy step in this direction has been taken by Nathan Rosenberg in two influential papers (Rosenberg, 1963a; Rosenberg, 1963b). In these papers, Rosenberg attempts a preliminary reconstruction of the emergence of independent machine-making industries adopting an interpretative framework that

[3] "There were mules and steam engines before there were any workers exclusively occupied in making mules and steam engines in the same way as men wore clothes before there were tailors….As inventions increased in number, and the demand for newly discovered machines grew larger, the machine-making industry increasingly split up into numerous independent branches, and the division of labour within these manufactures developed accordingly", Marx (1990, pp. 503-504). This reversal of the causal relationship between invention and the division of labour posited by Adam Smith had previously been contended by Thomas Hodgskin and John Rae, see MacLeod (2009).

[4] "Modern industry therefore had to take over the production of the machine itself, its own characteristic instrument of production, and to produce machines by means of machines. It was not till it did this that it could create for itself an adequate technical foundation and stand on its own feet." Marx (1990, p. 506).

[5] "It is only since about 1850 that a constantly increasing portion of these machine tools have been made in England by machinery, and even then not by the same manufactures as make the machines." Marx (1990, p. 495).

[6] For a discussion of some of the historical insights contained in Marx's model of transition between manufacture and modern industry, see Berg (1994, ch. 3).

is clearly borrowed from chapter XV of *Capital*. Rosenberg's studies are mainly focussed on the American case, but most of his historical reconstruction seems to have a general validity. The stages of the historical process described by Rosenberg are similar to those identified by Marx. Initially, machines were developed and produced by their users. Following the expansion of production in the user industries, a number of firms began to specialize in the production of machines themselves. Typically, these firms began as "specialist" producers of well-defined classes of machines. However, as the skills and the techniques used in the production of individual machines could be relatively easily "stretched" and employed in the production of other types of machinery, quite soon these firms extended their range of products. In a second phase, following an analogous process, machine tool producers split off from the machine-making industries. Interestingly enough, machine tool producers were normally highly specialized, limiting their operations to a rather narrow range of products. However, each of these individual machine tools could, with minor modifications, be adapted to cater to the needs of a wide range of possible users. Rosenberg labels this phenomenon "technological convergence". As we shall see, this feature of the evolution of the industry is particularly noteworthy.

To sum up, Rosenberg regards the evolution of the mechanical engineering industry during the nineteenth century as characterized by a process of progressive "vertical disintegration". This process of vertical disintegration was driven by two distinct sets of forces. The first one was the expansion of output in user industries which determined a sustained demand for machine and machine tools. As originally noted by Stigler, it can be expected that as industries expand, individual stages of production will increasingly be undertaken by specialist firms.[7] The second one is the process of technological convergence mentioned above. According to Rosenberg, the high degree of specialization characteristic of the US machine tool industry would have not been economically sustainable without the trend towards technological convergence. In this case, it is likely that the restricted size of the market would have prevented the emergence of "specialist" producers of machine tools (Rosenberg, 1963b, p. 17). This pattern of specialisation also affected the dynamics of innovative activities. Technically sophisticated industries imposed stringent requirements on the performance attributes of the various machines, stimulating innovations in design and favouring the consolidation in machine-tools producers of bodies of (technological) knowledge and skills.[8] This knowledge base could then be used for improving and refining the design of machine tools performing similar functions in less sophisticated industries. In this perspective, the emergence of an independent machine-tool industry played a key role in assuring a

7 "If one considers the full life of industries, the dominance of vertical disintegration is surely to be expected. Young industries are often strangers to the established economic system….[They] must design their specialized equipment and often manufacture it, and they must undertake to recruit (historically, often to import) skilled labour. When the industry has attained a certain size and prospects, many of these tasks are sufficiently important to be turned over to specialists. It becomes profitable for other firms to supply equipment and raw materials, to undertake the marketing of the product and the utilization of by-products and even to train skilled labour", (Stigler, 1951, p.190).

8 Examples are knowledge of the properties of metals in different conditions of use, properties of various lubricants, properties of feedback mechanisms and other control devices in various conditions of use. Most of this knowledge could not be fully articulated and codified and for this reason, it was very often embodied in workers' skills. See Rosenberg (1963b, p. 16).

timely dissemination of new technologies across industries. In addition, Rosenberg noted the existence of other processes of technological learning on the users' side that fed back on the accumulation of technological knowledge in machine tool producers, producing a further acceleration in the overall rate of innovation.

Ames and Rosenberg (1968, pp. 832-833) argue that these intertwined processes of vertical disintegration and technological convergence were a distinguishing feature of the development of the US mechanical engineering industry. In other countries, most notably Britain, the specialisation of production in mechanical engineering was carried out to a much more limited extent and, as a consequence, the dynamics of innovation in this industry were much less vibrant.[9] This difference, according to Ames and Rosenberg (1968), is explained by a number of contextual condition such as factor prices, nature of demand, etc. that were particularly suited to nurture the processes that we have described above. Clearly, this line of argument is reminiscent of "Habakkuk' s thesis" on the differences in American and British technology during the nineteenth century (Habakkuk, 1962).

This latter part of the Rosenberg's account, however, did not go unchallenged. A. E. Musson argued that when the historical record is examined in close detail, the American superiority in mechanical engineering *in the first half of the nineteenth century*, which was postulated by Habakkuk and his followers, cannot be taken for granted. According to Musson, the available evidence suggests that in many branches of mechanical engineering Britain ought to be considered the technological leader:

"Scholars such as Habakkuk and Rosenberg....have been misled by [Whitworth]'s inflated claims and his advocacy of 'the American system of manufactures' in the production of small arms leading to the establishment of the Enfield Arsenal in 1854. The Americans.....had a lead in light mass-production engineering of this kind, but as Whitworth himself pointed out, from his observation of American manufactures in 1853, Britain was at that time supreme in the iron industry and heavy engineering". (Musson, 1981a, p. 92).

On the basis of detailed historical studies of British mechanical engineering firms (Musson and Robinson, 1969; Musson, 1970; Musson, 1975; Musson 1980; Musson, 1981a, 1981b), Musson argues that the emergence of mechanical engineering as an independent industry, which Rosenberg (1963b) dates in the US to the early 1840s, was at that time already in full swing in Britain. In critical branches of mechanical engineering such as the making of steam engines, textile machinery, locomotives, and machine tools, Britain's technological lead over the US remained firmly established at least up to the 1860s (see Musson, 1975 and 1981). Remarkably, although highly critical of Rosenberg's evaluation of the relative technological position of Britain and the US in the first half of the nineteenth century, Musson considers Rosenberg's general account of the evolution

[9] "The central issue in the historical literature on technical change in the nineteenth century seems to be this: Americans clearly led the British in the adoption of many machine methods of production. If this precedence is not simply "Yankee ingenuity" working in a void it must reflect such economic factors as resource endowment, the structure of the labour force, the structure of prices and the nature of consumer tastes" (Ames and Rosenberg, 1968, p. 841).

of the mechanical engineering industry and of the strategic role of the industry in the early phases of industrialization to be fairly accurate (see Musson, 1975, footnote 141).

In the remainder of this paper, we will turn our attention to the existing literature on the early development of mechanical engineering in Britain, keeping as a possible frame of reference the account sketched in this section.

2. PATTERNS OF INDUSTRIAL GROWTH AND INNOVATION

Unfortunately we do not have yet fully reliable estimates of the output of the mechanical engineering industry for the classical period of the industrial revolution (1750-1850). From the data contained in the Censuses of Population for the years 1841 and 1851, it is possible to glean a picture of the size of the industry at the end of the period on which we focus here. It must be noted that the Censuses reported their figures in terms of "occupations", and not in terms of industrial classifications. Hence, the estimates of the size of the various industries in terms of employment are obtained by the aggregation of the relevant occupational groups. For this purpose, we can use the estimates of the size of the various branches of manufacturing constructed by Lee (1979) for the years 1841 and 1851.

Note that the occupational groups aggregated by Lee in the category "mechanical engineering" comprise millwrights, engine and machine makers, patternmakers, erectors, fitters, turners, etc. Clearly, Lee's estimates might have failed to include some relevant occupational groups that were instead included in categories such as "shipbuilding" or "metal fabrication". In this respect, it might be worth noting that the category "instrument engineering" comprises watchmakers and scientific instrument makers. Notwithstanding these difficulties, Lee's estimates of the size of the mechanical engineering industry appears to be consistent with those suggested by Clapham (1926, p.448) and Musson (1978, p.118), and probably provide a good indication of the relative size of the mechanical engineering industry in the mid nineteenth century.

According to Lee's data, in 1851, mechanical engineering has a share of only 3.21 % in total manufacturing employment. It is important to note, however, that according to Lee's figures for employment, between 1841 and 1851, mechanical engineering is the industry with the highest growth rate (9.42 % p.a.), and the industry with the second highest growth rate is chemicals (6.15 % p.a.).

The size of the firms operating in the industry was typically small. In the Census of 1851, there were 677 firms operating in the industry, of which 457 employed fewer than 10 men, 147 employed from 10 to 39, 39 from 40 to 99, 9 from 100 to 199, 8 from 200 to 299, 3 from 300 to 349, and 14 more than 350 (Clapham, 1926, p. 448). According to Clapham the beginnings of the rapid growth of the mechanical engineering industry may be dated to the years around 1850. In this phase, sustained growth was driven both by the creation of new firms and by growth of existing ones (Clapham, 1926, p. 448). Lee's data also shows that the main concentrations of the industry were in London and the South East (mainly London and Middlesex), in the West Midlands, in the North (especially Lancashire and

West Riding) and in Scotland. Clearly this pattern of localization reflects the connection of mechanical engineering with its user industries, such as textiles, iron, etc.

It is possible to cast additional light on the economic significance of the mechanical engineering industry by trying to asses its impact in terms of backward and forward linkages. In this case we rely on an Input-Output table for the UK economy in 1841 constructed by Horrel, Humphries and Weale (1994). Backward and forward linkages have been calculated using the inverse Leontiev matrix. Backward linkages have been computed as the sum of the columns of the matrix, whereas forward linkages have been computed as the sums of the rows. In this way the value of backward linkages of each sector represents the increase of gross output when the final demand of the sector in question is raised by £ 1. Vice versa, the value of forward linkages show the increase of the gross output of the sector in question when all the final demand of the other sectors is raised by £ 1. Table 1 sets out the results of our calculations.

TABLE 1. BACKWARD AND FORWARD LINKAGES IN 1841

Industry	Forward linkages	Backward linkages
Agriculture	2.552	1.1
Mining and quarrying	2.34	1.149
Food, drink and tobacco	1.233	1.72
Metal manufacture	2.106	1.422
Soap, candles and dyes	1.042	1.439
Textile, clothing and leather goods	1.442	1.45
Metal goods	1.333	2.182
Bricks, pottery and glass	1.157	1.178
Other manufacturing	1.101	1.112
Construction	1.083	1.317
Gas and water	1.102	1.279
Transport	1.524	1.224
Distribution	1.111	1.521
Domestic service	1	1
Other service	1	1
Public administration and defence	1	2.033
Housing services	1	1

Source: Own computations based on Horrell, Humphries and Weale (1994).

According to the definitions used by Horrell, Humphries and Weale, the sector that is closest to a plausible definition of mechanical engineering is "metal goods". This sector contains all the production of machinery and engines, although the aggregate is broader containing also simple metal goods, such as cutlery, rails, etc. The table shows that mechanical engineering is the sector with the highest value in terms of backward linkages, which indicates the key role of the sector in the generation of intermediate demand. In terms of forward linkages the significance of the sector appears to be significantly lower.

Economists and economic historians have frequently relied on patent data to gauge the volume of "invention". Of course, patents are a very imperfect proxy of invention and, especially for the period we are considering here, particular caution must be used in the interpretation of patent statistics (MacLeod, 1988).

Table 2 gives the share of mechanical engineering patents in the total number of patents. The table indicates that over the period 1780-1849 the share of mechanical engineering increased from 17% to a figure close to 30 %. [10] It is worth remarking, that the data do not include patents in machine-tools (in the period 1617-1852 we have identified 152 machine-tool patents, which would raise this share). Although not unexpected, the finding that in 1850 an industry which employed about 3% of the adult male labour force accounted for about 30% of patents is surely remarkable. In more general terms, table 2 provides quantitative support to the views of technical progress that we have summarized in the previous section and which regard mechanical technologies as the main source of innovation in early phases of the industrial revolution. In the table we have also analysed the share of mechanical engineering into various sub-categories. Interestingly enough, the category that displays systematically, throughout the period, the highest share of patents is "steam engines". In part, this reflects the rapid development of the technology (in the years following Watt's technological breakthroughs) but it may also reflect a higher propensity to patent innovations in expensive pieces of capital equipment.

[10] Our estimates are somewhat lower than those of Sullivan (1990, p. 355). This is due to the fact that Sullivan has adopted a broader definition of inventions related with machinery. The main difference in terms of interpretation is that our figures suggest that the share of patent inventions related with mechanical engineering was characterized by an increasing trend. Sullivan's figures show instead a stationary pattern.

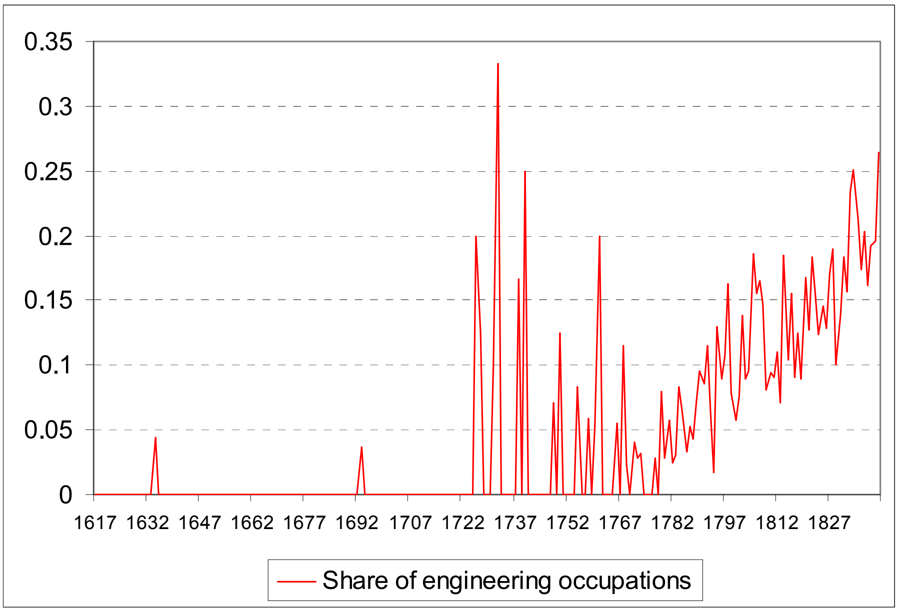
TABLE 2. SHARE OF MECHANICAL ENGINEERING (AND OF VARIOUS SUB-CATEGORIES) IN THE TOTAL NUMBER OF PATENTS, 1780-1849

Years	1780-1789	1790-1799	1800-1809	1810-1819	1820-1829	1830-1839	1840-1849
Total number of patents	478	643	923	1131	1450	2452	4631
Mechanical engineering (%)	17.78	20.68	21.34	20.34	29.72	33.77	28.57
Steam engines (%)	5.02	4.67	4.88	4.33	9.17	11.09	9.07
Spinning and preparatory machinery (undifferentiated) (%)	1.05	1.71	1.84	1.41	1.93	2.32	1.71
Spinning and preparatory machinery (cotton) (%)	0.00	0.62	0.65	0.27	0.76	1.43	1.77
Spinning and preparatory machinery (flax and jute) (%)	0.63	1.56	1.08	0.88	1.10	0.98	0.86
Spinning and preparatory machinery (wool and worsted) (%)	0.84	1.40	0.43	0.35	0.90	0.98	0.95
Silk Machinery (spinning,weaving and finishing) (%)	0.00	0.00	0.00	0.18	0.97	0.45	0.37
Carpet weaving machinery (%)	0.21	0.00	0.22	0.53	0.14	0.20	0.45
Weaving Preparatory Machinery (%)	0.00	0.16	0.76	0.09	0.48	0.65	0.60
Weaving: Looms and Jacquards (%)	1.05	1.40	1.52	0.62	2.07	2.20	2.48
Lace machinery (%)	0.84	0.31	0.54	0.62	1.45	2.69	0.73
Hosiery machinery (%)	1.46	0.93	0.65	0.35	0.07	0.41	0.93
Cloth finishing:wool (%)	0.42	0.47	0.98	1.86	2.83	1.18	0.28
Cloth finishing (cotton, linen, fustian) (%)	0.21	1.40	0.54	0.27	0.21	0.61	0.50
Paper making machinery (%)	0.00	0.62	1.08	1.15	0.69	1.63	0.93
Calico-printing machinery (%)	1.05	0.93	0.54	0.88	0.97	1.47	0.76
Sugar refining machinery (%)	0.42	0.31	0.43	1.15	0.69	0.65	0.82
Printing machinery (%)	0.21	0.16	0.43	1.41	2.00	1.10	1.06
Agricultural machinery (%)	3.35	3.42	4.12	3.36	0.83	1.67	2.76
Boilers (%)	1.05	0.62	0.65	0.62	2.48	2.04	1.53

Source: Authors' dataset based on Woodcroft (1854) and *Abridgments.*

Figure 1 provides a complementary perspective on the innovation "dynamism" of the mechanical engineering sector. The figure display the evolution of the share of patentees with stated occupations related to mechanical engineering (ie, "engineer", "millwright", "machine maker", "engine maker", etc.). From the 1760s, the time series displays a fluctuating behaviour around a clearly growing trend.

FIGURE 1. SHARE OF MECHANICAL ENGINEERING OCCUPATIONS IN TOTAL PATENTEES



Source: Authors' dataset based on Woodcroft (1854) and *Abridgments.*

In the light of the discussion in the previous section, it is of substantial interest to examine the sources of innovation of mechanical engineering patents (von Hippel, 1988; MacLeod, 1992). Shoud we expect that as the making of machines became an independent economic activity, machine makers assume the burden of innovation, progressively lifting it from the shoulders of machine users? Table 3 gives the number of patents in mechanical engineering divided into sub-categories and the relative shares that can be ascribed to users and to makers for the period 1780-1852. The table clearly suggests that the users were the predominant source of innovation in industrial production machinery (spinning, weaving, paper-making, etc.); this result also holds when one breaks down the figures into different sub-periods. The categories in which makers held a larger share are "agricultural machinery" and "boilers". An interpretation of these patterns, on the basis of a close scrutiny of the patent records and of a number of individual inventions, has been set out in MacLeod (1992).

TABLE 3. SHARE OF PATENTS GRANTED TO USERS OR MAKERS, 1780-1849

Type of machinery	Number of patents	User (%)	Maker (%)	Others/Unkown (%)
Spinning and preparatory machinery (undifferentiated)	237	27.85	33.33	38.82
Spinning and preparatory machinery (cotton)	176	44.89	32.95	22.16
Spinning and preparatory machinery (flax and jute)	128	32.81	24.22	42.97
Spinning and preparatory machinery (wool and worsted)	122	56.56	9.84	33.61
Silk machinery (spinning, weaving, finishing)	47	63.83	2.13	34.04
Carpet weaving machinery	65	56.92	4.62	38.46
Weaving preparatory machinery	69	53.62	8.70	37.68
Weaving: looms and jacquards	295	43.73	18.31	37.97
Lace machinery	142	80.99	11.97	7.04
Hosiery machinery	92	46.74	18.48	34.78
Cloth finishing (wool)	121	50.41	16.53	33.06
Cloth finishing (cotton, linen, fustian)	76	61.84	15.79	22.37
Paper making machinery	140	52.86	18.57	28.57
Calico printing machinery	134	41.04	18.66	40.30
Sugar refining machinery	114	12.28	28.95	58.77
Printing machinery	139	31.65	20.86	47.48
Agricultural machinery	343	19.24	41.69	39.07
Boilers	209	31.58	68.42	0.00

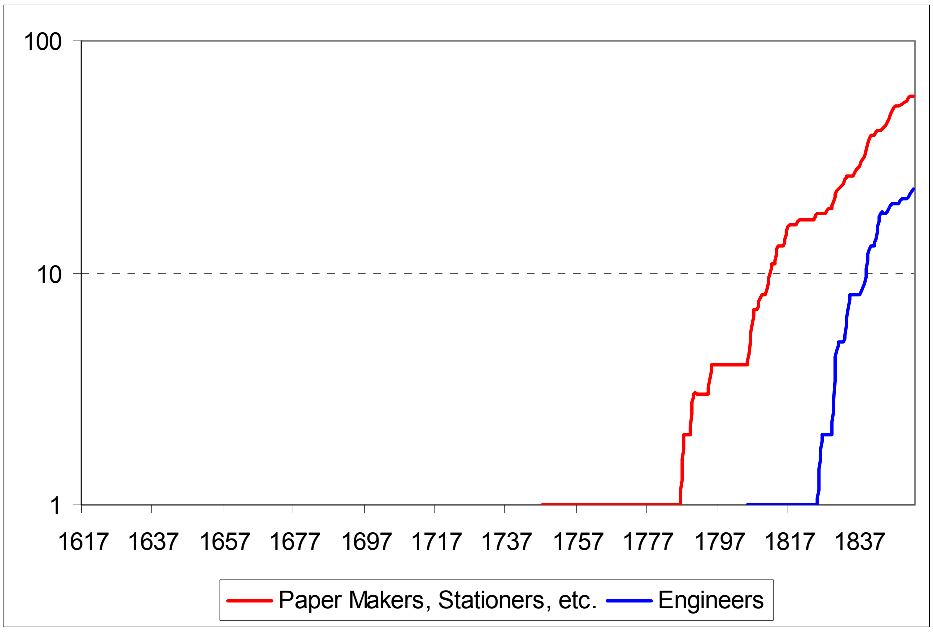
Source: Authors' dataset based on Woodcroft (1854).

As mentioned, the patent records suggest that machine users obtained the largest share of patents in industrial production machinery. This is perhaps not surprising when it is remembered that many user firms employed their own mechanics to build and maintain their machinery. Moreover, it was a reasonable strategy for an inventor to use any machine he patented in manufacturing consumer goods, rather than (or as well as) to produce it for sale. By contrast, machine makers were predominant in patenting inventions in the fields of heavy engineering, most notably, steam engines and machine tools (although patents in machine tools were scarce before 1840). This finding can perhaps be accounted for by the complexities of the invention process in heavy engineering, which had begun to rely upon relatively sophisticated bodies of technological knowledge (properties of steam, metals resistance, etc.). Moreover, power sources and machine tools were at one remove from the principal concerns of users, who naturally focused on the immediate processes and machinery they deployed in producing their goods.

In the field of industrial production machinery, instead, it appears that machine users were mainly responsible for radical inventions, whereas the inventive efforts of machine makers typically generated small incremental inventions. Although, it is hard to generalize, the development of such inventions seems to have been characterized by a typical pattern, in which the user-inventor made the initial technological breakthrough and the invention was subsequently refined and improved by machine makers. As patent protection became progressively more secure (especially after the 1830s), many users adopted the strategy of licensing their inventions; by contrast, the most common strategy before 1830 was to work the invention in secret. In this situation, machine makers assumed a leading role in the diffusion of inventions. They improved and refined the various generations of machinery, they took care of ensuring their wide dissemination, and they provided technical assistance that reduced some of the adoption risks for the machine users.

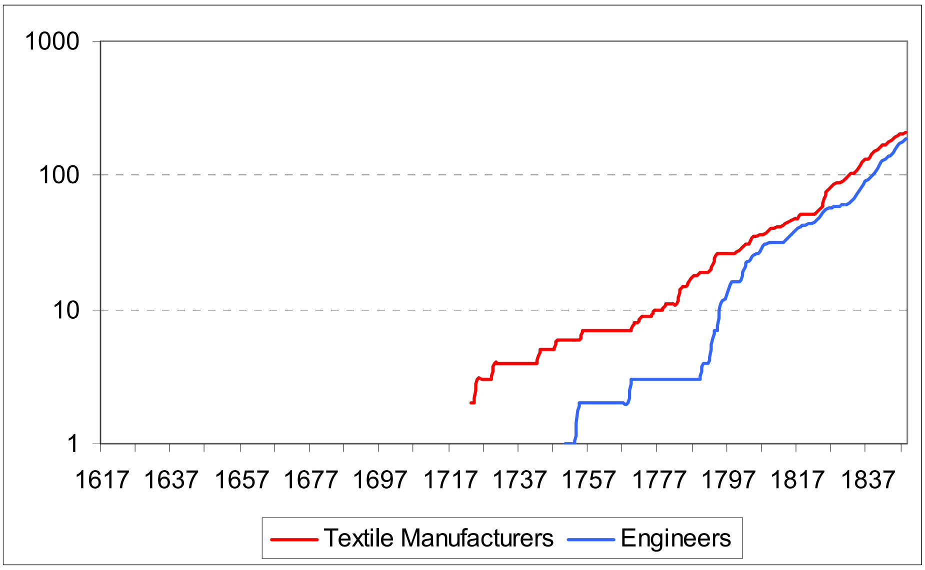
To sum up, the evidence from the patent records suggests the existence of a rather complex pattern of innovation-diffusion. The location of inventive activities to a certain degree did mirror the progressive redefinition of the boundaries of production activities caused by the emergence of machine making and machine tools as independent industries discussed by Rosenberg. Figure 2 and 3 illustrate this profile for the case of the paper making industry and for spinning machinery. The figures display the cumulative number of patentees in the industry on a log scale. Both figures show clearly a two-stage process. In a first phase, patents are mostly taken by inventors that identified themselves in terms of paper-related professions or textile manufacturing professions (i.e. they are user of machines). In a second phase, instead patentees increasingly come out of engineering professions.

FIGURE 2. PATENTEES IN THE PAPER-MAKING INDUSTRY



Source: Authors' dataset based on Woodcroft (1854) and *Abridgments.*

FIGURE 3. PATENTEES IN SPINNING MACHINERY



Source: Authors' dataset based on Woodcroft (1854) and *Abridgments*.

However, evidence of a more qualitative kind, suggests that, notwithstanding this shift, users maintained a very important role in innovative activities (this was probably due to their higher degree of intimacy with the problems involved in the mechanization of production). In these conditions, diffusion paths of innovations were to a major extent shaped by the strategies adopted by the user-inventors in the management of their intellectual property rights (MacLeod, 1992).

3. NEW FIRM CREATION AND PRODUCT SPECIALIZATION

Landes (1969, p. 61) refers to the formation of a strong base of "mechanical skills" in eighteenth-century Britain as a somewhat "mysterious" process. Clearly, the process described by Landes is tightly connected with the emergence of mechanical engineering as an autonomous industrial sector--as we have demonstrated.

In retrospect, it is possible to identify a number of distinct sources that contributed to the early formation of the mechanical engineering industry. The first one is the "downstream" diversification of a number of iron-producing firms. From the early eighteenth century the demand for some of the products supplied by these firms became more sophisticated, and iron firms were increasingly asked to meet more stringent specifications. The most outstanding example of this is the boring of cannons and steam-engine cylinders. After having moved to Britain from Holland in the early 1770s, Jan Verbruggen was appointed "Master Founder" at the Woolwich Arsenal and there he developed a new cannon-boring mill (Rolt, 1965, pp. 53-54). In a somewhat parallel fashion, stimulated by the growing demand for steam engine cylinders, a number of foundries had begun to work at the development of cylinder-boring machines. By the mid 1720s, the Coalbrookdale

Ironworks had begun to produce steam-engine cylinders using a cylinder-boring machine, whose design was inspired by contemporary cannon-boring mills. In 1760, John Smeaton designed for the Carron Ironworks in Scotland, a new improved cylinder-boring mill. Finally, around the mid 1770s, John Wilkinson developed a new generation of cannon-boring and cylinder-boring machines, which represented a substantial improvement of existing designs. Notoriously, Watt's steam engine benefited substantially from Wilkinson's cylinders. To recapitulate, a number of iron foundries during the eighteenth century were developing and increasingly making use of machine tools. In some cases, ironworks also began to undertake the production and installation of steam engines and other machinery. Again, the most notable example in this respect is John Wilkinson who installed a number of Watt "pirate" engines during the 1780s and 1790s. However, from the last years of the eighteenth century, specialized engineering companies such as Boulton & Watt and Matthew Murray increasingly undertook the complete manufacture of steam engines, standardizing the production of a number of engine components (Roll, 1930). Accordingly, these engineering workshops expanded their production facilities to include foundries and cylinder-boring machines.

The second source that contributed to the formation of an autonomous mechanical engineering industry was the millwrighting trade. Millwrights can be considered the most direct ancestors of professional engineers. As Jennifer Tann (1974) has shown, millwrighting was a traditional occupation that was progressively transformed by the expansion of mechanization. The pre-industrial revolution millwright was mostly involved in the design and implementation of power to traditional systems of machinery (corn milling, the fulling of cloth, blast furnace bellows, grinding equipment, etc.). In a famous passage, William Fairbairn described the activities of eighteenth-century millwrights in these terms:

"The millwright of the former days was to a great extent the sole representative of mechanical art, and was looked upon as the authority on all applications of wind and water, under whatever conditions they were to be used, as a motive power for the purposes of manufacture. He was the engineer of the district in which he lived, a kind of Jack-of-all-trades, who could with equal facility work at the lathe, the anvil and the carpenter's bench....Thus the millwright of the last century was an itinerant engineer and mechanic of high reputation. In the practice of his profession he had mainly to depend on his own resources. Generally he was a fair arithmetician, knew something of geometry, levelling and mensuration, and in some cases possessed a very competent knowledge of practical mathematics. He could calculate velocities, strength, and power of machines; could draw in plan and section, and could construct buildings, conduits and watercourses, in all the forms and under all the conditions required in his professional practice". [11]

The passage indicates that millwrights were integrating traditional empirical skills with a more reflective approach, making increasing use of systematic bodies of knowledge.[12]

[11] Fairbairn (1877), pp. 26-27.

[12] For a discussion of the influence of the sixteenth-century revolution of engineering practice see Hall (1961).

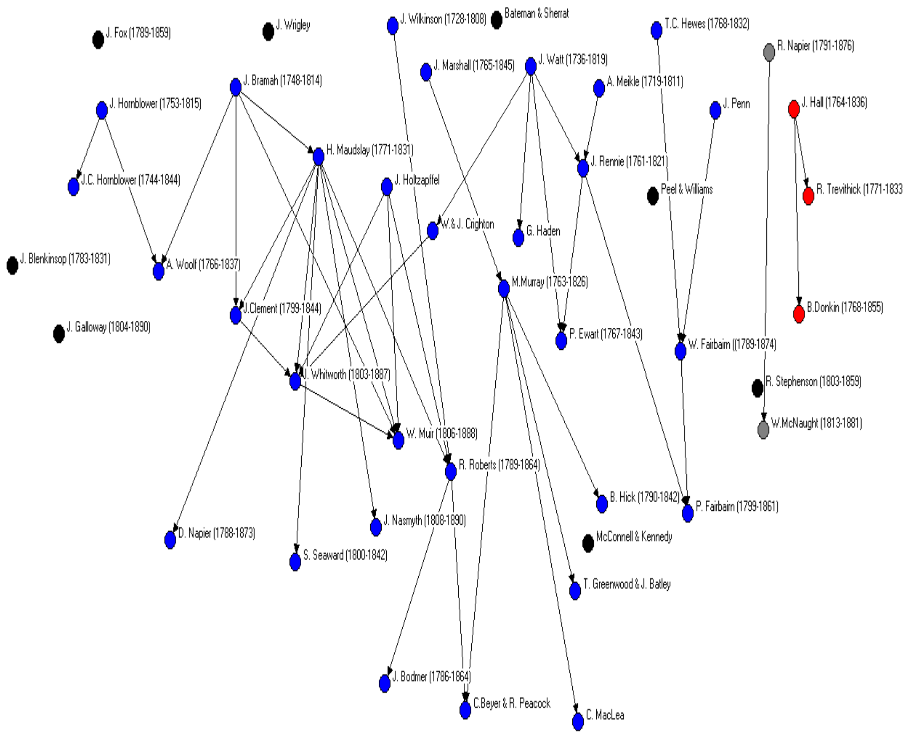
Machinery installed by millwrights was typically made of wood and there was an important connection between the wood-working machinery and many machine-tools developed in the first half of the nineteenth century (Willis, 1851).

The precision metalworking trades provide the third source from which mechanical engineering emerged: essentially, the clock-makers and scientific instrument makers. Also in this case it is possible to identify the palpable influence of tools used in the clock-makers' practice on the design and operation of various machine tools (Hall, 1961, p. 338).

For most of the eighteenth century the largest concentration of engineering workshops was in London. The concentration of these early engineering workshops in the metropolis reflected the needs of its million inhabitants and their industries (cranes, pulleys and related apparatus for the harbour; processing machinery for sugar, tobacco; locks and a range of consumer durables, etc.). [13] Not surprisingly, a roll-call of the most eminent eighteenth-century engineers (Watt although only briefly, Rennie, Woolf, Trevithick, Donkin, Bramah, Maudslay) shows several connections with the engineering activities taking place in London. The nascent industry developed, however, in numerous centres throughout the country. Overall, although there were surely examples of the type of "vertical disintegration" stressed by Rosenberg, the initial development seems to have been based, by and large, on processes of diversification or transformation of "traditional" trades (millwrights, smiths, iron founders, etc.)

[13] For a detailed overview of engineering activities in London in the second half of the eighteenth century, see Woolrich (2002).

FIGURE 4. GENEALOGY OF EMPLOYEE START-UPS IN THE BRITISH MECHANICAL ENGINEERING INDUSTRY, 1750-1850



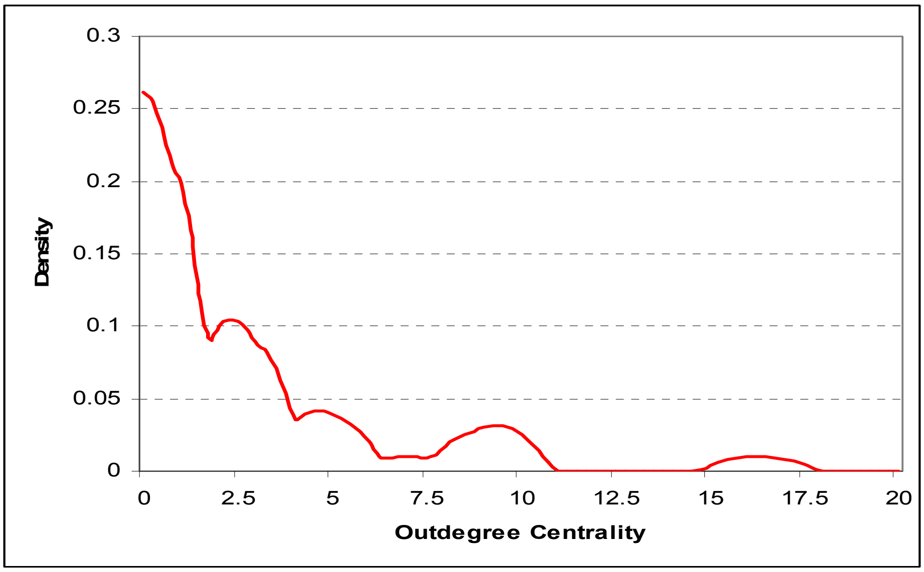
The subsequent expansion of the industry was nurtured by an intertwined process of apprenticeship networks and employee start-ups. Figure 4 charts the "genealogy" of the majority of the leading British mechanical engineering companies in the period 1750-1850 (the information was mostly gathered from two biographical dictionaries: the *Oxford Dictionary of National Biography* and Skempton (2002)). The arrows indicate employer-employee relationships (they are oriented in an employer-employee direction). The figure provides a sketch of the role played by spin-offs in the process of new firm creation. The first point that merits attention is the strong "connectedenness" of the network. Indeed, the majority of the firms belong to the same component indicated by the white nodes. We investigate this characteristic of the network more in detail in table 5, where we calculate centrality indicators.

TABLE 4. CENTRALITY INDICATORS FOR THE NETWORK DEPICTED IN FIGURE 4

Engineer	Outdegree Centrality (normalized)	Betwennes Centrality (normalized)
H. Maudslay	16.279	0.36
J. Bramah	9.302	0
J. Watt	9.302	0
M. Murray	9.302	0.221
J. Holtzapffel	6.977	0
J.Hornblower	4.651	0
R. Roberts	4.651	0.443
J. Rennie	4.651	0.111
J. Hall	4.651	0
J. Whitworth	2.326	0.166
W.Fairbairn	2.236	0.111
W & J. Crighton	2.326	0.111
J. Clement	2.326	0.028

Outdegree centrality is a measure of the edges that are generated by each node. In this context, it may be considered as an indicator of the capacity of a firm to transmit engineering skills and capabilities. As table 4 indicates, firms such as Boulton & Watt, Matthew Murray, and most of all Maudslay & Field stand out as incubators of several new firms. In figure 5 we have plotted the kernel density estimation of outdegree centrality. The figure shows a very skewed distribution, with a very restricted number of nodes displaying a strong capacity of attracting apprentices. This finding can be interpreted as an indicator of *preferential attachment* in the evolution of the network. In other words, would-be apprentices tended to select systematically from a very restricted number of firms for their training. Betweeness centrality is a measure of the likelihood of an actor being between other pairs of actors. In this context, the function of these actors is to connect the various components of the network, possibly fostering the integration of different engineering traditions. The table singles out Roberts, Murray , Maudslay and Whitworth in this role, and this is also corroborated by their personal biographies.

FIGURE 5. KERNEL DENSITY OF OUTDEGREE CENTRALITY



Overall, these findings seem to suggest that employee start-ups were primarily a vehicle for the reproduction of technical skills and routines. Remarkably, parent firms did not regard employee spin-offs with hostility, as unwanted competitors (Maudslay, in this respect, is the most prominent example). Rather, the process of new firm creation was perceived as favouring the consolidation of sound engineering traditions, so that the rapid growth of the industry could proceed unchecked by bottlenecks and shortages.[14] In this respect, one has to note that sub-contracting was fairly widespread in many mechanical engineering branches, so that competitive and cooperative behaviours and strategies co-existed and overlapped (see Cookson, 1997 for a discussion of these issues in the case of the Yorkshire textile engineering industry).

The process of firm creation was also bolstered by the low level of entry barriers in the sector. As noted by Crouzet:

"Engineering was an industry in which entry was always easy and opportunities for men of little capital, but with unusual skill and a gift for invention, were particularly good. These conditions appeared from the beginning of the industry, when millwrights, who had formerly been itinerant craftsmen, established shops for building machinery. And when specialized machine-making had emerged, a clever and skilled mechanic could set up with very small means, in one roomed premises, with a few machine tools which he built himself, sometimes alone, sometimes with one or two helpers. Some famous engineers, such as Henry Maudslay, William

[14] The main features of this process of new firm creation are consistent with the interpretive account of spinoffs in contemporary high tech industries suggested in Klepper (2001).

Fairbairn, Joseph Whitworth and James Kitson, started in such a modest way" (Crouzet, 1985, pp. 89-90).

Low entry barriers encouraged the proliferation of spin-offs based on the exploitation of the skills that the firm's founders had acquired in their previous employment.

By the early nineteenth century, following the expansion of the industry, a number of companies had come to specialize in the production of particular types of machinery—though rarely to the complete exclusion of other types ('general engineering'). In the London area, Donkin specialized in paper and printing machinery, Napier in printing machinery, Maudslay in marine engines, Bramah in hydraulic engineering, etc. (Musson, 1980, p. 93).

Interestingly enough, specialization seems to have been much more developed in the Manchester area. According to Peter Ewart, here the rapid growth of demand for textile machinery had favoured the emergence of a very extensive division of labour:

"[T]here are two or three classes of spindle makers, separate and distinct trades, masters and men. Before the demand was so great as it is, one master spindle would make several kinds of spindles; now....he confines his work to one kind of spindle only" (Ewart, 1824, cited in Lloyd –Jones and Lewis, 1988, p. 168).

It is worth noting that the extensive division of labour provided a wide range of business opportunities (market niches) for the entry of new firms with limited capital endowments. Furthermore, the division of labour in the Manchester area also proceeded 'upstream' with the emergence of specialist firms in the production of machine tools, such as Roberts, Nasmyth, etc. (perhaps surprisingly, the available evidence suggests that Maudslay never undertook the production of machine tools for sale). The importance of the textile industry for the emergence of machine-tool specialists has been stressed by Cardwell (1994, p. 219):

"The machine tool industry in early nineteenth century Britain was located in Glasgow, Leeds, Bradford, Manchester and London, all, with the exception of London, textile cities. The textile industry was the only industry that demanded large numbers of identical and complex machines substantially made of iron. On the other hand, Birmingham - the home of Boulton and Watt – Liverpool and the Cornish mining area, famous for its steam pumping engines, were not centres of machine tool technology. The rationale behind this seems to be that, although statistics are not available, the number of individual textile machines must have greatly exceeded the number of individual steam engines".

CONCLUSIONS AND OUTLOOK ON FUTURE WORK

This paper is intended to be a very preliminary recognition of the historical literature on the emergence of mechanical engineering in early industrial Britain. Our starting point has been the model of industrial evolution sketched by Rosenberg (1963a; 1963b). This model has served as a basis for outlining a number of features of the development of mechanical engineering in early industrial Britain. In particular our work has highlighted a number of points of interest:

1) the large and growing share of mechanical engineering in patented inventions, which provides support for the view that the industry was a fundamental engine of technical progress in the early phases of industrialization;
2) the large contribution of users to innovative activities;
3) the importance of employee spin-offs in the creation of new firms;
4) the emergence of stable patterns of product specialisation (although the overall process seems to reflect a much less tidy progression of the division of labour across firms than the one envisaged in Rosenberg's model).

In the near future, we hope to be able to link these findings in a more fully fledged reconstruction of the formation of some of the most important mechanical engineering centres (London, Manchester, Birmingham, Leeds, Glasgow and Cornwall) in the late eighteenth and early nineteenth centuries.

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