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After the great inventions: technological change in UK cotton spinning, 1780–1835

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This article analyses the improvement of cotton-spinning technologies in the years after the great inventions of Hargreaves, Arkwright, and Crompton. While these 'macro-inventions' have attracted considerable historical attention, our understanding of the major changes in types and sizes of spinning machines used in the UK between the 1780s and the onset of state-collected factory statistics in the 1830s is still largely based on the experience of high-profile firms or specific technologies and regions. A new dataset of 1,465 machinery advertisements published in newspapers in England, Scotland, and Ireland between 1780 and 1835 allows us to examine the temporal and spatial dimensions of the market for cotton-spinning machinery, the timings of transitions between different spinning machines, and increases in machine size. The article demonstrates the importance of post-invention technical improvements in the cotton industry, showing that the productivity increases associated with the initial transition from hand to machine spinning have been overstated and that larger gains were made in the 'micro-invention' phase, when spinning machines became larger and faster, and required fewer workers to operate them.

Economic historians have long sought to explain the technological breakthroughs of the second half of the eighteenth century, an investigation that François Crouzet likened to 'the quest for the Holy Grail'.[1] This quest continues, and a plethora of recent studies have re-examined the economic, political, and cultural incentives driving the famous cotton-spinning inventions of James Hargreaves, Richard Arkwright, and Samuel Crompton.[2] While these 'macro-inventions', to borrow Mokyr's terminology, constituted substantial departures from previous productive potential, Mokyr has argued that it was 'micro-inventions'—improvements to existing machines—which ensured the initial productivity gains in industrializing Britain did not 'fizzle out like similar

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[1] Crouzet, *Britain ascendant*, p. 100.

[2] Allen, *Global perspective*; idem, 'Spinning jenny: a fresh look'; Mokyr, *Enlightened economy*; Parthasarathi, *Global economic divergence*; Riello, *Cotton*; Styles, 'Fashion'; idem, 'Spinning jenny'; Ashworth, *Industrial revolution*; Humphries and Schneider, 'Spinning'.

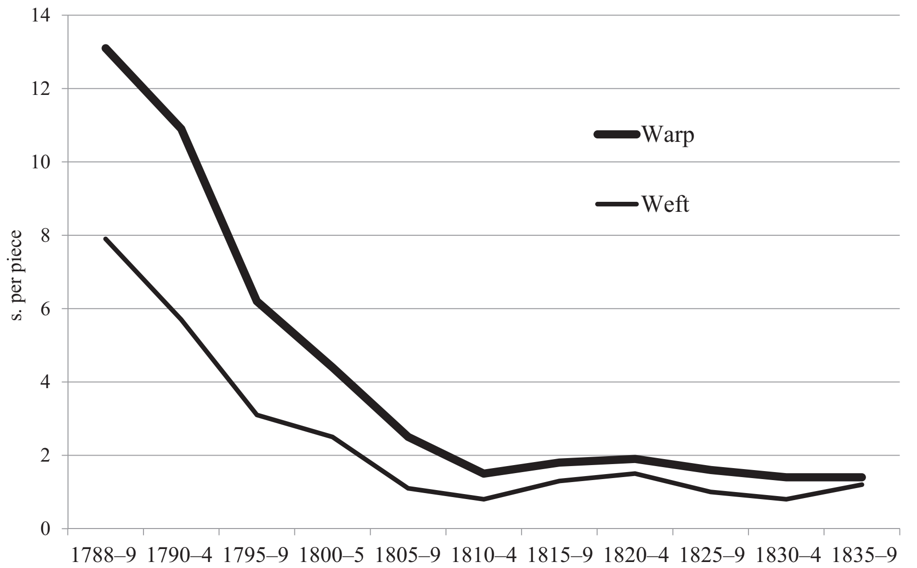


Figure 1. *Yarn added-value (based on printed cloth woven from 36s yarn), 1788–1839*
Source: Harley, 'Cotton textile prices', p. 64.

bursts of macro-inventions in earlier times'.[3] Recent work on the watch industry in the eighteenth century has also shown the importance of such incremental technical improvements in generating rapid productivity change, even in the absence of major inventions.[4] In short, a full understanding of the industrial revolution requires a detailed analysis not just of the invention of new machines but also their improvement and diffusion.[5]

Harley's estimates of the value-added in cotton spinning provide useful context for the research presented in this article. Figure 1 shows that real value-added in spinning fell sharply between the late 1780s and the early nineteenth century, and declined again in the 1820s. Harley's estimates begin after the great inventions, so they capture post-invention productivity increases rather than the immediate effects of the transition from hand to machine spinning in the 1760s and 1770s. Technological transitions take time, as new technology needs to be embodied in investments in machinery or plant. David, for example, has argued that the impact of electricity on manufacturing productivity was delayed because its advantages were wrapped up with the change from vertical to horizontal factory organization.[6] Mechanical cotton spinning was also tied up with factory organization and, although there was no overhang of fixed investment comparable to the case of electricity, it still took time for entrepreneurs to learn about the new technology and to mobilize the resources to build factories. Another reason is that both managers and workers needed experience with the new technology to reap its productivity

[3] Mokyr, *Lever*; idem, *Gifts*, p. 29 (quotation); idem, *Enlightened economy.*
[4] Kelly and Ó Gráda, 'Adam Smith'.
[5] For a recent call for emphasis on the diffusion of cotton-spinning machinery, see Hahn, 'Spinning', p. 232.
[6] David, 'Dynamo'.

gains, although there is controversy on the extent to which 'learning by doing' was significant in the early cotton industry.[7] Still another reason is that these new technologies were susceptible to considerable improvement: Mokyr's micro-inventions. It is the improvement and diffusion of the prototype spinning inventions that is the focus of this article.

Post-invention improvements in cotton-spinning technologies and their installation in factories have not attracted the attention they deserve. The most detailed research has focused on the late eighteenth century and on water-powered 'Arkwright mills' at the expense of the more modest first-generation jenny and mule factories.[8] The years between *c.* 1795 and the onset of the state-collected factory statistics in the mid-1830s are less well documented. There are important company histories, notably on the Arkwright, Oldknow, Ashworth, Fielden, Greg, Murray, and M'Connel & Kennedy firms, as well as articles on individual mills. However, these business histories document only a tiny fraction of the enterprises active in the late eighteenth and early nineteenth centuries and are biased towards large, enduring firms.[9] More general studies of the cotton industry during this period are also surprisingly limited, although Daniels, Edwards, Chapman, Farnie, Timmins, Lloyd-Jones, Lewis, Cooke, and Nisbet have offered important insights on the technological history of cotton spinning.[10] Even so, the most comprehensive studies of the building and equipping of cotton-spinning factories are still to be found in local studies of particular townships and parishes not aimed at an academic audience, especially those by Haynes on the districts around Oldham and Ashton and by Rothwell on north-east Lancashire.[11]

This article focuses on the four main cotton-spinning technologies used in the UK between 1780 and 1835: the spinning jenny invented by Hargreaves in the mid-1760s; the water-frame invented by Arkwright later in the same decade; the mule invented by Crompton *c.* 1779; and the throstle, not definitively associated with a particular inventor or a precise date of invention, although Cookson has traced its origins to improvements to the water-frame's power-transmission system begun in Stockport in the late 1770s.[12] The new spinning machines operated either 'intermittently' or 'continuously'. Intermittent spinning pre-dated the industrial revolution: on the one-spindle hand wheel used to spin cotton, the spinner first stretched out ('drafted') and twisted a portion of roving (a lightly twisted tube of cotton which had already been subject to a number of pre-spinning processes), before halting and backing off the wheel to wind on that section of newly spun yarn. Hargreaves's jenny and Crompton's mule upgraded this 'intermittent' principle,

[7] Chapman, 'Arkwright mills', pp. 10–14; David, 'Learning by doing'; Bessen, 'Technology and learning'.

[8] Chapman, 'Fixed capital formation'; idem, *Early factory masters*; Aspin, *Water-spinners*; Ingle, *Yorkshire cotton*. The Scottish industry has been better served: Cooke, *Scottish cotton*; Nisbet, *Renfrewshire*. On Ireland, see Bielenberg and Solar, 'Irish cotton'.

[9] For book-length studies, see Fitton and Wadsworth, *Strutts and the Arkwrights*; Unwin, *Oldknow and the Arkwrights*; Boyson, *Ashworth cotton*; Lee, *M'Connel and Kennedy*; Fitton, *Spinners of fortune*; Law, *Fieldens*; Rose, *Gregs*; Miller et al., *Murray*. For articles, see Chaloner, 'Early factory system'; Mackenzie, 'Bakewell'; Lindsay, 'Evans' cotton mill'; Chapman, 'Peels'; Clark, 'Chorlton Mills'; Cooke, 'Stanley Mills'; Robertson, 'New Lanark'.

[10] Daniels, 'Revolutionary and Napoleonic Wars'; Edwards, *Cotton*, pp. 4–5, 182–215; Chapman, *Early factory masters*; Farnie, *Cotton*; Timmins, 'Technological change'; Lloyd-Jones and Lewis, *Manchester*; Cooke, *Scottish cotton*; Nisbet, *Renfrewshire*.

[11] This literature is too extensive to cite in full but representative publications are: Haynes, *Stalybridge*; Rothwell, *Ribble Valley*.

[12] Cookson, *Age of machinery*, p. 59.

using sliding cloves or carriages that drafted and twisted the rovings as the machine moved out and wound the yarn as it moved in. By contrast, water-frame and throstle spinning was 'continuous', with drafting, twisting, and winding occurring in a single, uninterrupted motion. Continuous spinning also had a hand-technology antecedent in the foot-pedalled spindle-and-flyer wheel, although this was used primarily to spin flax. The continuous processes mainly produced tight-spun warp yarns, while intermittent spinning was better adapted to the softer, less twisted yarn used for weft. The mule was the most versatile machine in that it could spin warps and wefts and could produce coarse, medium, and fine yarns.

This article draws on newspaper advertisements, the only source known to contain significant evidence on the types and sizes of UK cotton-spinning machines between 1780 and 1835. While Chapman has used such advertisements to trace changes in the size and layout of factories, we know of only two systematic studies of cotton-mill machinery based on this source.[13] Suzuki extracted information from the *Manchester Mercury* between 1780 and 1820, but only concerning water-frame spinning, and Watmough, in a more limited foray, looked at all types of spinning machines advertised for sale in the *Manchester Mercury* in a single year, 1795.[14] We cover a longer period, with a much broader set of newspapers. We have extracted 1,465 advertisements from UK newspapers, referring to sales of more than 20,000 spinning machines.

After surveying contemporary and modern evidence on the diffusion of the different spinning technologies in the next section, we discuss machinery advertisements as a source, and then consider the regional dimensions of the public market for spinning machinery, which was centred on Manchester and, to a lesser extent, on Glasgow and Belfast. The following section analyses the overall mix of different machines in UK cotton spinning, showing the timing of the transitions from the jenny to the mule in intermittent spinning in the 1790s and, around a decade later, from the water-frame to the throstle in continuous spinning. We then show how the numbers of spindles on these machines increased over the period, with mules showing by far the largest change. The final section assesses the contribution of micro-inventions to the productivity gains achieved in cotton spinning before 1835, demonstrating the importance of post-invention improvements.

I

Contemporary estimates provide sporadic evidence on the use of different cotton-spinning technologies during the industrial revolution (table 1). The earliest, produced by Arkwright in 1784, suggests there were around 283,000 jenny spindles, 60,000 water-frame spindles, but only 4,200 mule spindles in use in the cotton industry. Arkwright was, of course, well informed on the use (licensed or otherwise) of the water-frame, but his jenny count was more speculative, not least because he reckoned that two-thirds of jennies were in the homes of workers rather than in factories. His figure of just 4,200 mule spindles in 1784 is plausible as the machine had only been made public in 1780.

[13] Chapman, 'Arkwright mills', pp. 26–7.
[14] Suzuki's book is reviewed in English in Yuzawa, 'Review'; Watmough, 'Manchester', pp. 44–6.

Table 1. *Contemporary estimates of machine spindleage in the UK cotton industry (spindles, 000)*

	Jenny		*Mule*		*Water-frame*		*Throstle*		*Total*
1784	283	(82%)	4	(1%)	60	(17%)	0		347
1787	1,605	(83%)	50	(3%)	286	(15%)	0		1,941
1789	1,400	(58%)	700	(29%)	310	(13%)	0		2,410
1811	156	(3%)	4,200	(90%)	311 (7%)				4,667
1845	0		13,000	(74%)	0		4,500	(26%)	17,500

Sources and notes:
1784: Richard Arkwright's estimates, which refer to England only, are given in full in Fitton, *Spinners of fortune*, pp. 212–13. Arkwright stated that two-thirds of jennies were in domestic use and had up to 30 spindles, and one-third in the possession of firms or people operating on a larger scale with an average of 74 spindles. The nos. of jenny spindles given here assumes that domestic jennies averaged 16 spindles. If the domestic jennies are assumed to average 24 spindles, the no. of jenny spindles would increase to 325,350 and their share of spindles to 84%.
1787: Patrick Colquhoun, referring to Britain, *Important question*, p. 3; idem, *Important crisis*, p. 4.
1789: Patrick Colquhoun, referring to Britain, *Case of the British cotton spinners*, p. 7.
1811: Samuel Crompton survey: Bolton History Centre, Crompton Papers, ZCR/16a, ZCR 16c (England and Scotland). Crompton's survey did not distinguish between water-frames and throstles.
1845: based on contemporary statistics compiled by du Fay & Co. of Manchester, reported in McCulloch, *Dictionary of commerce*, p. 465. Refers to England, Scotland, and Ireland.

Patrick Colquhoun's two estimates in the late 1780s suggested that significant diffusion of all machine types (except the throstle) had taken place. His estimates of jenny and water-frame spindles in 1787 were four to five times higher than Arkwright's, while mule spindles were more than 10 times higher. The rapid uptake of the mule is further suggested in a second set of Colquhoun estimates published two years later, indicating British mule spindles had increased from 50,000 in 1787 to 700,000 in 1789. His estimates of water-frame spindles showed a slight increase over the same two years, while he considered jenny spindles to have fallen from 1.6 million to 1.4 million.

The next estimates—Crompton's famous spindle 'census'—did not appear until 1811, by which time mules dominated UK cotton spinning. However, Crompton's enquiry was made in attempt to win parliamentary compensation for his own invention, and he might have downplayed the prevalence of other machines. He also, rather unhelpfully, did not distinguish throstles from water-frames, overlooked the English midlands and north Wales (both enthusiastic adopters of Arkwright's frame), and provided no detailed returns for Scotland or Ireland. Hence, the apparent stagnation of continuous spindles between 1789 and 1811 implied by table 1 is probably overstated. The accuracy of the nine-fold decline in jenny spindles from Colquhoun's estimate is also difficult to assess, but Crompton's survey did include detailed observations from Manchester, Stockport, and Wigan, where jenny spinning had been most extensive in the 1780s. By 1832, Scottish mill manager James Montgomery considered that the 'common jenny…[was] entirely out of use'.[15] Even in Stockport, the jenny was said to be 'fast going out of use' by 1832.[16]

After Crompton's survey, only John McCulloch's *Dictionary of commerce* includes aggregate information on the relative use of mules and throstles, and only for

[15] Montgomery, *Carding and spinning*, p. 137.
[16] *Labour of Children in the Mills and Factories* (P.P. 1831–2, XV), evidence of William Longston, p. 433.

a single year: 1845. These estimates, based on information provided by du Fay & Co., merchants of Manchester, suggest a three-fold increase in mule spindles between the Napoleonic Wars and the mid-1840s, but a much larger increase in twist spinning on throstles. While such an increase might be overstated by using Crompton's 1811 estimates as a base, other contemporary evidence adds weight to the idea of a revival in continuous spinning in the postwar period. Montgomery's 1832 technical manual suggested that the demand for fine cottons in the early nineteenth century meant that 'frames … were, in great measure, superseded by mules', before the diffusion of the powerloom encouraged coarser cottons, so that 'the attention of the trade seems now wholly engrossed with the throstles'.[17] The total spindles reported in the 1845 estimates (17.5 million) also fit well with the subsequent factory returns of 1850, the first to include spindle counts, which recorded 20.9 million cotton spindles in the UK, a figure that included roughly 0.5 million spindles used in 'doubling'.[18] The UK factory statistics from 1850 onwards do not distinguish between machine types or report numbers of machines and so offer no guidance on the mix of mules and throstles or on average machine size.[19]

Historians' attempts to build on these contemporary estimates have produced an uneven coverage of the adoption of different machine types. Water-frame spinning has attracted most attention, with no fewer than 210 Arkwright-inspired, water-spinning mills identified in Lancashire and Yorkshire by the mid-1790s, together with roughly 100 in the English midlands, and something like 50 in Scotland. Chapman considered this the apogee of water-frame spinning—he tentatively estimated a total of 1.25 million spindles—and did not allow for any extension of continuous spinning in his estimates of new fixed-capital formation in the cotton industry between *c.* 1795 and 1815. However, the insurance policies that underpinned much of this research on water-frame spinning provide few details on mill technologies and hence do not help to track incremental improvements in machine design or the timing of the frame's replacement by the throstle.[20]

Research on hand-powered jennies and mules has been more limited, not least because they were initially used in workers' homes or in converted buildings that have a less conspicuous presence in the surviving records than the more visible water-powered mills.[21] By the mid-1790s, power-assisted mules had been introduced into larger, purpose-built factories, making the subsequent diffusion of the mule easier to trace, although this has not yet been done systematically. One reason is that business records for early UK cotton spinners are rare and information in them concerning machinery even rarer. Another potentially useful source would be the records of specialist machine-makers, which began to appear from the 1790s.[22] But early machine-making firms were often small and evanescent, and few of their business records survive before the 1830s and 1840s. Cookson, in her recent study of Yorkshire textile engineers, drew on a wide variety of sources to

[17] Montgomery, *Carding and spinning*, pp. 145–6.
[18] *Returns on the Number of Cotton, Woollen, Worsted, Flax and Silk Factories* (P.P. 1850, XLII). 'Doubling' refers to the making of thread from spun yarn.
[19] On the state-collected factory statistics after 1850, see Jenkins, 'Factory returns'.
[20] See n. 8.
[21] Chapman, 'Fixed capital formation', pp. 243–5.
[22] Daniels, *Cotton industry*, pp. 127–8.

tell us much about their social origins and their businesses, but found only scattered information on the technical history of the machinery they constructed.[23] Only in the later nineteenth century, when firms like Platt Bros., Oldham, became large-scale suppliers of textile machinery to the UK and the world, do documents such as order books and machine drawings survive as a rich body of information on the types and size of machines used to spin cotton.[24]

Hence, the chronology of the rise of the mule and the decline of the jenny has proved elusive. Edwards, for example, has contended that jenny spinning reached its peak in the 1780s, while Chapman and Timmins have emphasized that in some places jenny spinning survived into the nineteenth century.[25] This question has been re-opened in a recent study by Sugden, which draws on bridegrooms' occupations in Lancashire and Cheshire between 1780 and 1813 to trace the diffusion of the mule, a machine mainly operated by adult men. Sugden found that the proportion of Manchester and Stockport bridegrooms described as cotton spinners had already peaked by the early 1790s, and had, by the middle of that decade, also reached significance in Bolton, Bury, and Blackburn. His conclusion that the mule had rendered the jenny 'obsolete' by the mid-1790s is thus plausible, but the evidence is not definitive because the marriage licenses rarely specified the bridegrooms as *mule* spinners and, by the later 1780s, larger jennies were also mainly operated by men.[26]

In sum, current studies have provided patchy coverage of the diffusion of cotton-spinning machines after *c*. 1780. Our knowledge of early cotton spinning in the UK continues to rely on untested contemporary estimates, circumstantial evidence, or the experience of high-profile firms.

II

Newspaper advertisements provide a more abundant source of information on early cotton-spinning machinery than other sources used by historians. Our data are taken from newspapers published throughout the UK between 1780 and 1835 and constitute something close to the universe of newspaper advertisements for cotton-spinning machinery during this period. The bulk of our observations arise from a systematic study of hard-copy newspapers published in Manchester, Blackburn, Leeds, Glasgow, and Belfast or similar work done by others, and made available to us, on newspapers published in Derby, Nottingham, Preston, and Glasgow.[27] This has been supplemented by searching in digitized newspapers published in the more peripheral centres of cotton-spinning, via the following

[23] Cookson, *Age of machinery*.
[24] Saxonhouse and Wright, 'Technological evolution'.
[25] Edwards, *Cotton*, pp. 8, 182–99; Timmins, 'Technological change', pp. 54–6; Chapman, *Early factory masters*, pp. 53–9.
[26] Sugden, 'Adult male'; Pinchbeck, *Women workers*, p. 148; von Tunzelmann, *Steam*, p. 176; Styles, 'Spinning jenny', pp. 26–8.
[27] We are grateful to Stanley Chapman for sharing notes from the *Nottingham Journal*; to Stuart Nisbet for sharing his notes on advertisements of Renfrewshire mills in Glasgow newspapers, to Ian Miller for notes from Preston newspapers; to Thomas Reid for providing us with the notes of the Industrial Archaeology Group of the Stockport History Society from the *Stockport Advertiser*, and to Graham Brooks for his notes from the *Carlisle Journal*. We also draw on joint work by John Cockerill and Peter Solar on Belfast newspapers.

Table 2. *Data sources and locations of machinery (number of advertisements)*

	Adverts	*Centre*	*InnerBelt*	*Periphery*	*Other*
Source locations					
ENGLAND AND WALES					
Manchester and Stockport	953	424	248	264	17
Derby and Nottingham	30	0	1	28	1
Blackburn, Lancaster, and Preston	122	1	9	112	0
Leeds	112	4	2	106	0
Other England and Wales	22	0	0	22	0
SCOTLAND					
Glasgow	140	36	77	24	3
Other Scotland	14	1	5	8	0
IRELAND					
Belfast	62	29	22	11	0
Other Ireland	10	1	0	9	0
TOTAL	1,465				
Periods (%)		Centres	Inner Belts	Peripheries	
1780–1810		37.8	16.6	45.6	
1811–35		32.5	27.4	40.1	

Notes: Regions for source locations: England and Wales: centre = Manchester (parish) and Stockport; inner belt = surrounding area to about 15 miles from Manchester; periphery = rest of England and Wales; other = Scotland and Ireland. Scotland: centre = Glasgow; inner belt = Dumbarton, Renfrew, Stirling, and rest of Lanark; Periphery = rest of Scotland; other = England and Wales and Ireland. Ireland: centre = Belfast; inner belt = counties Antrim and Down to about 15 miles from Belfast; periphery = rest of Ireland; other = England and Wales and Scotland.
Sources: Manchester and Stockport: *Manchester Mercury* (388 observations), *Manchester Chronicle* (353), *Manchester Guardian* (201), *Stockport Advertiser* (11). Derby and Nottingham: *Derby Mercury* (29), *Nottingham Journal* (1). Blackburn, Lancaster, and Preston: *Blackburn Mail* (92), *Lancaster Gazette* (22), various Preston (8). Leeds: *Leeds Intelligencer* (67), *Leeds Mercury* (45). Other England and Wales: *Carlisle Journal* (7), *Macclesfield Courier* (5), various London (7), various others (3). Glasgow: *Glasgow Advertiser* (5), *Glasgow Chronicle* (27), *Glasgow Courier* (86), *Glasgow Herald* (20), *Glasgow Mercury* (2). Other Scotland: *Caledonian Mercury* (14). Belfast: *Belfast Newsletter* (47), *Belfast Commercial Chronicle* (13), *Northern Whig* (2)/ Other Ireland: various Dublin (9), other (1).

search terms: 'cotton spinning', 'cotton mill', 'cotton machinery', 'cotton spinner', 'mule', 'jenny', 'throstle', and 'water frame'.[28]

In total, our database contains 1,465 advertisements (table 2). As advertisements often ran for several issues, we have excluded repeated adverts for the same combination of machinery in the same region. In section III, we first explore this complete set of 1,465 advertisements to illuminate the geography of advertising. However, as some adverts appeared in more than one region, sections IV and V evaluate a subset of 1,331 advertisements from which such inter-regional duplicates have been excluded.

Cotton-spinning machinery was advertised in several contexts. The most common, accounting for 63 per cent of the observations (starting at around 50 per cent and rising to 70 per cent over the period), was to announce public auctions for the sale of mills and machinery, or of machinery only, usually following bankruptcies or proprietors' deaths.[29] Advertisements to sell or let by private contract rather than by auction accounted for most of the remaining observations (36 per cent). There were, in addition, a handful of advertisements placed either by machine-makers selling their wares or by factory proprietors seeking managers

[28] See the notes to tab. 2 for the no. of observations by newspaper title.
[29] Bankruptcy was not unusual in the cotton industry. In 1815, the *Manchester Mercury* reported that 'Four fifths of persons who have started spinning factories in Manchester and neighbourhood have failed', cited in Aspin, *Water-spinners*, pp. 37–8.

or labourers in connection with certain sorts of machinery. The results shown below do not differ significantly when broken down by type of advertisement. Since the advertisements primarily concern the sale of second-hand rather than new machinery, there was a time lag between the initial introduction of new machines and their advertisement in newspapers, a feature of the data to which we shall return in section IV.

The newspapers advertisements provide essentially three levels of detail about spinning machinery. The advert shown in figure 2a is indicative of the least informative, mentioning only the *type* of machine being sold or let. Thus, the Stockport mill advertised for private sale in 1784 simply was said to contain 'a Number of Valuable SPINNING JENNIES'. All 1,465 of our observations provide at least this basic information. These adverts underpin the analysis of the diffusion of jennies, water-frames, mules, and throstles presented in section IV. At the second level are advertisements, like the one shown in figure 2b, which describe both the number of machines and the total number of spindles available to purchase or rent, allowing the *average* size of the spinning machines to be calculated. The water-powered mill on sale in Chipping, Lancashire, in 1788 contained 20 water-frames with a total of 1,032 spindles: hence, an average of 52 spindles per frame. Average spindleage by machine type can be calculated in 958 of our adverts.[30] At the third level, the most informative, are advertisements that itemized the type and size of each machine offered for sale or hire. The advertisement shown in figure 2c for a mule factory in Ancoats, Manchester, in 1794 included one mule of 216 spindles, one of 156 spindles, eighteen of 144 spindles, and four of 120 spindles. Overall, 822 of our adverts record the full range of machines for sale and these adverts inform the discussion of machine size presented in section V.

The location of the machinery is specified in most adverts. This allows us to discuss the market for spinning machinery (section III) and the diffusion of spinning machines by region (section IV). In other respects, the advertisements are less informative. Only one advert mentions the price the seller hoped to attain.[31] Likewise, the advertisements offer few details on the age, construction, or condition of the machines, favouring generic marketing language like 'most modern and approved Construction', 'nearly new', or 'newest and best principle'.[32] By the 1820s, however, some advertisements for spinning machines indicated makers of the machines, when specialist engineers like Jenkinson & Bow (of Salford), Isaac Dobson (of Bolton) and Sharp, Roberts & Co., Henry Gore, and Hewes & Wren (of Manchester) had begun to establish reputations for quality.[33]

In the 1780s, when cotton spinning was being established as a distinct activity, there were only a handful of advertisements each year. From the early 1790s, as figure 3 shows, advertisements averaged about 28 annually, with peaks (for example, 1805, 1827) and troughs (for example, 1801–2) that echo the time path

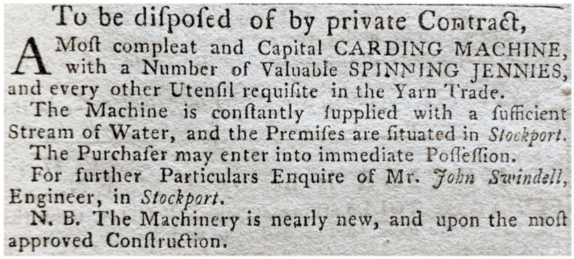
[30] Note these 958 adverts are inclusive of the 822 adverts where we can observe the size of each machine offered for sale/hire.

[31] *Blackburn Mail*, 9 Dec. 1801. The advert indicated a price range of £10–£12 for mules of between 144 and 168 spindles. Six years earlier McConnel & Kennedy of Manchester sold new 144-spindle mules of their making for £33. See Edwards, *Cotton*, p. 200. For prices of spinning jennies, see n. 41.

[32] These quotations come from: *Blackburn Mail*, 21 Sept. 1796, 29 Nov. 1797; *Manchester Mercury*, 23 March 1813.

[33] On these firms, see Musson and Robinson, *Science*, pp. 70–1, 98–9, 442–3, 447, 478–80; Edwards, *Cotton*, p. 202.

a) *Manchester Mercury*, 13 Apr. 1784



To be diſpoſed of by private Contract,

A Moſt compleat and Capital CARDING MACHINE, with a Number of Valuable SPINNING JENNIES, and every other Utenſil requiſite in the Yarn Trade.

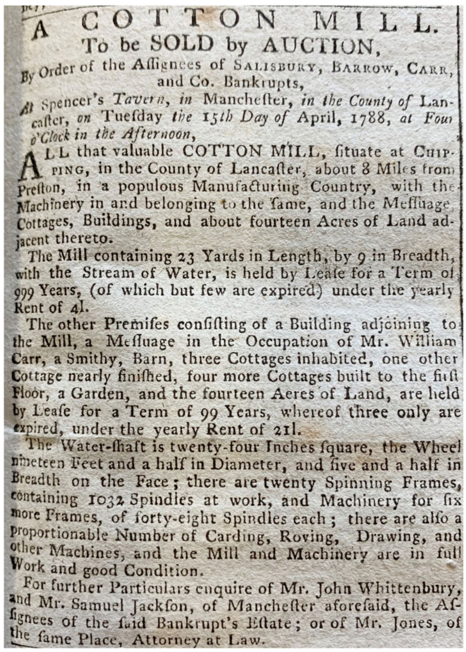
The Machine is conſtantly ſupplied with a ſufficient Stream of Water, and the Premiſes are ſituated in *Stockport.*

The Purchaſer may enter into immediate Poſſeſſion.

For further Particulars Enquire of Mr. *John Swindell,* Engineer, in *Stockport.*

N. B. The Machinery is nearly new, and upon the moſt approved Conſtruction.

b) *Manchester Mercury*, 8 Apr. 1788



A COTTON MILL.

To be SOLD by AUCTION,

By Order of the Aſſignees of SALISBURY, BARROW, CARR, and Co. Bankrupts,

At Spencer's *Tavern, in* Mancheſter, *in the County of* Lancaſter, *on* Tueſday *the* 15*th Day of* April, 1788, *at Four o'Clock in the Afternoon,*

ALL that valuable COTTON MILL, ſituate at CHIPPING, in the County of Lancaſter, about 8 Miles from Preſton, in a populous Manufacturing Country, with the Machinery in and belonging to the ſame, and the Meſſuage Cottages, Buildings, and about fourteen Acres of Land adjacent thereto.

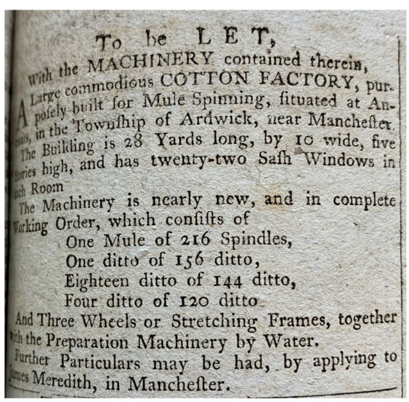
The Mill containing 23 Yards in Length, by 9 in Breadth, with the Stream of Water, is held by Leaſe for a Term of 999 Years, (of which but few are expired) under the yearly Rent of 4l.

The other Premiſes conſiſting of a Building adjoining to the Mill, a Meſſuage in the Occupation of Mr. William Carr, a Smithy, Barn, three Cottages inhabited, one other Cottage nearly finiſhed, four more Cottages built to the firſt Floor, a Garden, and the fourteen Acres of Land, are held by Leaſe for a Term of 99 Years, whereof three only are expired, under the yearly Rent of 21l.

The Water-ſhaft is twenty-four Inches ſquare, the Wheel nineteen Feet and a half in Diameter, and five and a half in Breadth on the Face; there are twenty Spinning Frames, containing 1032 Spindles at work, and Machinery for ſix more Frames, of forty-eight Spindles each; there are alſo a proportionable Number of Carding, Roving, Drawing, and other Machines, and the Mill and Machinery are in full Work and good Condition.

For further Particulars enquire of Mr. John Whittenbury, and Mr. Samuel Jackſon, of Mancheſter aforeſaid, the Aſſignees of the ſaid Bankrupt's Eſtate; or of Mr. Jones, of the ſame Place, Attorney at Law.

c) *Manchester Mercury*, 20 May 1794



To be LET,

With the MACHINERY contained therein,

A Large commodious COTTON FACTORY, purpoſely built for Mule Spinning, ſituated at An- ants, in the Townſhip of Ardwick, near Mancheſter.

The Building is 28 Yards long, by 10 wide, five ories high, and has twenty-two Saſh Windows in ch Room

The Machinery is nearly new, and in complete Working Order, which conſiſts of

One Mule of 216 Spindles,
One ditto of 156 ditto,
Eighteen ditto of 144 ditto,
Four ditto of 120 ditto

And Three Wheels or Stretching Frames, together with the Preparation Machinery by Water.

Further Particulars may be had, by applying to mes Meredith, in Mancheſter.

Figure 2. *Examples of advertisements for cotton-spinning machinery [Colour figure can be viewed at wileyonlinelibrary.com]*

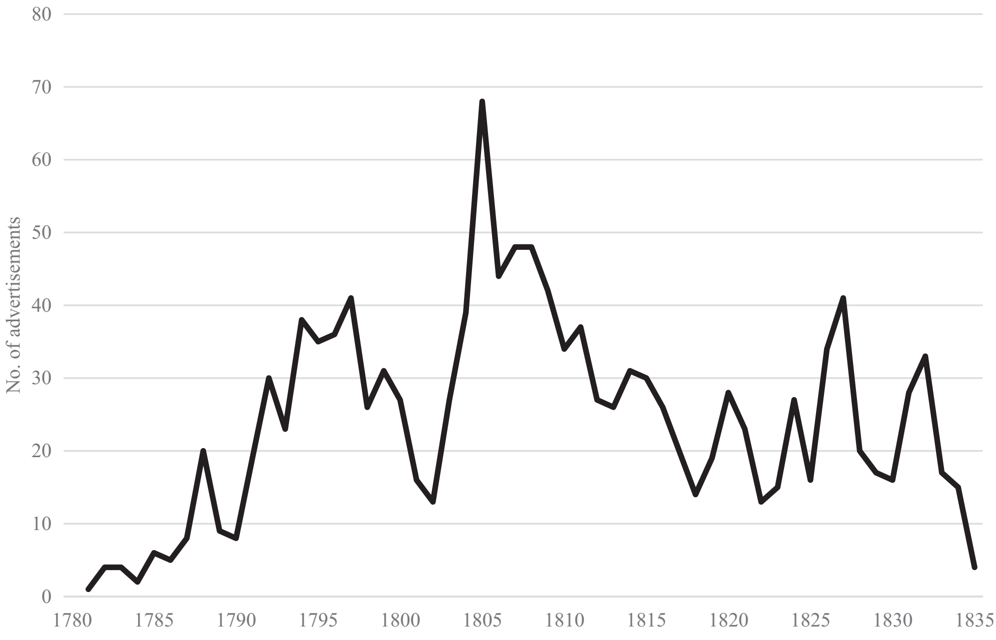


Figure 3. *Cotton spinning machinery advertisements, 1780–1835*
Sources: See tab. 2.

of bankruptcies.[34] Information on the number of UK mills becomes available with the advent of the factory returns, the inspectors recording over 1,800 cotton mills (including some weaving factories) in 1838. Hence, we might be observing annually on average the machinery in about 1.5 per cent of all cotton mills.[35] Over the period, we have information on 1,083 distinct cotton-spinning mills in the UK and more than 20,000 machines, the largest dataset yet assembled to study cotton-spinning machines between the great inventions and the appointment of the factory inspectors. While the adverts provide little detail on the value or construction of these machines, they permit a more nuanced portrayal of two dimensions of technological change in the micro-invention phase of mechanized cotton spinning—the diffusion patterns for particular machine types and increases in their size as measured by the number of spindles—in the UK as a whole or in individual regions.

III

The market for cotton-spinning machinery in the UK had distinct regional elements that reflected the broader geography of the industry. While in the mid-eighteenth century, the hand-spinning of cotton was largely undertaken *within* the fustian-, print-, and check-weaving areas in south-east Lancashire and around Glasgow, the advent of mechanized spinning caused the dispersion of the spinning

[34] On bankruptcies, see Solar and Lyons, 'English cotton spinning', p. 306.
[35] *Persons Employed in Cotton, Woollen, Worsted, Flax and Silk Factories* (P.P. 1839, XLII), pp. 4–352.

branch, motivated both by the search for water-power and the fabled profitability of the pioneer generation of mills. Hence, in tracking advertisements for cotton-spinning technologies in the late eighteenth and early nineteenth centuries, we consulted newspapers published not only in established cotton towns like Manchester, Blackburn, and Glasgow, but also in those like Derby, Nottingham, Leeds, Edinburgh, Belfast, and Dublin that adopted cotton spinning from the later eighteenth century.

Table 2 shows a breakdown of the number of advertisements for cotton-spinning machinery by kingdom (England and Wales, Scotland, Ireland) and newspaper, indicating whether the machines had been installed in the kingdom's principal centre of cotton spinning, in this centre's immediate hinterland ('inner belt'), or elsewhere, either in the kingdom ('periphery') or another kingdom ('other'). The centre for England and Wales is Manchester (with Stockport), and the inner belt is the ring of textile towns within 15 miles, which includes places such as Bolton, Oldham, and Ashton and nearby parts of Cheshire, and Derbyshire. The periphery is everywhere else in England and Wales. The centre for Scotland is Glasgow. Its inner belt comprises the counties of Renfrew, Dumbarton, and Stirling, with most sites situated within 15 miles or so of Glasgow. The periphery is everywhere else in Scotland. In Ireland, the inner belt for Belfast is south county Antrim and north county Down. Its periphery is the rest of Ireland. The 'other' category in each case takes in advertisements for machinery located in another kingdom.

The 'other' column in table 2 shows that each kingdom was largely a distinct market for advertising machinery. Irish newspapers rarely carried advertisements for machinery in British mills. Scottish newspapers included few advertisements for machinery in Ireland or England, and these usually referred to mills in nearby Cumberland and Northumberland. Machinery from mills in Scotland and Ireland was advertised in Manchester, but adverts were few relative to those in Scottish and Irish newspapers. Only 84 adverts appeared in two different source locations, 26 in three, and just two in four (the source locations are those listed in column 1 of table 2). Most of the widely advertised machinery involved large numbers of spindles. For example, Slater's Mill in Carlisle, with 24,480 mule spindles, was advertised in May 1817 in the *Manchester Chronicle*, then in February 1818 in the *Carlisle Journal*, and finally in March 1818 in the *Glasgow Chronicle*.

Within each kingdom the dominance of one town is evident in the 'centre' and 'inner belt' columns. Whereas machinery all over Ireland was advertised in Belfast, there was only one advertisement for machinery from mills in Belfast and its inner belt in newspapers published elsewhere in the country. In Scotland, the situation was similar. Edinburgh's *Caledonian Mercury*, although it kept track of cotton-mill bankruptcies and fires at cotton mills in western Scotland, advertised little machinery from there. In contrast, machinery from eastern Scotland was advertised in the Glasgow newspapers. Manchester newspapers carried advertisements for machinery throughout England and Wales, but newspapers published in north Lancashire, Yorkshire, and the east midlands mainly publicized local sales and rarely carried adverts for machinery in Manchester or its inner belt.

Over time, the dominance of Manchester and Glasgow in machinery advertising increased. Newspapers in these towns always published most advertisements—65 per cent of all our adverts appeared in Manchester newspapers, with Glasgow newspapers providing another 10 per cent. Before 1815, their share was about

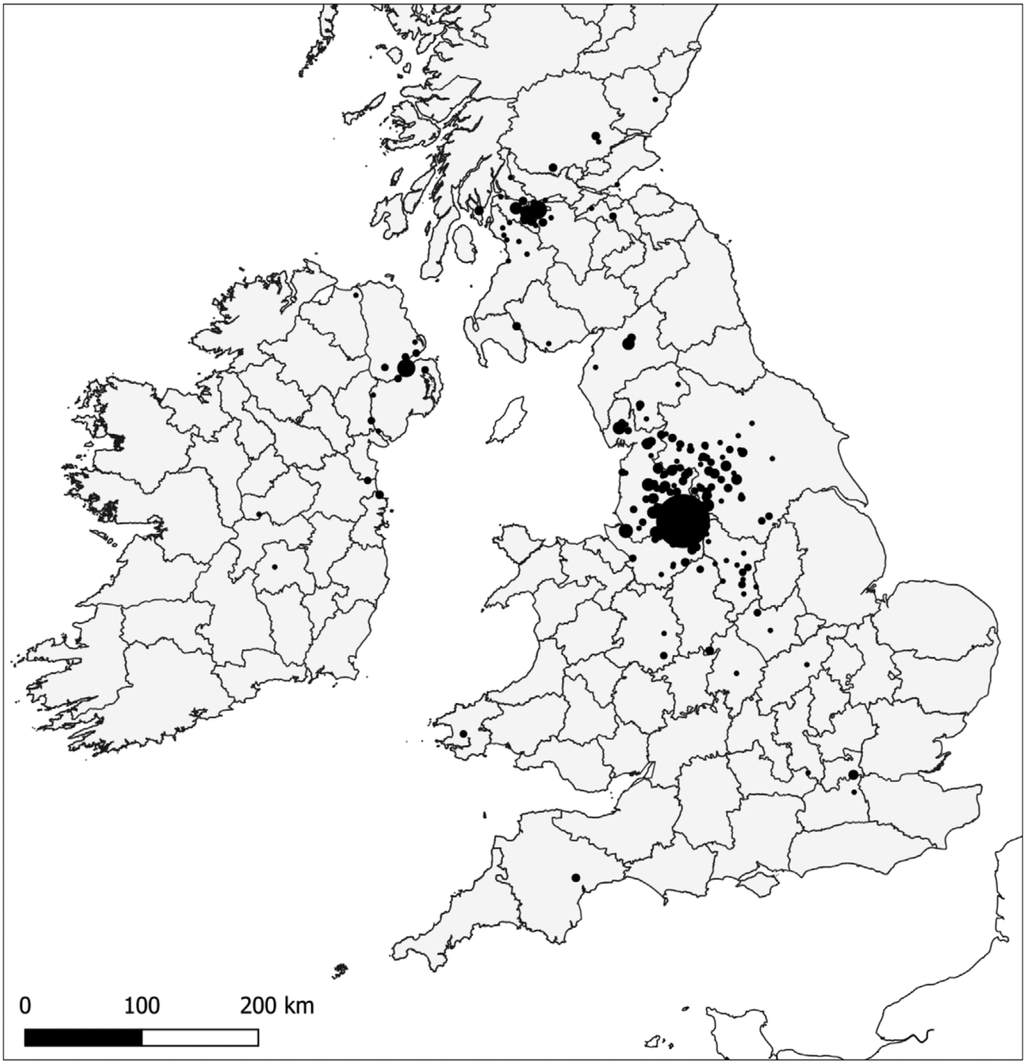


Figure 4. *Advertisements for UK cotton-spinning machinery, by location, 1780–1811*
Sources: See tab. 2.

70 per cent of our adverts; afterwards, around 80 per cent. Over the period, the locations of the machinery advertised also tended to concentrate around Manchester and Glasgow, though not so much in the towns themselves as in the smaller settlements within a range of 15 miles around them (figures 4 and 5 and the lower panel of table 2). After 1810, less machinery was put up for sale in the south of England, in eastern and southern Scotland, or in Ireland outside Ulster. There were also fewer adverts for machines located in northern and western Lancashire, western Cheshire, and northern Yorkshire. The market for cotton-spinning machinery thus mirrored wider currents of spatial concentration in UK cotton spinning.

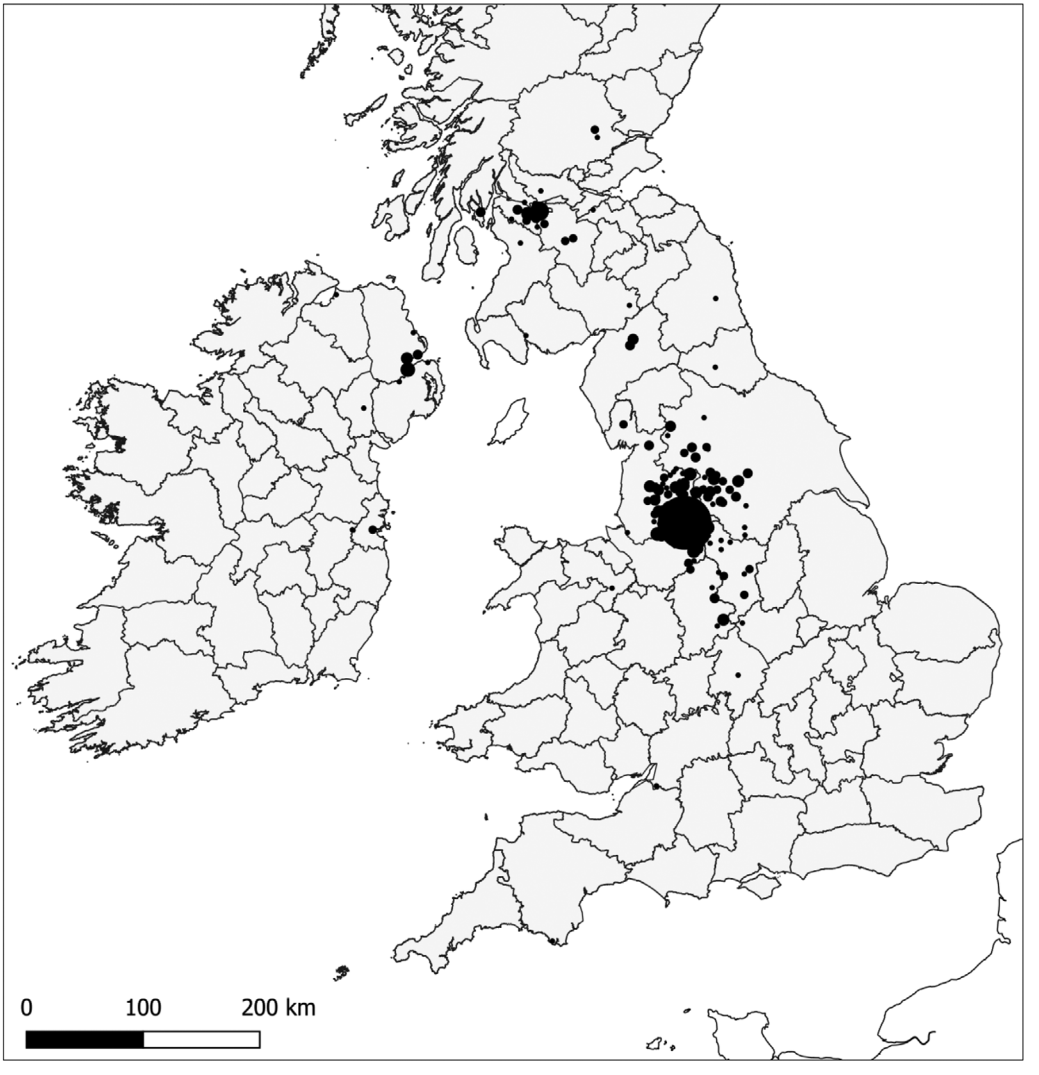


Figure 5. *Advertisements for UK cotton-spinning machinery, by location, 1812–1835*
Sources: See tab. 2.

IV

An important element of technological diffusion in UK cotton spinning was the replacement of the jenny by the mule in intermittent spinning and the transition from the water-frame to the throstle in continuous spinning. Figure 6, which summarizes the share of advertised machines by type in five-year, centred moving averages, provides a starting point to understanding the timing of these transitions. In intermittent cotton spinning, the advertisements suggest, at first sight, that the shift from jenny to mule took place in the mid-1790s. Jennies had featured in around 80 per cent of adverts in the early 1780s, and still over 60 per cent at the end of that decade, but appeared in under half by the mid-1790s, and only one in

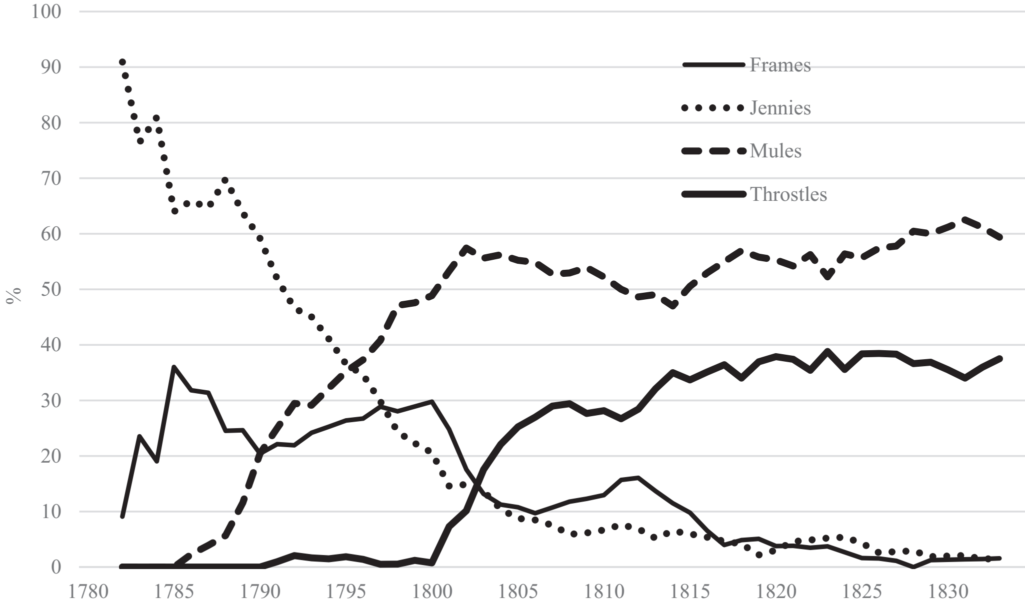


Figure 6. *Machinery advertisements by type of machine*
Note: *Five-year centred moving averages.*
Sources: See tab. 2.

five at the end of the century. The first advertisement for a mule only surfaced in 1788. The mule's share of advertised machines rose rapidly thereafter, exceeding advertised jennies around 1795 and featuring in 50–60 per cent of all adverts in the first three decades of the nineteenth century.

The transition from water-frame to throstle was less dramatic and occurred slightly later, between 1800 and 1805. Water-frames featured in about a quarter of advertisements until *c*. 1800, when their share fell to about 10 per cent, followed by a further decline from around 1815. The first advertisement for a throstle appeared in 1793, but there were only five others up to 1801, from which point advertisements for throstles spiked, exceeding those for water-frames just two years later. This was well before 1815, and, contra Montgomery, was apparently unrelated to the introduction of the powerloom, which had made limited progress before the end of the Napoleonic Wars.[36] Between 1810 and 1830, the throstle was the second most prevalent spinning technology, featuring in around 30–40 per cent of all adverts.

A potential problem with this analysis is the possibility of lengthy lags between the first installation of machines and their advertisement in newspapers. In the 1820s, for example, some machinery was advertised in mills built 30 or more years earlier. However, this does not seem to be a major problem. In figure 7, we restrict the sample to observations specified as new or where we can date the establishment of the mill to no more than five years earlier. This reduces the sample size

[36] Baines, *Cotton manufacture*, p. 235, indicates 2,400 power-looms in use in 1813; Montgomery, *Carding and spinning*, pp. 145–6.

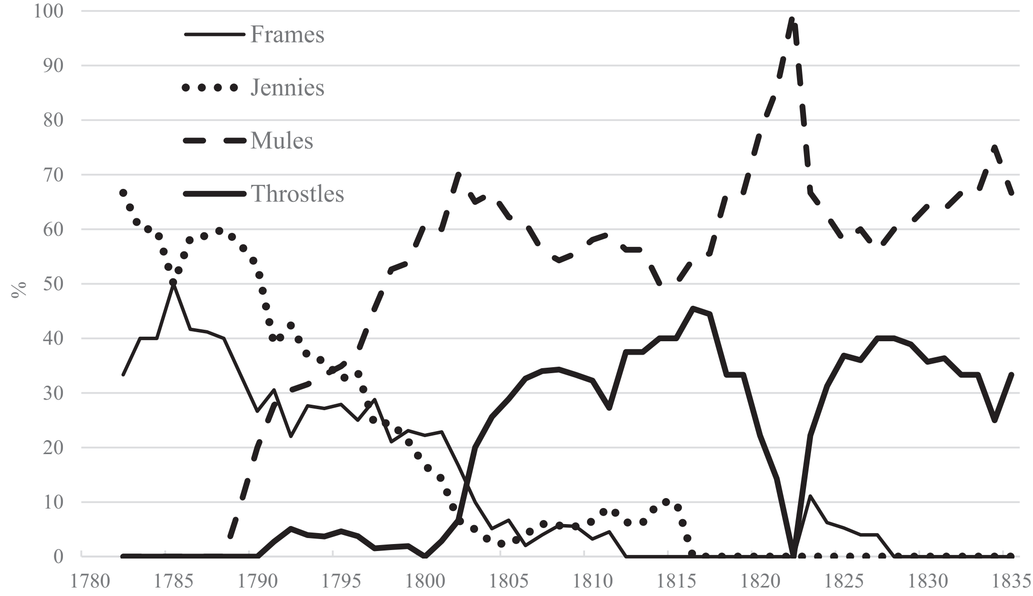


Figure 7. *Cotton machinery by type of machine, recent observations*
Sources: See tab. 2.

drastically, from 1,331 to 227 advertisements, but the general picture remains the same. Strikingly, the years in which mules exceeded jennies and throstles exceeded water-frames do not change, implying a relatively short average lag between first installation and advertisement. This is consistent with evidence on machine lives. In 1816, a Scottish millowner claimed that cotton-spinning machinery needed to be replaced every 'four or five years'.[37] Historians consider the depreciation for textile machinery in this period to be between 7.5 to 15 per cent, implying average machine lives from 6.7 to 13.3 years.[38] If machines were still worth selling, they had probably not exhausted their usefulness. Hence, a rough guess would be that the average lag between installation and sale might be three to five years. Such a lag would suggest the primacy of the mule in intermittent spinning had been established by the early 1790s and that of the throstle in continuous spinning by *c*. 1800.

The water-frame persisted longest in Scotland, where very few throstles were advertised. According to Cooke, throstles were significantly adopted only after 1830, when the Danforth throstle, which ran at higher speeds, was introduced. Cooke attributes the initial lesser use of the throstle in Scotland to differences in product mix.[39] In Ireland, by contrast, throstles were adopted relatively early and were more prominent in machine sales than in England, perhaps because throstles

[37] Cited in Chapman, 'Fixed capital formation', p. 250.
[38] von Tunzelmann, *Steam*, p. 189; Jenkins and Ponting, *Wool*, pp. 17–18; Law, *Fieldens*, pp. 284–5.
[39] Cooke, *Scottish cotton*, p. 107. The Danforth throstle, a US invention of 1828, replaced the water-frame and throstle's spindle-and-flyer arrangement for twisting and winding with a hollow conical cap that guided the yarn onto the bobbin via a stationary spindle, reducing vibration that had limited the maximum speeds of the older throstles. See Wallace, *Rockdale*, pp. 139–43, 196–7.

economized on energy or were less reliant than mules on skilled labour. Within England and Wales, Manchester embraced both mules and throstles perhaps four or five years earlier than its inner belt, with the latter being relatively more committed to mule spinning than elsewhere. The decline of jenny spinning was apparent in all regions by the early nineteenth century. There were no adverts for jennies in Scotland after 1813, and only two in Ireland. In England, the biggest decline was in Manchester, which had accounted for half of adverts for Lancashire jennies in the 1780s, but none in the years after 1805. The largest concentrations of nineteenth-century jenny advertisements related to machinery in Stockport (or places close by) and in the Wigan, Leigh, Walton, and Winnick parishes in western Lancashire.

Newspaper adverts thus furnish a clearer picture of the prevalence of particular machines in early UK cotton spinning than other sources. Our analysis of these advertisements has provided support to those historians—Edwards, and more recently Sugden and Styles—who have argued that the jenny's ascendancy in weft spinning was short-lived: the adverts confirm the dominance of the mule by the early 1790s.[40] Nonetheless, the adverts suggest that the jenny was *by far* the most prevalent spinning technology in the 1780s, a finding that holds even though the smaller domestic jennies with fewer than 40 spindles were too cheap to be captured by our sample of advertisements.[41] The importance of the jenny in the 1780s also emerges from the contemporary estimates given in table 1, but contradicts those historians who have assumed that the water-frame, with its highly visible mills, dominated cotton spinning before the heyday of the mule.[42] In fact, the water-frame did not long survive the death of its creator in 1792. By the earliest years of the nineteenth century, the throstle was the technology of choice in continuous warp spinning, even if the mule dominated UK cotton spinning as a whole, especially in Manchester, Glasgow, and their inner belts.

V

Cotton-spinning machines were subject to significant improvement in design and construction in the years after the great inventions. Some of these innovations were either sufficiently distinct, or well-publicized by contemporaries, to attribute them to specific inventors, while others were improved by artisans who will remain forever anonymous. Machine size as measured by spindle numbers is the most tangible measure of improvements in machinery design and construction. While there has been widespread agreement that spinning machines increased in size over time, no systematic attempt has been made to measure these increases, with most accounts relying on examples specific to certain firms at particular dates.[43] Our

[40] Edwards, *Cotton*, pp. 8, 182–99; Sugden, 'Adult male'; Styles, 'Spinning jenny', pp. 32–3.

[41] Styles, 'Spinning jenny', p. 26, cites prices of 34 and 36 shillings for domestic jennies purchased in Lancashire in the 1770s. Landes, *Unbound Prometheus*, p. 65, gives the figure of 120 shillings for a 40-spindle jenny in 1792; Aspin, *Water-spinners*, pp. 93–4, cites an 84-spindle jenny costing 84 shillings and a 105-spindle jenny costing 204 shillings in the early 1790s. The domestic jennies thus may not have borne the cost of advertising. Styles, 'Spinning jenny', pp. 31–2, uses evidence from embezzlement convictions to show that domestic jennies rapidly fell out of use from the late 1780s.

[42] See, for example, Ingle, *Yorkshire cotton*, p. 15; Cooke, *Scottish cotton*, p. 108.

[43] Daniels, *Cotton industry*, pp. 162–3; Wadsworth and de Lacy Mann, *Cotton*, pp. 155–63; Fitton and Wadsworth, *Strutts and the Arkwrights*, pp. 81–6; Edwards, *Cotton*, pp. 200–1; Catling, *Mule*, pp. 25–30; Hills, *Power*, p. 59.

sample of newspaper advertisements provides more detailed and comprehensive information on the sizes of the different machines operating in the early years of UK factory-cotton spinning. The trends in the average spindles per machine type, distinguishing between intermittent and continuous spinning, are shown in figure 8, which is based on the 958 advertisements that either itemized the size of each machine offered for sale/let or provided sufficient detail for us to calculate average sizes for each machine type. The most striking development was the growth in the size of mules. Between the late 1780s and the late 1790s, the average number of spindles on advertised mules doubled, from about 100 to about 200. After 1800, growth slowed until another burst of innovation in the late 1820s pushed the average number of spindles per mule over 300. All the other spinning machines carried fewer spindles, averaging between 50 and 100 spindles in the late eighteenth century and between 100 and 150 spindles in the first three decades of the nineteenth century.

The dataset also allows us to analyse the range of different machine sizes advertised over time. The four panels of figure 9 plot the number of spindles carried by each machine in our sample. It shows that, across the whole period, the most commonly advertised jennies had 84, 100, 106, 120, and 126 spindles: by the late 1780s, 84-spindle jennies had become standard; from the mid-1790s onwards 120- and 126-spindle machines were most prevalent. As to best practice, jennies with more than 100 spindles were observed as early as 1780, and the largest jennies, of 160 spindles, were observed in the mid-1790s.

Figure 9 shows that water-frames were the smallest machines, the most prevalent having just 72, 48, and 84 spindles. Frames with over 100 spindles were available by the 1790s, but do not seem to have been widely used. The limited development of the water-frame probably reflected the shift to the throstle as the technology of choice in continuous spinning. The newspaper advertisements make clear that the transition from frames to throstles, *c.* 1800, involved an increase of about 50 per cent in the average number of spindles per machine in continuous spinning: from the outset, most throstles had between 96 and 144 spindles, but there was little discernible further growth before the late 1820s. The throstle arose from multiple attempts to simplify the heavy gearing of the water-frame in which separate arrangements of drum-and-pulleys transmitted power to each 'set' of four or six spindles. On the throstle, this was replaced by a single horizontal tin cylinder lying below the machine that drove all the spindles, economizing on power and enabling larger machines.[44]

Figure 9 also indicates that mules came in a much wider range of sizes than the other machine types, with less clustering around certain standard sizes: before 1800, mules with only 56 or 64 spindles were advertised alongside those with over 300. While best-practice mules grew rapidly in size—mules with over 400 spindles were advertised as early as 1807 and, by the 1830s, the largest advertised mules had 500–600 spindles—only the smallest mules with fewer than 100 spindles were

[44] Baines, *Cotton manufacture*, p. 208; Montgomery, *Carding and spinning*, p. 146; Aspin, *Water-spinners*, pp. 120–7; Cookson, *Age of machinery*, p. 59.

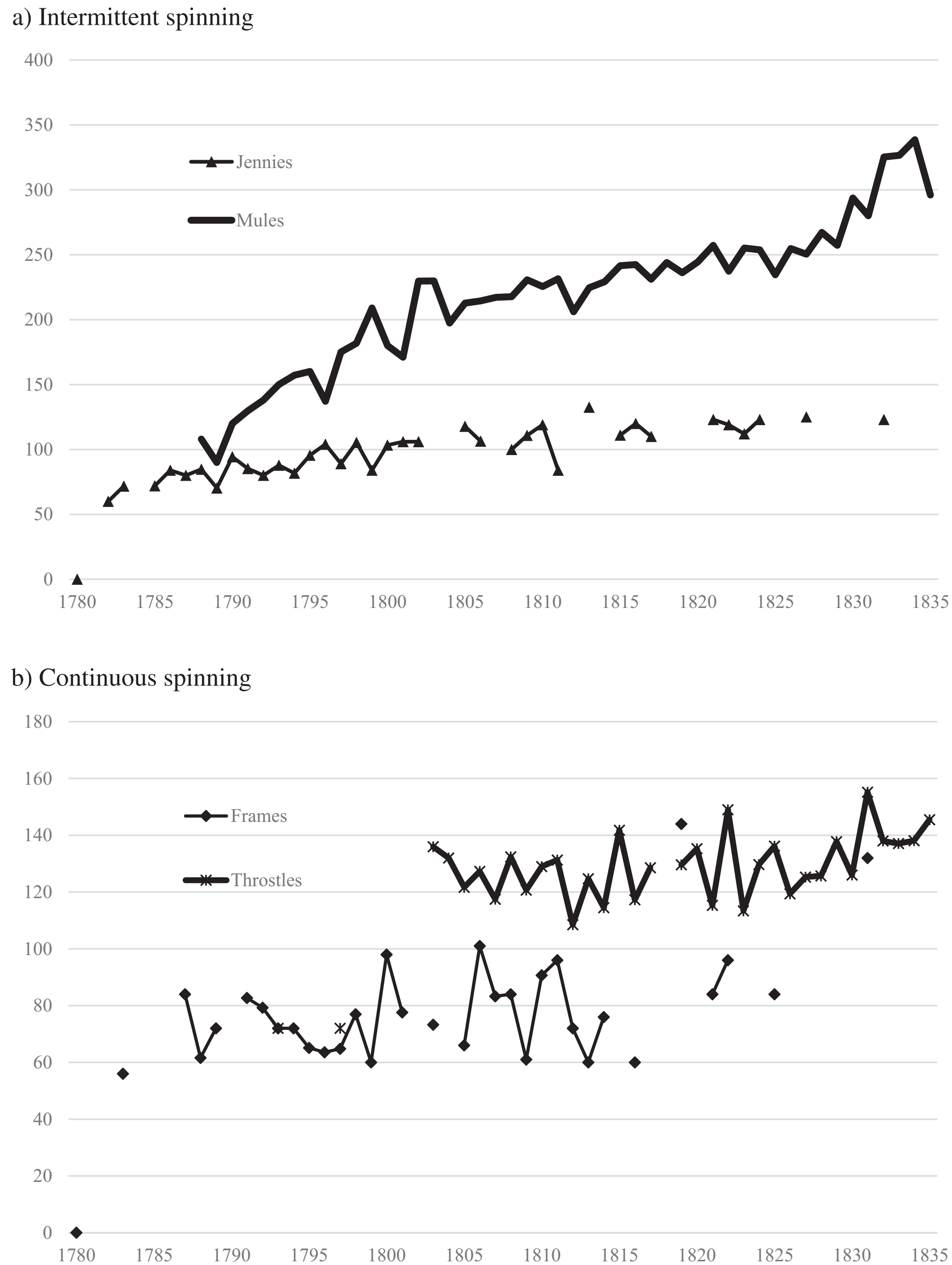


Figure 8. *Intermittent and continuous cotton-spinning machinery, average spindleage by type (spindles)*

Note: Five-year centred moving averages.
Sources: See tab. 2.

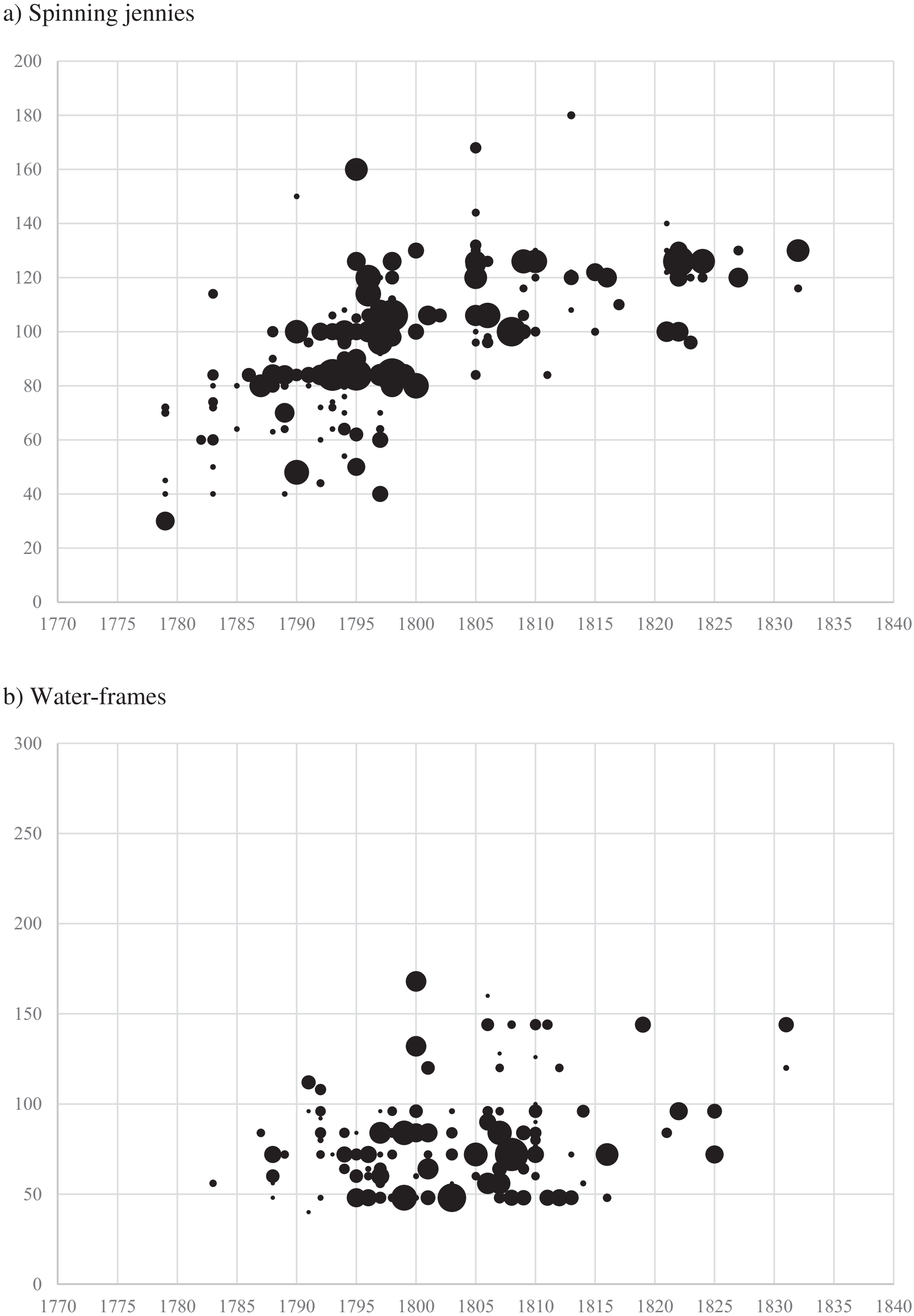
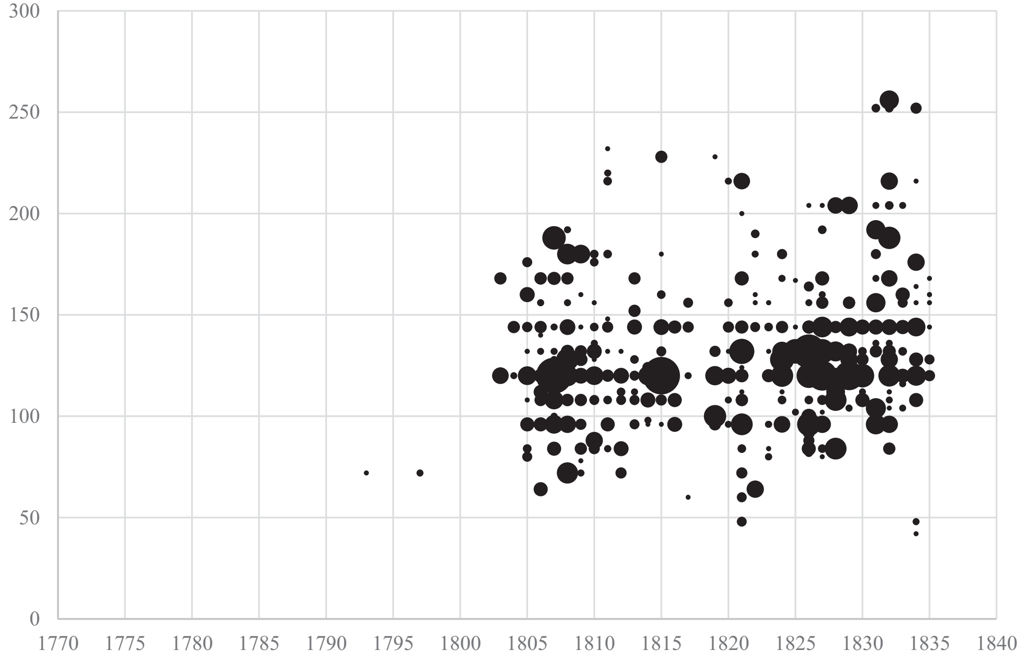


Figure 9. *Size of advertised spinning machines (spindles)*
Note: Size of circles indicates the nos. of machines advertised.
Sources: See tab. 2.

c) Throstles



d) Mules

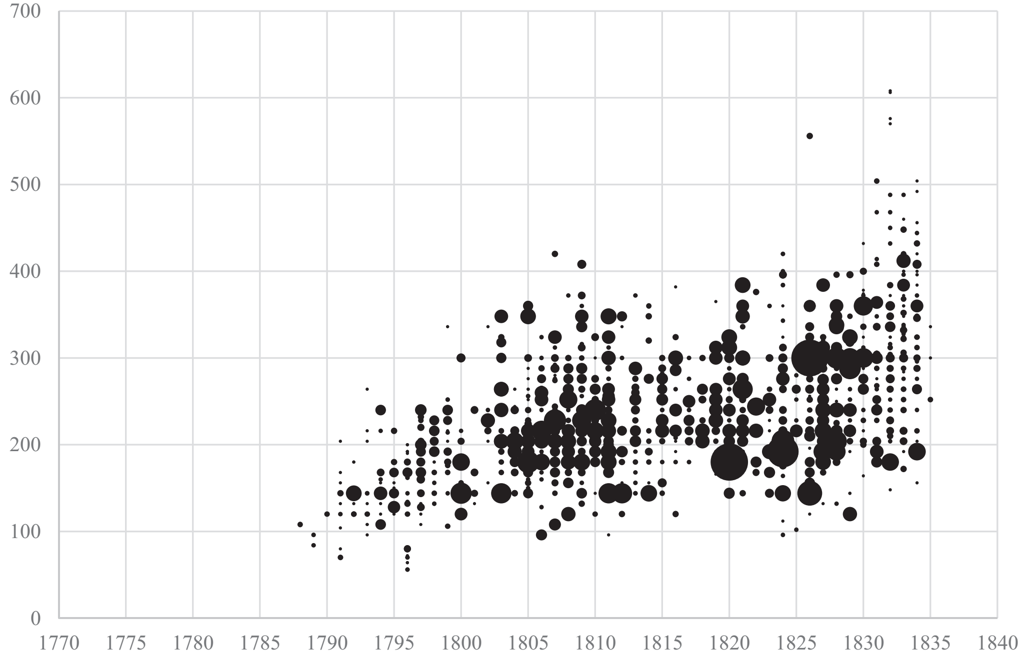


Figure 9. *Continued*

obsolete by 1800. Mules of around 200 spindles still featured prominently in the advertisements as late as the 1820s.[45]

This analysis of the different average sizes of jennies, mules, water-frames, and throstles has implications for the machinery transitions discussed in the previous section. In intermittent spinning, the average advertised jenny and mule carried similar numbers of spindles (around 100) in the late 1780s, but a large gap opened from the early 1790s, when power began to be applied to some operations of the mule. Hence, even if we assume that there were roughly equal numbers of jennies and mules in the early 1790s, the much larger capacity of mules would imply significantly more mule spindles. Likewise, the greater size of mules dampens the effect, suggested in figure 6, of the increase in continuous spinning after 1810. Although, by *c.* 1830, throstles appeared in around 40 per cent of adverts, they had half as many spindles as mules on average, and so probably accounted for only around 20 per cent of total cotton spindles.

The adverts thus make clear that the rapid diffusion of the mule in the late eighteenth and early nineteenth centuries was central to increasing machine size in UK cotton spinning, amounting to a threefold increase in the intermittent branch. The transition from frame to throstle had a less significant impact on machine size, although it still amounted to a 50 per cent increase in average machine size in continuous spinning. The next section discusses the implications of growing machine size for productivity increases in UK cotton spinning.

VI

How did the productivity increase in the micro-invention phase of mechanized cotton spinning compare with that achieved in the era of the great inventions? Here, after reviewing previous work, we offer new estimates of labour productivity in cotton spinning based on the number of 'hanks' of 840 yards that a worker could produce in a single day at given 'counts' of yarn.[46] A count of 16s, for example, means that 16 hanks (or 13,440 yards) of spun yarn would weigh one pound avoirdupois. The estimates, shown in table 3, reflect four time points: the era of hand spinning immediately before on the onset of machine spinning (the 1760s), the years of the great inventions (the 1770s), the early diffusion phase (the 1790s), and the end of our period (the early 1830s). The underlying sources discussed in this section are laid out in more detail in appendix I. Even though the sources are admittedly fragmentary, the results tell a convincing story about the importance of continuous improvement.

Catling has produced the most influential estimates of labour productivity during the initial transition from hand to machine cotton spinning *and* during its subsequent development in the late eighteenth and early nineteenth centuries. His estimates refer to the time taken to spin 80s yarn. Catling estimated that a

[45] Montgomery stated in 1832 that some millowners reckoned that mules with 264–88 spindles were most profitable to run because of their high spindle productivity, and because they were easier to work and maintain than larger machines; see Montgomery, *Carding and spinning*, p. 167.

[46] This is the approach taken in Leunig, 'British industrial success', for the early twentieth century, albeit using more detailed contemporary data. For comparison, in *c.* 1910, British mules were reckoned to turn off about 500 lbs of 40s yarn per week, per worker (spinners and other operatives) or 83 lbs per day in a six-day week, a bit less than four times our figure for operatives on mules spinning 40s, *c.* 1835.

Table 3. *Productivity indicators in cotton spinning*, c. *1760*–c. *1835*

	Spindles per machine	*Spinners per machine*	*Spindles per spinner*	*Operatives per machine*	*Hanks spun per spindle, per day (and 'count')*		*Daily output per spinning machine (hanks)*	*Daily output per spinning machine (lbs)*	*Daily output per operative (hanks)*	*Change factor since 1760*
Hand spinning, 1760s	1	1	1	1	8	(16s)	8	0.5	8	
Spinning jenny, 1770s	16	1	16	1	1.6	(16s)	25.6	1.6	25.6	3.2
Water-frame, 1770s	48	1	48	1.5	1.6	(24s)	76.8	3.2	51.2	6.4
Hand mule, 1770s	48	1	48	1.5	1.25	(40s)	60	1.5	40	5
Spinning jenny, 1790s	93	1	93	1.5	1.2	(16s)	111.6	7	74.4	9.3
Water-frame, 1790s	69	1	69	1.5	2	(24s)	138	5.8	92	11.5
Hand mule, 1790s	169	1	169	1.5	1.25	(40s)	211.25	5.3	140.8	17.6
Throstle, early 1830s	142	0.67	213	0.84	4.5	(24s)	639	26.6	760.7	95.1
Power-assisted mule, early 1830s	298	0.5	596	1.08	3	(40s)	894	22.4	827.8	103.5

Notes and sources: See app. I.

hand spinner would need around 42 working days to spin one pound of yarn of this quality, before Crompton's prototype mule of 1779 brought the time down to within two working days, a reduction of more than 95 per cent.[47] Catling considered the rate of productivity growth between 1780 and 1825 to have been almost as dramatic; by the latter date, he judged that the power-assisted mule would have required little more than an hour to process a pound of raw cotton into 80s yarn, a time reduction after 1780 of a further 93 per cent. Catling's estimates, however, are not ideal because a yarn count of 80 was much higher than the average spun in our period and not one produced in the UK at all before the invention of the mule, leaving Catling to base his estimates of hand-spinning rates on the experience of Indian rather than UK workers.

Another approach taken by historians, albeit a much less satisfactory one, has been to assume that labour productivity was proportional to machine spindleage. Edwards, for example, claimed, in reference to 80-spindle jennies in the early 1780s, that 'it was thus possible for a jenny spinner to produce eighty times as much yarn as on a single-spindle wheel'.[48] Landes, apparently following the same logic, claimed that the spinning jenny increased spinning productivity by six to 24 times depending on machine size.[49] Allen rejected this approach, observing that 'a woman operating a 24-spindle jenny did not spin twenty-four times as much per day as a woman operating a hand wheel. The gain was much less'. Based on the piece-rate earnings of hand and jenny spinners, Allen infers that labour productivity was around three times higher on the jenny, a much lower increase than that envisioned by Edwards or implied by Catling's discussion of the mechanization of fine-yarn spinning.[50]

The productivity of hand spinning has recently attracted much attention, not least in the pages of this journal.[51] The crucial issue has been the weight of cotton a hand spinner was able to process into yarn in a single day. Allen, drawing primarily on eighteenth-century prescriptive sources, posits a figure of one pound (lb) for a full day's spinning by hand. His most detailed estimates relate to 13s and 16s, close to the average spun in Lancashire in the mid-eighteenth century.[52] At these counts, a pound weight of cotton would produce 10,920 or 13,440 yards of yarn, a tall order for a single working day. Humphries and Schneider, who have found scattered archival observations of the spinning rates actually achieved in the eighteenth century, albeit mainly for non-cotton fibres, consider one pound a day to be rather optimistic. They consider 0.417 lb as more realistic for a day's cotton spinning, although do not specify a count.[53] Applying this rate of work to an average mid-eighteenth-century count of 16s would suggest a hand spinner could produce 5,604 yards or slightly more than $6\frac{1}{2}$ hanks of yarn per day. This figure fits well with Ralph Mather's 1780 description of thousands of Lancastrian women who 'must take a

[47] Catling, *Mule*, pp. 54 estimates 50,000 hours to process 100 lbs of cotton by hand: hence, 500 hours (or 41.6, 12-hour working days) to turn off one 1 lb.
[48] Edwards, *Cotton*, p. 4.
[49] Landes, *Unbound Prometheus*, p. 85.
[50] Allen, 'Spinning jenny' (2007), p. 10.
[51] Allen, 'Spinning jenny' (2009); Humphries, 'Aggregates'; Allen, 'High-wage economy'; Humphries and Schneider, 'Spinning'; Allen, 'Spinning their wheels'; Styles, 'Spinning jenny'; Humphries and Schneider, 'Losing the thread'.
[52] Allen, *Global perspective*, pp. 188–95; idem, 'Spinning their wheels', pp. 6–7; Styles, 'Spinning jenny', p. 12.
[53] Humphries and Schneider, 'Spinning', pp. 134–40; eisdem, 'Losing the thread', pp. 5–7.

long day to card, spin and reel 5,040 yards of cotton'.[54] Mather's figure of 5,040 yards equates exactly to six hanks, which was presumably what he thought was possible in a single day, although he included preparation and reeling for which the spinner would have had help. Styles cites mid-eighteenth-century evidence which indicates that one woman could card and rove for three spinners: hence, we could infer that a hand spinner working full-time at the wheel might produce roughly eight hanks of coarse yarn in day.[55] Our estimate of eight hanks per spindle, per day for the hand wheel lies between those of Allen and Humphries/Schneider, but is closer to the latter. Substituting Allen's hand-spinning rate would dampen the initial effect of the new machines reported here; using Humphries/Schneider's rate would slightly heighten it. Note here that we are considering only the productivity of the spinning process, narrowly defined, not taking account of workers occupied in preparing, nor of improvements in preparing machinery. Later, we show that a broader productivity measure that takes the preparatory processes into account produces similar results.

How far did the great inventions improve on this daily rate of spinning? The act of installing multiple spindles—between eight and 48 on the prototype machines of Hargreaves, Arkwright, and Crompton—did increase the amount of yarn that each spinner could process in a day but, contra Edwards (and others), the increase was not proportionate to the number of spindles on each machine. Thus, while Arkwright was confident in 1772 that each worker in his newly established Cromford factory would soon reach the daily rate of '40–50 lb' or 'a Thousand Hanks' of yarn, this was not achieved until well into the nineteenth century.[56] In fact, output per spindle fell significantly during the transition from hand to machine spinning—none of the new spinning machines developed was able to turn off more than two hanks per spindle, per day, one-quarter or less the rate of the humble hand wheel—muting the productivity increase associated with the initial mechanization of spinning.[57] The lower output rates per spindle of the new machines reflected both the increase in the fineness (count) of the yarns produced and the difficulty of reproducing the dexterity of human fingers in drawing and twisting, which resulted in increased broken yarns and production interruptions to repair them.

Assessing the gains brought about by the spinning jenny is the most straightforward because the invention little affected the qualities of the yarn produced or the number of workers operating each machine. Table 3 suggests a single spinner on a 16-spindle jenny could turn off about 26 hanks of 16s yarn per day, a bit more than three times the eight hanks per day estimated for the hand wheel, and roughly the same rate of productivity increase as inferred by Allen from cotton spinners' earnings.[58] The output rates achieved by water-frames and mules were greater, even though they mainly produced higher counts of yarn than the wheel. Despite the additional input of child labour, the estimates presented in

[54] Mather, *Poor spinners*, p. 13; James, *Worsted manufacture*, p. 325, writing in 1857, reckoned that hand-spinners of worsted could process 5,040 to 5,600 yards per day in the late eighteenth century.
[55] Styles, 'Spinning jenny', p. 8.
[56] Quoted in Hills, *Arkwright*, p. 42. See tab. 3 for daily output of cotton spinners and their assistants. Spinning 45 lbs of 24s would produce 1,080 hanks of yarn.
[57] See Endrei, *L'évolution*, pp. 20–3, 110–12, 151–3, and Thompson, 'Transferring', p. 34, for evidence from continental sources along similar lines.
[58] See n. 50.

table 3 show output per operative increased five times for the mule and over six times for the water-frame even before yarn quality is taken into account.

Productivity advance continued into the micro-invention phase of mechanical cotton spinning after 1780. Significant *additional* advances in labour productivity had already been achieved by the 1790s, following a rapid period of diffusion for all machine types (except the throstle). For the jenny and the mule, which remained hand operated and powered in this period, the increase in output appears to have come from a major growth in the size of machine worked by each spinner (see section V). Water-frames increased less in size, but some water-twist mills began to achieve higher daily rates of output per spindle at around this time, perhaps via the incremental improvements in their power-transmissions that would eventually lead to the separate name of throstle.[59] Although the jenny, water-frame, and mule produced different qualities of yarn, the number of hanks of yarn produced per operative per day in the 1790s was nine to 18 times more than their hand-spinning predecessors and around $1\frac{1}{2}$ to $3\frac{1}{2}$ times the output of their counterparts working the first-generation machines before 1780.

By the early 1830s, output per worker was much higher than in the late eighteenth century. Daily output per mule operative was almost six times higher than in the 1790s.[60] This increase can be partitioned into three elements. First, the number of spindles on the average mule increased by 76 per cent. Second, the number of mules per operative increased by 39 per cent as the semi-powered mule that enabled one spinner, with the help of two full-time child piecers and the occasional assistance of a scavenger, to operate *two* mules simultaneously. Third, the amount of yarn turned off by each spindle increased by 140 per cent, a development largely reflecting faster machine speeds.

The transition from water-frame to throstle brought about a significant increase in the productivity of continuous spinning. By the 1830s, daily output per operative spinning 24s on throstles was eight times higher than their predecessors producing the same quality on late eighteenth-century water-frames. This rise in labour productivity in continuous spinning occurred through a 106 per cent increase in machine size, a 125 per cent increase in output per spindle, and a 79 per cent increase in operative per machine. These gains appear to have been achieved by the throstle's 'lighter' operation compared to the water-frame's, which allowed faster machine speeds and the driving of more spindles. Throstles also operated with fewer workers than water-frames had done in the late eighteenth century.[61]

The mechanization of cotton spinning thus produced ongoing productivity advances. Some historians have overstated productivity advance in the macro-

[59] Chapman, 'Arkwright mills', pp. 10–15; Aspin, *Water-spinners*, pp. 120–7.

[60] Our underlying estimate of 1,788 hanks of 40s yarn per mule spinner per day (that is, one mule spinner looking after two mules of 298 spindles, each spindle producing 3 hanks of 40s per day) fits well with available wage data. In 1830, the *Manchester Mercury* (14 Dec. 1830) reported that mule spinners on piece rates were paid on average 42d. per 1,000 hanks for 40s yarn. By our estimates, the spinner would have turned off approximately 10,000 hanks per week, earning 420d. or 35s. From this, they would have to pay around one-quarter of this (8s. 9d.) to their piecers and scavengers, bringing the mule spinners' wages to 26s.3d., close to the average earnings for mule spinners in 1833 of 26s. reported in *Factories Inquiry Commission. First Report* (P.P. 1833, XX), pp. 426–7. Likewise, the *Manchester Courier* (27 Dec. 1828) reported that 40s mule-spinners received 2d. per lb on average in 1828 and this rate was offered by E. & W. Bolling of Bolton for spinning 40s in the same newspaper (13 March 1830). Our estimates suggest the spinner would (with his assistants) process around 220 lb per week earning 440d., less 110d. for the assistants, or around 27s. 6d.

[61] von Tunzelmann, 'Time-saving', pp. 13–14; Sutcliffe, *Treatise*, pp. 32–41 (quotation p. 32).

invention period either through assuming constant rates of output per spindle or focusing on fine counts of yarn. Productivity gains in the macro-invention phase, nevertheless, were considerable. The jenny's three-fold increase in productivity over the wheel was overshadowed by the rates achieved on the water-frame and the mule. In reality, the advances were much higher as the latter machines produced finer yarns than did the spinning wheel. Even so, the rapid diffusion of spinning machines *after* 1780 was accompanied by significant technical and organizational improvements: machines became larger, faster, and more stable, and could be operated by fewer workers. Productivity leapt in the spinning process, narrowly defined—by 20 times in mule spinning and 15 times in continuous spinning by the early 1830s—emphasizing the importance of improvements that had been made to the original designs of Hargreaves, Arkwright, and Crompton.

A broader, but cruder, measure of productivity in spinning is the weight of yarn produced per worker per annum, thus taking into account the labour involved in preparing. If, following Styles, one woman could card and rove for three hand spinners, then, in a 250-day working year, yarn output per full-time worker would be about 94 lbs. For an early spinning jenny, producing three times as much yarn by weight, up to one preparer per spinner might have been necessary, implying an annual output per worker of perhaps 187 lbs. Early frames and mules would also have required additional labour in preparing, but probably not so much since they were more likely to be served by power-driven carding machines. In the late 1780s, Colquhoun's figures put yarn output per worker (counting children as 0.5) at 223 lbs.[62] John Kennedy, a very well-informed contemporary, calculated the output of yarn per worker in 1817 as 894 lbs, about five times that of the early jenny.[63] In 1850, the UK imported about 600 million lbs of cotton and factory-cotton spinning occupied about 185,000 workers.[64] With a weight loss in processing of about 10 per cent, these figures imply that the weight of yarn produced per worker per year was 2,919 lbs, more than 15 times the 187 lbs produced on the early spinning jenny.[65] Unlike the calculations in table 3, these estimates take no account of yarn count or the type of spinning machine, but they do confirm the importance of continuous improvement in cotton-spinning technology after the great inventions.

VII

In the 1830s, Edward Baines considered that the 'unexampled extension' of the UK cotton industry since the mid-eighteenth century was due to 'a series of splendid inventions and discoveries', the outcome of which was that 'a spinner now [1835] produces as much yarn in a day, as by the old processes he could have produced in a year'.[66] The evidence analysed in this article suggests that the mechanization

[62] Colquhoun, *Case of the British cotton spinners*, app.
[63] Kennedy, *Observations*, p. 22.
[64] Mitchell and Deane, *Historical statistics*, p. 179. In specialized spinning mills there were 94,600 workers; in integrated mills there were 189,000 workers involved in both spinning and weaving. Integrated mills produced lower counts, and hence used fewer workers per spindle. This suggests about 90,000 preparing and spinning workers in the integrated mills, for a total of about 185,000 workers in spinning overall; see *Returns on the Number of Cotton, Woollen, Worsted, Flax and Silk Factories* (P.P. 1850, XLII), pp. 2–3, 10, 12. The 250-day year is based on Allen, 'High-wage economy', p. 7.
[65] Montgomery, *Carding and spinning*, p. 247, reckons on a loss rate of 9.4%.
[66] Baines, *Cotton manufacture*, p. 7.

of cotton spinning in the 1760s and 1770s, combined with the technological improvements made over the next 50 years, did increase productivity by this order of magnitude. If, in the mid-eighteenth century, a (female) hand spinner could produce roughly eight hanks of the then-prevailing average yarn count each day, then her hypothesized 250-day working year would yield around 2,000 hanks of yarn. By the 1830s, a (male) spinner working two typically-sized mules with the help of a few children, and spinning the average counts of that period, would produce nearly as many hanks of yarn (1,788) in one of his very long working days.

Long heralded as the most technologically advanced sector of the industrial revolution, it should come as no surprise that cotton spinning was subject to substantial improvement in the micro-invention phase. However, much of our understanding of the early cotton industry has been based on unusually large firms, discrete regions, or narrow periods. The analysis of newspaper advertisements presented in this article has permitted a much more detailed evaluation of the types of spinning machines in use and the extent they increased in size over time. It has highlighted that, even in cases like cotton spinning when the original macro-inventions had already generated significant productivity advances, incremental improvements to machines could vastly increase the rate of output per unit of input.

Newspaper advertisements are not a perfect source. They reveal little about how the machines were made or the people responsible for designing or improving them. As such, they cannot shed much light on important recent discussions about the importance of formal knowledge, membership of scientific societies, apprenticeship, or the patent system in stimulating technological innovation.[67] However, by providing thousands of observations of spinning machines in use in the UK, they are the only source hitherto exploited that has permitted a detailed analysis of the diffusion and development of all types of spinning machines during the industrial revolution. The mechanization of cotton spinning was a long process. The inventions of Hargreaves, Arkwright, and Crompton owed much to previous hand-spinning techniques. Both the jenny and the mule could trace their origins to the humble spinning wheel used to spin wool and cotton, while the water-frame (and later the throstle) lent on the more complex flyer-wheel used in silk and flax, as well as, of course, the trailblazing roller-spinning machine of Lewis Paul. Equally, there was significant scope to improve the great inventions: iron could replace wood; gearing and power mechanisms could be made more efficient; machines could run faster, or more smoothly, and hence save the labour time spent in repairing broken threads. Running multiple spindles on a single machine was not straightforward. The three great inventors made crucial breakthroughs and deserve their place among the pantheon of the industrial revolution, but their machines did not raise the productivity of cotton spinning by 8, 16, or 48 times. The post-invention refinements were as important as the initial technological discoveries and should be considered a critical aspect of the history of the first industrial revolution.

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[67] On these dimensions, see Jacob, *Scientific culture*; Mokyr, *Enlightened economy*; Ben Zeev, Mokyr, and van der Beek, ‘Apprenticeship’; Bottomley, ‘Invention’; Wallis, ‘Apprenticeship’.

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Appendix I: Sources and notes on productivity calculations

The productivity estimates presented in table 3, and discussed in section VI, are primarily based on indicators of the number of spindles installed on each machine; the number of workers operating each spinning machine; and the number of hanks produced by each spindle. Here we review the (often fragmentary) data available in contemporary sources relating to different machines' sizes, labour requirements, and per-spindle output.

Spindles per machine

For the 1770s, the number of spindles per *spinning jenny* was based on Hargreaves's patent (an earlier version developed by Hargreaves was said to have had only eight spindles), while for the *water-frame* and the *mule*, we referred to the sizes of original machines built by Arkwright and Crompton.[68] For the 1790s and 1830s, we used the average numbers of

[68] For example, Aspin and Chapman, *Hargreaves and the spinning jenny*, pp. 42, 52–3; Catling, *Mule*, p. 37; Chapman, 'Arkwright mills', p. 10.

spindles for each type of spinning machine from our sample of newspaper advertisements, 1790–9 and 1830–5.

Spinners and operatives per machine

'Spinners' refers to designated spinners only, and not those involved in the preparatory processes before spinning (such as cleaning, carding, and roving), those assisting the spinners (for example, piecers, scavengers, and doffers), or those involved in post-spinning processes (reeling and warping). 'Operatives' refers to spinners and those assisting them directly in running spinning machines. Adults were counted as one operative; children as 0.5.

For the *spinning jenny*, we assume one person was sufficient to operate the early domestic jennies used in the 1770s without the assistance of a piecer to mend broken threads. By *c*. 1790, adult spinners on the larger jennies were usually helped by a single child piecer.[69] The *water-frame* was operated by two types of workers—a 'spinner', usually a young woman, who attended to the broken threads, and a 'doffer' (a boy or girl), who was responsible for replacing the bobbins. There has been little discussion of how many of each type of worker was required to operate each water-frame in the late eighteenth century. In 1783, American merchant Samuel R. Fisher visited a water-frame mill near Manchester, reporting that 'a Boy or Girl is required to attend ab[ou]t one to every 14 threads'.[70] Most frames would have had 48 spindles at this early stage of water spinning, implying roughly three workers per frame. However, it is likely that Fisher's observation included mill workers involved in the preparatory processes as well as spinners and doffers. This is suggested by Hills's more detailed breakdown of the labour force at Quarry Bank Mill, Cheshire, in 1789, when the mill contained 2,400 water-frame spindles, and employed 50–55 workers in the spinning room, 65–70 in the carding room, and a further 35 child apprentices. The Quarry Bank staffing numbers only equate with Fisher's figure of 14 spindles per worker if all millworkers are considered (there were roughly 15 spindles per worker at Quarry Bank in 1789).[71] However, if we assume the 2,400 spindles comprised 50 frames of 48 spindles each, then it suggests roughly one spinner per frame in the spinning rooms, who probably received some assistance from the younger apprentices as doffers. Aspin also cites evidence from a water-frame mill near Brough, Westmoreland, that indicates a ratio of roughly one doffer per spinner in 1788–9.[72] We thus assume for water-frames that each spinner was assisted by one child doffer in both the 1770s and the 1790s. By 1835, the *throstle* had replaced the water-frame in continuous spinning. At this time, it was usual for each throstle spinner to attend three or four 'sides': a 'three-side spinner' would operate both sides of one throstle and one side of another, while a 'four-side spinner' would look after the spindles on both sides of two machines. Evidence from the early 1830s favours the idea of 'three-side spinners' being more prevalent, with 'four-side spinners' perhaps more typical by the 1840s, although this partly depended on the age and experience of the spinner.[73] It is likely, based on the available evidence, that every two throstle spinners had the assistance of one doffer in the 1830s.[74]

[69] Colquhoun, *Important crisis*, p. 2

[70] Winterthur Library, Del., diary of Samuel Rowland Fisher, 20 Nov. 1783.

[71] Hills, *Power*, pp. 245–6.

[72] Aspin, *Water-spinners*, pp. 92–3.

[73] *Factories Inquiry Commission. First Report* (P.P. 1833, XX), evidence of Anne J., p. 644; *S.C. on State of Manufactures, Commerce and Shipping* (P.P. 1833, VI), evidence of William Rathbone Greg, p. 689; *Reports of the Inspectors of Factories* (P.P. 1842, XXII), p. 442; Ure, *Cotton manufacture*, p. 131; Law, *Fieldens*, pp. 62–3.

[74] *Factories Inquiry Commission. First Report* (P.P. 1833, XX), evidence of Anne J., p. 644; *Return of Names and Salaries* (P.P. 1834, XLIII), p. 477.

On the original *hand mule*, the rollers, spindles, and carriage were all operated manually, which meant that one (usually male) spinner was required to operate each mule. For the 1770s and the 1790s, we follow Lazonick's suggestion that the early hand mules also required the assistance of a child piecer.[75] It was only in the late 1790s that the hand mule began to be replaced by the power-assisted mule, in which a water wheel or steam engine powered the outward draw of the carriage.[76] From this point onwards, it became feasible, and indeed standard practice, for one spinner to operate *two* mules laid out in parallel, manually pushing in the carriage of one mule (while winding the cop), while the engine drew out the carriage of another.[77] In operating a pair of machines, mule spinners received the assistance of piecers and scavengers (the latter responsible for cleaning the machines), both of whom were usually children. A survey of 1833 recorded 3,797 mule spinners in 151 Lancashire factories, as well as 7,157 piecers, and 1,247 scavengers. We thus assume that each mule spinner spinning 40s yarn supervised two piecers and had a third share in the services of a scavenger.[78]

Hanks spun per spindle per day

The per-spindle output achieved by the jenny, mule, water-frame, and throstle reflected the nature of the spinning process (intermittent or continuous), the size of machines, the extent to which they were externally powered, and the counts of the yarn they produced.

For the *spinning jenny*, information on per-spindle output rests on two observations from the late eighteenth century that are not precisely dated. The first contains information on the weight of cotton that could be spun on an early (40-spindle) jenny producing yarn for coarse fustians (that is, around 16 hanks per pound) in Philadelphia. The estimate was published in 1789 as part of a compendium of older texts. It gave the rate of 4 to 6 lbs. per day, equating to 1.6 to 2.4 hanks per spindle.[79] The second observation comes from the third edition of the *Encyclopaedia Britannica*, which was published in 1797, but written in stages between 1788 and 1797, as part of a much-expanded section on the cotton industry from the second edition published in 1778. It specified that an 84-spindle jenny could spin around 100 hanks per day, which would equate to 1.2 hanks per spindle.[80] Our estimate for the 1770s takes the lower bound of the earlier range (that is, 1.6 hanks per spindle, per day) as more plausible, and retains the rate of 1.2 hanks per spindle for the 1790s.

For the *water-frame*, the earliest observation comes from Mather in 1780, who in making the case for the displaced hand spinners, asserted that the water-frames turned off 24s yarn at the rate of two hanks per spindle per day.[81] At Peel's mill at Bury in 1783, however, the 48-spindle water-frames, as reported by former workers to John Holker, turned off only 3.5 lbs. per day of 20s yarn and 3 lbs of 28s, which equates to 1.46 and 1.75 hanks per spindle respectively.[82] Thus, Mather's two hanks per spindle might be optimistic for 1770s: 1.6 hanks per spindle per spindle seems reasonable for a count of 24s. By the 1790s, there is a wider range of observations to evaluate. In 1797, the 6,000 spindles at Oldknow's

[75] Lazonick, 'Industrial relations and technical change', p. 233.
[76] Barlow & Dobson only began to sell mules consistently in pairs in 1798; see Barlow & Dobson Ltd., *Samuel Crompton*, pp. 82–3; Hills, *Power*, pp. 128–9.
[77] Baines, *Cotton manufacture*, pp. 266–7; Lazonick, 'Industrial relations and technical change'.
[78] *Factories Inquiry Commission. First Report* (P.P. 1833, XX), p. 417; see also Cohen, 'American management and British labor', pp. 616–17, and Catling, *Mule*, p. 54. In fine spinning, more piecers were employed, averaging four piecers per spinner in three Manchester mills; see *Factories Inquiry Commission. Supplementary Report* (P.P. 1834, XIX), pp. 385–8.
[79] Anon., 'Estimates', p. 225.
[80] *Encyclopaedia Britannica*, 3rd edn., vol. 5, p. 488.
[81] Mather, *Poor spinners*, p. 13.
[82] We are grateful to John Styles for providing us with this information. As late as 1792, the water-frames at Embsay mill, Yorkshire, produced 1.3 hanks per spindle, per day, for 24s; see Aspin, *Water-spinners*, p. 37.

Mellor Mill produced 2.2 hanks per spindle per day of an average of 20s yarn.[83] Earlier in 1791, Whitehead's Garratt Mill in Manchester used 1,000 water-frame spindles to turn 600 lbs of yarn per week. The count is not specified in the source but, assuming it was similar to Oldknow's, implies around two hanks per spindle, per day.[84] Chapman and Aspin cite some much-higher rates of daily output for the 1790s, including 3.3 hanks per water-frame spindle at a mill in Leeds in 1795, spinning 20s, and 4.8 hanks per spindle taken from a more notional example produced by Hugh Watts of the Sun Fire Office referring to 22s.[85] However, these higher rates of spindle productivity sit uneasily with British customs' data on retained cotton imports, which are in the 20–30 million lbs. range in the 1790s: at Watts's rate of 66 lbs per water-frame spindle per year, fewer than 500,000 frame spindles could have spun the entirety of the annual British cotton import, without the need for jennies or mules. As such, the lower rate of two hanks per water-frame spindle, per day (roughly 25 lbs per spindle, per year) would seem more appropriate for a count of 24s in the 1790s. Information on *throstle* spinning in the 1830s is more abundant and comes from well-known authorities within the industry. Our estimate of 4.5 hanks per spindle for the *throstle* is a compromise between the rate of 4.33 cited in Montgomery's 1836 technical manual (referring to 25s) and a statement presented by Samuel Greg & Co. to Parliament in 1834 that a throstle spindle would turn off 4.2 to 5 hanks per spindle of 'coarse twist' per week.[86]

For *mules*, von Tunzelmann synthesizes a number of contemporary estimates to adduce the figure of one hank per spindle for hand mules spinning the average count of 40s in the period between the late 1770s and the late 1790s.[87] Catling has adduced a similar figure for Crompton's original mule based on the assumption that an adult worker could have drawn out the mule carriage once a minute for 12 hours a day. At this pace of operation, the spinner would have produced 1,080 yards of yarn (around 1.25 hanks) daily per spindle. Like von Tunzelmann, Catling posits no further increase in per spindle output in the next 20 or so years.[88] Direct observations from Oldknow's hand-mule factory in Stockport in 1793 show a similar rate of output per spindle: one spinner of 42s turned off 0.9 hanks per spindle, per day; another spinning 35s produced only 0.7 hanks per day, and still another spinning 52s turned off 1 hank per spindle, per day.[89] For the late eighteenth century, it thus seems reasonable to conclude that 'about the year 1790 the average product of the spinner of yarn No. 40 was little more than a hank per spindle per day'.[90] We settle on the figure of 1.25 hanks per spindle for the mule in the 1770s and the 1790s. James Kennedy's oft-cited figures record a steady rise in the output of mule spindles from around two hanks per day for 40s in around 1812 to around 2.75 hanks per mule spindle in 1830.[91] This can be compared to the output per spindle on 40s reported at Jesse Howard's Stockport mule factory, which increased from 2.3 hanks per spindle per day in 1806, to 2.8 in 1823 and 3.5 in 1832.[92] Thus, it seems reasonable to allow for three hanks per spindle for spinning 40s yarn on semi-automated mules in the early 1830s.

[83] Unwin, *Oldknow and the Arkwrights*, pp. 194–6.
[84] Aspin, *Water-spinners*, p. 38.
[85] Chapman, 'Arkwright mills', p. 15; Aspin, *Water-spinners*, p. 125. Note that these estimates have been converted from annual observations of lbs spun per spindle to the daily number of hanks spun per spindle.
[86] *Factories Inquiry Commission. Supplementary Report* (P.P. 1834, XIX), pp. 495–6; Montgomery, *Theory and practice*, p. 219 (referring to a count of 25 hanks per pound).
[87] von Tunzelmann, *Steam*, pp. 203, 210–1.
[88] Catling here assumes that Crompton's original mule had the same length of outward draw (54 inches) as the later standard design; Catling, *Mule*, pp. 37, 53.
[89] Williams, *Accounting for steam and cotton*, p. 119.
[90] *Encyclopaedia Britannica*, 7th edn., vol. 7, p. 403. The volume was published in 1842 but written in 1832.
[91] Cited in von Tunzelmann, *Steam*, pp. 210–11. See also Montgomery, *Theory and practice*, p. 219.
[92] *Labour of Children in the Mills and Factories* (P.P. 1831–2, XV), evidence of William Longston, pp. 428–33. These figures appeared in Babbage, *Economy of machinery*, p. 334.