More Machines, Better Machines...Or Better Workers?

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Abstract: How much of the rapid growth in labor productivity in nineteenth century cotton weaving arose from capital-labor substitution and how much from technical change? Using an engineering production function and detailed information on inventions, I find that factor substitution accounts for little growth. However, much of the growth and most of the apparent labor-saving bias arose *not* from inventions, but from improved labor quality—better workers spent less time monitoring the looms. The inventions themselves were almost technically neutral because innovations in general purpose technologies were capital-saving. Labor quality played a critical role in the persistent association between economic growth and capital deepening in this important sector.

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A typical weaver in the U.S. in 1902 produced over 50 times as many yards of cloth in an hour of weaving as did a weaver a century earlier producing a comparable cloth. The weaver in 1902, however, achieved that output using eighteen power-driven looms while the weaver of 1802 used a single handloom. Similar patterns of productivity growth accompanied by capital deepening are seen in many other technologies. The association of capital deepening with labor productivity growth has been one of the "stylized facts" about economic growth.

Clearly the factors causing this association might reveal important aspects about technical change and economic growth. But there are at least two major explanations for it. An earlier debate[1] asked how much of such growth in labor productivity came from "more machines" and how much came from "better machines." In the "more machines" story, rising wages relative to capital costs drove greater investment and hence greater capital deepening, pushing production to more capital intensive techniques on the production possibilities frontier. This accords with the traditional view of nineteenth century labor productivity growth. In the "better machines" story, new techniques improved labor productivity more than they improved capital productivity, increasing capital intensity—that is, technical change was biased.

This paper attempts to assess how much of the growth in labor productivity in nineteenth century weaving arose from factor substitution and how much from biased technical change and what accounts for such bias. I do so by looking in detail at the technology employed at benchmark mills and the inventions that allowed this technology to change over time. This detailed approach reveals aspects about technology that are difficult to ascertain from more aggregate data.

In fact, researchers have had difficulty empirically identifying the extent of factor substitution, technical bias and the influence of factor prices on this bias. As is well known (see below), the elasticity of substitution and the technical bias cannot both be identified using aggregate data unless some strong assumptions are made. This has left the role of these factors in economic growth controversial, for example, in the recent debate about the sources of East Asia's rapid growth (see Hsieh 2002, Kim and Lau 1994, Nelson and Pack 1999, Rodrik 1997, and Young 1995).

Economists have found little direct evidence to support the hypothesis that factor prices influence the direction of technical change except possibly in agriculture. In agriculture, Hayami and Ruttan

1 This language comes from the literature on the differences in capital intensity and labor "scarcity" between early America and the England, including Rothbarth (1946), Habakkuk (1962), Temin (1966b), Fogel (1967) and Clarke and Summers (1980), who used this phrase. The "more machines" story corresponds to the transitional dynamics of the neoclassical growth model (Solow 1956, Swan 1956). The "better machines" story (with a labor-saving bias) corresponds to growth models of Champernowne (1963) and Zeira (1998).

(1970) and others found support for a factor price induced bias. However, that work has been challenged (Olmstead and Rhode 1993) and more recent research is inconclusive at best (Liu and Shumway 2009).

Because this paper uses an "engineering production function," I am able to identify the sources of growth, the technical bias and the contribution of individual inventions to that bias. Measuring capital and labor productivity at benchmark mills during the nineteenth century, I find that "more machines" and "better machines" do not provide a full explanation for the changes in productivity. A third factor is needed, namely, labor quality. I find that weavers early in the century would take far more time to monitor the looms than weavers at the end of the century, suggesting that the early weavers either had inferior skills, or they exerted less effort, or both. There are three major findings:

1. Very little of the growth in labor productivity in cotton weaving over the nineteenth century can be attributed to the substitution of looms for labor. Most is from inventions that improve the machines, but I attribute about a quarter of the labor productivity growth to better quality labor.
2. Labor productivity grew substantially faster than capital productivity, producing an apparent labor-saving bias. However, very little of that difference can be directly attributed to *inventions* —they were almost technically neutral with little effect on the capital/labor ratio. Instead, and contrary to an assumption in most of the theoretical literature, the labor-saving bias depended on complementary growth in labor quality.
3. The sources of bias from inventions provide a clue why inventions do not exhibit a strong labor-saving bias. While the main labor-saving inventions were specific to the textile industry, the main capital-saving inventions occurred in general purpose technologies, including advances in power generation and transmission and machine construction. This meant that the costs of developing capital-saving inventions were spread over many industries, while the costs of developing labor-saving inventions were not. This counteracted any bias that rising wages might have exerted in favor of labor-saving inventions. For this reason, factor prices might have played a secondary role in determining the bias of inventions.

I explore these changes in a single technology, cotton weaving. Cotton weaving was a central part of industrialization. Textiles were a leading sector in the Industrial Revolution in the United States and Britain. Clark (2007, p. 233) attributes over half of the productivity gain achieved between 1760 and 1860 in England to gains in textile production, with most of this gain coming from cotton.[2] Cotton

2 Harley (1999), using a revision of McCloskey's estimates (1981), attributes 36% of the UK productivity growth between 1780 and 1860 to textiles.

has also been an historically important sector in more recent development.[3] Because cotton weaving was so central to technical change, a failure of either the "more machines" or the "better machines" story for cotton weaving would pose a significant problem for these explanations in the aggregate economy.

Cotton weaving was also one of the key technologies that Habakkuk used to compare the US and UK. US weavers handled more looms than their UK counterparts from the 1840s on. Habakkuk (1962, p. 47) argued that factor prices influenced "the training that the American manufacturers gave their workers so that each was able to handle more looms." Thus Habakkuk, too, recognized the importance of labor quality for understanding the bias of technology, although this is not the way that Habakkuk is typically interpreted.

The big advantage of studying cotton textile technology is that it is a simple mechanical technology that has been extensively researched. I build an engineering model of cloth production and show how the technology imposes constraints on the nature of technical change and factor substitution. I then look at the major inventions that were widely applied to weaving during the nineteenth century and seen as important by contemporaries. Using data from a variety of sources including trade publications, patent specifications, weaving manuals and measurements taken on working museum models, I estimate the increases in labor and capital productivity brought by each invention. Using data on realized performance at large mills, I validate these estimates and identify other sources of productivity growth.

Chenery (1949) recognized that detailed engineering production functions could help disentangle factor substitution from technical change. But only a limited number of researchers have attempted to build such engineering models (see Wibe 1984 for a review) and only a few of these papers have looked at technical change (for example, Smith 1957, and Pearl and Enos 1975). Levhari and Sheshinski (1970) and Arrow et al. (1972) build a model for the "repairman problem" that is similar to a simplified version of the model I build.

Beginning with Brown and De Cani (1963), David and van de Klundert (1965), and Ferguson (1965), econometric studies have estimated technical bias for aggregate production functions, generally rejecting the null hypothesis of Hicks neutrality.[4] My analysis confirms a labor-saving bias at the micro

3 In Japan, cotton textiles became the first industry to dominate export markets. Japan went from being a net importer to the world's largest exporter in a matter of decades. Toyota began as a loom manufacturer (Toyoda). Cotton textiles have also been an important industry in China's recent economic growth.

4 Empirical studies that formally test and reject the hypothesis of Hicks neutrality include Antras (2004), Berndt and Khaled (1979), Binswanger (1974), Brown and De Cani (1963), David and van de Klundert (1965), Ferguson (1965), Jorgenson and Fraumeni (1981), Kalt (1978), Klump et al. (2007). May and Denny (1979), Moroney and Trapani

level, but it also reveals important details about the nature and origins of this bias.

At least since 1932, biased technical change has been seen as a feature of economic development. Hicks (1932, p. 124) suggested,

> A change in the relative prices of the factors of production is itself a spur to invention, and to invention of a particular kind—directed to economizing the use of a factor which has become relatively expensive.

Following Hicks, researchers have proposed that high relative wages explain the greater labor saving character of US technology compared to the UK (Rothbarth 1946, Habakkuk 1962), they have proposed "induced innovation" models where factor prices influence the bias of technology (Acemoglu 2003, 2007, Ahmad 1966, David 1975, Fellner 1961, Kennedy 1964, Samuelson 1965),[5] and some have suggested that high wages might even spur innovation (Acemoglu 2009, Allen 2009). Allen (2009) recently argued that the Industrial Revolution began in Britain because high wages encouraged labor-saving inventions. My analysis suggests that the apparent labor-saving bias might reflect other factors in addition to relative prices, such as labor quality and the application of general purpose technologies.

Weaving Technology and Technical Change

Biased Technical Change

Assuming constant returns to scale in a two factor production function, a Hicks neutral technical change is a change that leaves the capital-labor ratio unchanged at constant factor prices.[6] If, instead, the capital-labor ratio increases (decreases), the change is said to be labor-saving (capital-saving). However, the capital-labor ratio could also change in response to factor price changes.

These two types of change are illustrated in Figure 1. The solid curve represents the initial unit isoquant (output equal to one yard of standard quality cloth) and the solid line represents a constant cost curve with a slope equal to minus *w*, the relative factor cost (labor wage to capital rental). The initial cost minimizing point for unit production is A where this curve is tangent to the isoquant. Variable X_l is the required labor input, that is, the amount of labor time required to produce one unit of

(1981), Panik (1976), Sato (1970), Wilkinson (1968), Wills (1979) and Yuhn (1991). Berndt and Wood (1982) could not discriminate between different technical biases. Toevs (1980) could not reject the Hicks neutral hypothesis against a restricted alternative. Berndt et al. (1993) reject Harrod neutrality, but could not reject Hicks neutral technical change.

5 Nordhaus (1973) criticized much of this literature for failing to provide much of an explanation, since the innovation possibilities frontier itself was seen as an exogenous construct.

6 Formally, a Hicks neutral change is one that leaves the ratio of the marginal products of capital and labor unchanged, however, under constant returns to scale these two are equivalent. See Blackorby et al. (1976).

output. X_k is required capital input, that is, the loom time needed to produce one unit of output. The capital-labor ratio at point A is then X_k/X_l.

The figure depicts a biased technical change: the isoquant shifts to the dashed curve and, at the same relative factor price, *w*, the cost minimizing point is now B. This labor-saving technical change raises the capital-labor ratio. The figure also shows factor substitution: an increase in the relative wage shifts the constant cost curve to the dashed straight line with a cost minimizing point on the initial isoquant at C. In this case, too, the capital-labor ratio increases as the firm uses more capital intensive production to compensate for the relatively higher labor wage. The first change represents a switch to a previously unknown technique; the second change represents a movement along the initial isoquant to a different technique that was already known.

However, economists rarely have detailed information about the state of technical knowledge. They simply lack information about which techniques are known when. If all they observe is aggregate data, they cannot usually distinguish between these two changes unambiguously. Indeed, as Diamond et al. (1978) show formally, neither the production function nor the path of technical change are identified when empirical researchers only have aggregate data on inputs, outputs and prices over time, without some additional structure. Since most of the research on these questions has been based on aggregate statistics, economists often impose *a priori* assumptions about the shape of the production function and/or the rate and bias of technical change.

The engineering production function approach avoids this difficulty. With the engineering production function, changes in X_l and X_k can be decomposed into changes based on new inventions and changes arising from factor substitution. With this decomposition, one can determine how new inventions and factor substitution affected the ratio of X_l and X_k and hence the technical bias. And since labor productivity is $1 / X_l$, this decomposition serves to analyze the sources of labor productivity change as well.

Note that the unit of X_k is loom time (minutes or hours). This is not a quality adjusted measure of capital because in this exercise I am attributing improvements in capital to technology. As it is, improvements in technology also reduced the nominal price of looms over the course of the century (see footnote 16).

Mechanization

Weaving is one of many technologies that were mechanized during the early nineteenth century. Mechanization involves the application of machines driven by inanimate power to tasks previously performed by human or animal power. Typically, mechanization brings three main advantages:

1. More machines can be used per worker. Weavers can tend more than one loom and spinners can handle hundreds of spindles.
2. Machines can be run faster.
3. Well-regulated machines can sometimes produce higher quality goods, for example, finer yarns or more even cloth.

I focus on the first two advantages and I control for quality by looking at weaving on a relatively standard set of coarse cloths. I consider production of cloths of about 44-64 threads to the inch of weft, using plain weaves, typically sheeting, shirting or print cloths, and narrow, 28-36 inches wide. I hold quality constant not because it is unimportant—in fact the evidence suggests that over the course of the nineteenth century machines were increasingly able to handle finer yarns, multiple shuttles, and more complex weaves. Rather I hold quality constant because my focus here is on the sources of capital deepening and these can be more cleanly measured at a given quality level.

Weaving is performed by interlacing two sets of threads, the warp and the weft, at right angles to each other. The warp consists of long, closely spaced threads that are stretched between two beams, the warp beam, for the bare warp threads, and the cloth beam, for the woven cloth. For the looms I study, the warp threads might be two or three hundred yards long with 1,800 or so threads across. Each warp thread passes through a small opening in a "heddle" that is used to raise or lower the thread. The loom alternately raises and lowers different sets of warp threads creating an opening called a "shed." A shuttle holding a bobbin of weft yarn (also called "filling") is propelled through the shed across the warp, leaving a new weft thread behind. This motion is called "picking" and the speed of the machine is frequently expressed in picks per minute. The weft thread left by the shuttle is pushed against the previously woven cloth by a comb-like "reed" (the process is called "battening"), adding it to the cloth. The entire process is repeated over and over again with different sets of warp threads raised and lowered for each pick according to the specific weave pattern.

The tasks of shedding, picking, battening, letting off warp from the warp beam and taking up cloth on the cloth beam were all performed manually (with some mechanical assistance) by handloom weavers and these tasks were all automated on the first power looms. This automation generally allowed a skilled weaver to tend two power looms at a time instead of one handloom. Also, these power looms generally ran at faster pick rates than those that handloom weavers realized.

Although mechanization reduced the labor required to produce a given output, it did not eliminate the need for labor. There are two reasons for this. First, some tasks were too difficult to automate, at least initially. For example, when the bobbin ran out of weft yarn, the loom had to be stopped and the empty shuttle replaced by one with a full bobbin. This task was performed manually until the appearance of the Northrop loom at the end of the nineteenth century. Second, the machines were hardly perfect. In textiles, for example, effective operation of the machines was sensitive to variation in humidity and temperature and of the quality of raw materials; also, the machines themselves were subject to breakdowns and sometimes depended on sensitive adjustments. Yarn would break and shuttles would fly out of the looms or get stuck in the emerging cloth.[7] These errors took time to fix. The time to perform tasks, both deterministic and stochastic, determined the capital and labor requirements at each level of technology.

Production with a single loom per weaver

Consider the machine time requirement for a single loom operated by a weaver. Assume, for the moment, that the weaver works without shirking at whatever task needs to be performed and that she works as quickly as a typical skilled weaver. The tasks that a weaver needs to perform on the first power loom circa 1819 are listed in Table 1 (I discuss the sources of these data below). In no particular order, the weaver had to replace shuttles and empty bobbins, fix broken warp and weft and smashes, adjust the loom temples (sides of the cloth) and warp tension, and replace the warp and the cloth beam. Over time, various of these tasks were automated, so that a weaver later in the century no longer performed all of them.

Let the running speed of the loom be s yards per minute. This means that it takes $1 / s$ minutes of loom running time in order to produce a yard of cloth. Now the weaver would perform some tasks—replace the empty bobbin and adjusting warp tension—while the loom was running. These tasks therefore did not require any additional loom time to complete. However, the weaver would perform other tasks only after the loom was stopped and so these tasks added to the total loom time requirement. For instance, when the shuttle ran out of yarn, the weaver had to stop the loom, replace the shuttle and re-start the loom. On coarse cloth, this would occur once half a yard was woven and I estimate that it took a skilled weaver about 0.2 minutes to perform this operation.[8] This means that for

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7 Rick Randall, Exhibit Specialist at Lowell National Historical Park, who operates early twentieth century looms at the museum, wondered how early loom fixers got by without tape. A rough surface on some parts of the loom could cause a shuttle to fly out and he showed me a loom where he had progressively taped over one area after another until he had fixed a persistent problem. One alternative used historically was to cover these surfaces in leather, which had to be replaced periodically.

8 Assuming a single loom and no wait, the weaver would stop the loom as soon as the shuttle ran out and so would not

every yard of cloth woven, the weaver would spend 0.2 / 0.5 ≈ 0.4 minutes replacing the shuttle (actually 0.38, as listed in the last column). During the 0.4 minutes, the loom would be stopped and so this contributed to the total loom time requirement. Similarly for the other tasks listed on the bottom portion of Table 1.

In other words, the loom time requirement for a skilled weaver operating a single loom with no shirking would be

$$X_k = \frac{1}{s} + \sum_{i=1}^{N} \frac{T_i}{R_i}$$

where N is the total number of tasks that involve stopping the loom (7 not counting cleaning and oiling), T is the time to perform the task, and R is the mean number of yards produced before the task needed to be performed. For tasks such as fixing warp end breaks, these would occur randomly, but on average they occurred every R yards of cloth woven.

Because there is one weaver per loom, it takes as much weaver time to produce a yard of cloth as it takes loom time, that is, $X_l = X_k$. However, it is interesting to look in further detail at the weaver's activity, because she is not actively working all the time. The weaver is active while performing all of the tasks listed in Table 1, including those that are performed while the loom is running. Therefore the weaver is active for

$$Z_l \equiv \sum_{i=1}^{N} \frac{T_i}{R_i} + \sum_{j=1}^{n} \frac{T_j}{R_j}$$

minutes per yard of cloth produced, where n is the number of tasks performed while the loom is running (in this case, 2). If W is the time that the weaver watches the loom without actively performing a task, then

$$X_l = \sum_{i=1}^{N} \frac{T_i}{R_i} + \sum_{j=1}^{n} \frac{T_j}{R_j} + W \quad .$$

For the example at hand, I estimate that the weaver is active for 4.7 minutes for each yard of cloth (from summing the last column of Table 1). However, for a loom running at .044 yards per minute (an estimate for the Waltham mill in 1819), it takes 26.6 minutes of loom time to produce a yard of cloth. In other words, a weaver operating a single loom would only be active for about a quarter of the time. A key benefit of automation was that a single weaver could operate more than one loom. Additional looms would keep the weaver active for a larger portion of her time.

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need to backup the loom.

Engineering model with multiple looms

However, adding additional looms introduces a complication: one loom might sit idle while the weaver works on another. That is, with multiple looms, more than one loom might be stopped at any point in time. Each loom will unavoidably be idle for some minutes during the production of each yard of cloth. Let the idle time be *I*. Then, following from above, the loom time required to produce one yard of cloth can be written

$$(1) \qquad X_k(k) = \frac{1}{s} + \frac{1}{s}\sum_{i=1}^{N}\frac{T_i}{M_i} + I(k) = Z_k + I(k), \qquad Z_k \equiv \frac{1}{s} + \sum_{i=1}^{N}\frac{T_i}{R_i}$$

where I have written idle time *I* a function of *k*, the number of looms per weaver. Z_k represents the time that the loom is running or is actively worked on.

A little inspection shows that idle time per loom increases with the number of looms per weaver, $I(k)$ is an increasing function. Clearly, from above, $I(1) = 0$. Adding a second loom allows for the possibility that both looms will be stopped at the same time, so idle time becomes positive with two looms per weaver. Further increases in the number of looms increases the probability that any one loom will sit idle while one of the $k - 1$ other looms is being worked on. This means that the more looms assigned per weaver, the longer it takes any one loom to complete a yard of cloth.

Equation (1) implies that the output per loom-minute, the capital productivity, is $1/X_k$. Similarly, *y*, labor productivity measured as output per weaver-minute, must be the output rate per loom times the number of looms per weaver, so that *y* is a function of *k*,

$$(2) \qquad y(k) = \frac{k}{X_k}$$

Additional looms also affect the portion of time that the weaver watches the looms without actively performing a task, *W*. In the above example with a single loom, the weaver actively performed tasks 4.7 minutes per yard, but it took a total of 26.6 minutes to produce a yard, leaving the watch time at 21.9 minutes per yard. With two looms, the weaver would actively perform tasks 2 x 4.7 = 9.4 minutes per yard, leaving a watch time of 17.2 minutes. Thus watch time *W* is a decreasing function of the number of looms per weaver.

The tradeoff between labor and capital is captured in the tradeoff between loom idle time, *I*, and weaver watch time, *W*. This is illustrated in Figure 2, where *y* is shown by the solid curve. This represents the production function for a given technology. The diagonal dashed line equal to k/Z_k represents the maximum output that *k* looms could achieve with I=0. The segment AB thus represents the output lost to idle loom time; this segment increases with k. The horizontal line $1 / Z_l$ represents the theoretical maximum output per weaver that could be achieved if watch time W were zero. The segment AC thus represents the output lost to weaver watch time; this decreases with k.

As the number of looms increases, however, weaver's watch time reaches a limit, shown in the figure by the fact that the asymptote of y falls below the theoretical maximum. The weaver might not be willing or able to work actively 100% of the time without rest, hence W does not go to zero. Also, the weaver needs some time to monitor the looms, to respond to errors (it takes some time to walk between 18 looms), and to coordinate activity. Of course, these latter requirements depend on the weaver's willingness to exert effort and skill. If we loosely designate this effort and skill as "labor quality," q, then watch time can be written as a function of looms per weaver and labor quality, $W = W(k, q)$. Then the weaver time requirement can be written

$$(3) \qquad X_l(k) = Z_l + W(k,q), \qquad Z_l \equiv \sum_{i=1}^{N} \frac{T_i}{R_i} + \sum_{j=N+1}^{N+n} \frac{T_j}{R_j}$$

where Z_k is the time the weaver is active (exclusive of watching) per yard output. Since the output rate per weaver must be the inverse of the weaver time required per yard,

$$(4) \qquad y(k) = \frac{1}{X_l}$$

providing an alternative to (2).

Equations (1) and (3) describe the unit isoquant in parametric form. Equations (2) and (4) are equivalent expressions of the production function. This is a two factor production function with constant returns to scale. Other input factors were also important. For example, cotton prices influenced the choice of cotton quality, power costs affected the speed of machinery, and both of these affected weaver and loom productivity. Also, there do seem to have been scale economies related to energy production. However, my primary inquiry here concerns capital-labor substitution and its effect on labor productivity, so I control for these other factors, but do not directly model or estimate them.

Decomposing changes

These equations provide a framework for analyzing the effects of technology and of factor prices on labor productivity, y, and on the bias of technical change. The sources of change in labor productivity can be analyzed by looking at the sources of change in X_l. The sources of change in the labor saving bias can be understood by looking at the sources of change in $X_k - X_l$.

Changes in labor time and loom time requirements, ΔX_l and ΔX_k, can be decomposed into three components:

1. Changes in loom speed, task duration and task frequency, including the complete automation of a task. Since all of the inventions during this period were directed to automating tasks, partially or fully, thus reducing their duration and frequency, or increasing loom speed, these changes correspond to the direct effect of inventions on the isoquant and are captured as changes in Z_l and Z_k, designated ΔZ_l and ΔZ_k. Technology might have also had *indirect* effects on production.

2. Changes in loom idle time, *I*, and weaver watch time, *W*, that can be attributed to changes in relative factor prices, *w*. These can be calculated given estimates of the elasticity of substitution, σ, and the capital share of output, s_K. In the Appendix I show that

(5) $$\frac{d \ln X_l}{d \ln w} = -s_K \sigma, \qquad \frac{d \ln X_k}{d \ln w} = (1-s_K)\sigma$$

Using these formulas, the changes in *W* and *I*, that can be attributed to changes in relative factor prices are

(6) $$\Delta^w W = -s_k \sigma X_l \cdot \Delta \ln w, \qquad \Delta^w I = (1-s_k)\sigma X_k \cdot \Delta \ln w \quad .$$

Note that this calculation assumes stable values of the elasticity and output shares. I show evidence below that these variables did not change substantially over the course of the nineteenth century. This also means that technology did not apparently affect these variables significantly. Thus the quantities in equation (6) can be interpreted as the effect of factor price induced substitution.

3. Finally, there are residual changes, $M_k \equiv \Delta I - \Delta^w I$ and $M_l \equiv \Delta W - \Delta^w W$. Below, using some additional data, I interpret the residual in *I* as largely due to an indirect effect of technology and I interpret the residual in *W* as largely an effect of changing labor quality. I show that the effect of technology on *W* was likely of the wrong sign to explain the change in the *W* residual.

By construction, these three components provides a complete decomposition of the loom and labor requirements. Applying the difference operator to (1) and (3),

(7) $$\begin{aligned} \Delta X_k &= \Delta Z_k + \Delta I = \Delta Z_k + \Delta^w I + M_k \\ \Delta X_l &= \Delta Z_l + \Delta W = \Delta Z_l + \Delta^w W + M_l \end{aligned} \quad .$$

Production Function Estimates

I begin by estimating (1) and then using (2) to obtain estimates of labor productivity. To do this, I obtain estimates of loom speeds and task frequencies and durations from a variety of sources and I combine these in a simulation analysis to obtain estimates of *I*.

Duration and frequency of tasks

I use two sorts of data to estimate task frequencies and durations. First, for each of the major tasks involved in weaving I obtained estimates of the time it would take a skilled weaver (mostly circa 1900) to perform each task and of the frequency of occurrence. I obtained this information from trade publications, the Transactions of the National Association of Cotton Manufacturers, patent specifications, and weaving manuals. I also took time-and-motion and measurements on working museum models in Lowell. I list these estimates in Table 1. Note that where tasks were partially automated, I include estimates of the duration and frequency both before and after the improvement.

Second, using these sources and additional historical accounts, I obtained a list of the major inventions that automated these tasks, either fully or partially, and those that allowed the looms to run at faster speeds. I provide a list of these in Table 3 and I will discuss them below. These changes include both major discrete inventions, such as the weft fork, as well as minor improvements, such as the changes in loom construction that gave the looms greater stability at higher speeds, allowing them to run faster without creating as many defects. In one case, the task of adjusting warp tension, I was able to independently verify the estimate with an econometric analysis of individual weaver monthly productivity from the Lawrence Company.[9]

Finally, I also conducted an analysis of how sensitive this model is to changes in task parameters. For example, the most time-consuming task for most of the century was replacing the empty shuttle. This task was automated by the Northrop loom. But a 10% change in the frequency of this task, including the time required to stop and back up the loom prior to the adoption of the weft fork, only changes the task time per yard by 0.17 minutes or less, a change of 2-3% in the weaver time per yard. Ten percent variations in other parameters generated smaller variations.[10] This suggests that my estimates of active and idle time are reasonably robust to errors in the task parameter values.

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9 The estimate of duration and frequency implies that automating this task should increase labor productivity about 3%. Since we know that this task was automated in May 1835 at the Lawrence Company (Lazonick and Brush 1985, Montgomery 1840), I estimated a production function for this mill using a dummy variable that was one for all dates after this and zero before. The regressions (not shown) were of the form $\ln y = \ln k + \ln\left(1-e^{b1*u*k^{b2}}\right) + Z$, where u measures weaver experience and Z is a vector of dummy variables, including this technology dummy, plus year and month dummies and, in various combinations, variables for cotton quality and weaver literacy and ethnicity. I find that the coefficient on the technology dummy ranges from 1% to 3%, in line with the result from Table 1.

10 Since (1) is a linear combination, the combined effect of multiple variations would be a simple linear combination where some errors would likely offset others.

Simulation Results

The engineering production function I have described is an instance of a standard operations research problem known as a queueing problem with a finite calling population (see also Levhari and Sheshinski 1970 and Arrow et al. 1972). Although *I* cannot be described analytically, it can be estimated using simulations.

I ran simulations for a number of benchmark mills from the nineteenth and early twentieth centuries.[11] I used the values from Table 1 selected for the technology configuration of each mill plus historical estimates of loom speeds and looms per weaver.[12] In Table 2, I compare the actual labor productivity of each mill, *y*, with the value of labor productivity predicted by the simulations, $\hat{y}$. As can be seen, the predicted values were quite close to the actual ones. The mean error relative to the actual value of *y* is -0.4%, suggesting no substantial bias. The share of the variance in *y* that is "explained" by the simulation (that is, the R^2) is 0.994.

The mills in my sample were presumably selected for comment by contemporaries because they represented the technology frontier. In 1879, mills below that frontier can be compared to typical mills from a supplementary report to the Census (Wright 1880). These are listed as "5 steam powered mills" and "6 water powered mills" in the table. The productivity of the steam powered mills is quite close to that of Boott Mills, Mill No. 1 in 1876. On the other hand, the water powered mills likely had older technology and have a labor productivity that is substantially lower.

The next two columns of Table 2 report the actual loom-minutes per yard for each mill and the estimated number of idle minutes per yard obtained from the simulations. The final two columns report the actual weaver-minutes per yard produced and the estimate of *W*, calculated as a residual from equation (3). Note that some of these values are particularly large. I will explore these below.

A variety of factors might affect my estimates. Some conditions might have changed over time, for example, weavers at early mills might not have had the same skill level as the weavers whose

11 My simulations were for 10 weavers running *k* looms each for 60 hours. In simulating (1), I assumed that the weavers immediately began work on a stopped loom unless they were already working on another loom. For each of the 7 tasks that caused the loom to stop (bottom panel of Table 1), the time to the next stop for that task was calculated for each loom. Some of these times were deterministic and some were random. Fully automated tasks never caused a stop, of course. The loom then "ran" until the lowest stop time was reached. The stop times for the remaining tasks were decremented by the elapsed time, the loom was idle while it was worked on or while previously stopped looms were worked on, and then the loom was restarted with a newly calculated value for the task just completed. The looms were jointly run for 60 hours and then the amount of cloth produced was tabulated.

12 Typically, weavers in the same mill were assigned different numbers of looms depending on their skill and experience. For example, new recruits might only work on a single loom at first, and piece rate workers might work on 4, 6 or 8 looms (earning different piece rates). For the early mills, I averaged the total number of looms over the total number of weavers, so the number of looms per weaver is non-integer. For the later mills, I chose the number of looms that was indicated as being most typical of skilled weavers.

performance is listed in Table 1. Or cotton quality might have improved over time. If these were true, however, there would be a growing gap between predicted and actual output rates.[13] The fact that the gap did not grow suggests that changes in these factors were not significant.

One of the largest residuals occurs at the Fall River Ironworks. This might be explained by local conditions where Young (1902, p. 11) reports an exceptionally low rate of warp end breaks because of extra effort put into warp preparation. Also, the benchmark mills produced slightly different cloths with different numbers of threads per inch (from 44 to 64) and different widths (from 28 inches to 36 inches). The later mills tended to produce narrower widths but with more threads per inch (roughly offsetting). However, the predicted output rates for the later mills do not appear to be consistently biased one way or the other with respect to cloth parameters. I ran a version of my estimates with adjustments for both of these factors and found that my qualitative conclusions are robust to these adjustments.[14]

Also, some weaving tasks were performed by workers other than weavers; I have accounted for some of this in my estimates for the Northrop looms because sources clearly indicate that other workers removed cloth and fix smashes. However, it is possible that these tasks could have been performed by non-weaving personnel for weavers on plain looms in 1902 and 1903.[15] This might contribute to slightly greater output than predicted on these looms.

Sources of Change in Labor and Capital Productivity

Both labor and capital productivity grew dramatically in cotton weaving over the course of the nineteenth century with a corresponding dramatic drop in the labor time and loom time needed to produce a yard of cloth. From Table 2, the labor requirement, X_l, fell from 39.6 minutes per yard produced using the handloom circa 1819 to 0.8 minutes per yard produced using Northrop looms circa 1900, a drop of 38.8 minutes per yard. The corresponding loom requirement, X_k, fell from 39.6 minutes per yard produced on the handloom to about 14 minutes per yard produced on the Northrop looms, a reduction of just over 25 minutes per yard. From the first powerlooms at BMC in 1819 to the Northrop

13 Moreover, the evidence on biological innovation suggests that cotton quality likely improved from 1820 through 1840, but not after that (Olmstead and Rhode 2008). Alan Olmstead suggests in a private communication that cotton quality probably increased for the two decades prior to 1840, then remained roughly constant until the Civil War, which was followed by a decrease in quality.

14 These factors affected the speed of the loom and possibly the frequency of errors. The number of picks per inch in the cloth proportionately reduced the number of yards per minute for a given pick rate. The narrower width reduced the number of warp threads and allowed the loom to run at a faster pick rate (see Draper 1907, p. 170). To test the sensitivity of my results, I calculated estimates both with and without these various speed adjustments.

15 This is not an issue at the earlier mills because I include all labor excluding overseers in calculating looms per worker at these mills.

loom, both the labor time required to produce a yard of cloth and the loom time required to produce a yard of cloth fell about 15 minutes.

What accounts for these reductions? The decomposition of equation (7) permits us to allocate these changes to the direct effect of weaving inventions, the substitution of looms for labor and a residual. I calculate the change in each of these components from the handloom to the Northrop loom and from the BMC powerloom to the Northrop loom.

Weaving inventions

I begin analyzing the sources of change by evaluating the direct technology terms, Z_l and Z_k. The nineteenth century inventions responsible for the main changes in productivity are shown in Table 3, organized by the task that was automated. This list of inventions is described further in the Appendix and it corresponds closely to those inventions mentioned by contemporaries and historians as being important in coarse cotton cloth production (Barlow 1878, Copeland 1912, Draper 1907, Fox 1894, Gilroy 1844, Harriman 1900, Hayes 1879, Jeremy 1973, Macmillans 1862).

Drawing on the data in Table 1 and on data about loom speeds, Table 3 shows the direct impact of the various inventions on Z_k and Z_l. These sum to a reduction in weaver minutes per yard of 28.3 minutes and a reduction of loom minutes per yard of 24.8 minutes between the handloom and the mills using Northrop looms in 1902-3. From the BMC mill in 1819 to the Northrop looms, the direct effect of inventions was to reduce weaver minutes per yard by 5.2 minutes and to reduce loom minutes per yard by 15.7 minutes.

Loom-Labor Substitution

Next, I turn to estimating the second component, the effect of change in loom idle time and weaver watch time that can be attributed to changes in the relative factor price, $\Delta^w I$ and $\Delta^w W$. From equation (6), this requires estimates of s_K, w, and σ. Layer (1951) calculates semi-annual factor shares of output for several mills in Lowell for much of the nineteenth century. For the Lawrence Company, the mean capital share of value added is 42%, calculated as one minus the labor share. Although there is some significant year-to-year variation, the mean appears to be stable over time and the standard error, 0.6%, is small.

To calculate changes in the relative wage, w, I use two different wage series. One is the series for unskilled wages from David and Solar (1977); the other I impute from Layer's (1957) quinquennial series for textile workers' hourly wages multiplied by his series for the relative wages of weavers. I divide both by the prices of looms from historical sources.[16] These give a change in the log relative wage of 1.00 and 1.25 respectively from 1819 to 1902.

I estimate the elasticity of substitution between looms and labor both using simulated data and historical data. First, for a given set of task duration and frequency parameters typical of mid-nineteenth century production, I ran simulations where weavers were assigned different numbers of looms than the historically assigned numbers. In doing the simulations, I assumed that weavers might actively perform the tasks in Table 1 for 100% of the time if the number of looms was large enough to keep them that busy. In reality, of course, no weavers would or could maintain such a high level of activity. However, I can show that the effect of limiting the weaver's minimum watch time is to reduce the estimates of the elasticity of substitution (calculation available from author). That is, the simulations will tend to overstate the magnitude of the elasticity of substitution somewhat.

The results of one such simulation is shown in Figure 3 where the mean output per weaver minute is shown against the number of looms used in each simulation.[17] On inspection, this appears quite similar to a constant elasticity of substitution (CES) production function. Using Non-Linear Least Squares, I fit a CES production function to that simulated data, that function shown as the solid curve in Figure 3. The estimated elasticity of substitution for these data is 0.11.[18]

To test the robustness and stability of this estimate, I repeated this exercise for a wide range of parameters typical for nineteenth century plain looms, but using a wide range of loom assignments.[19] For all of these simulation runs, I obtained estimates of the elasticity of substitution ranging from 0.09 to 0.17. Given the wide range of parameters and the wide range of looms per weaver, these results suggest that the elasticity of substitution was quite stable and unlikely to change significantly with

16 Montgomery (1840) and Gibb (1950) report the price of a power loom during the early decades was $75 (the Waltham loom cost more, but was quickly replaced by Gilmour's design). Young (1903) and Uttley (1904) report prices of plain looms in 1901-3 at $49.92, $56, and $58; I take the average of these three.

17 This simulation run was for cloth 48 picks to the inch in the weft, 36 inches across, a loom speed of 130 picks per minute, a task that occurred every time 960 yards of weft were used that took 90 seconds of time while the machine was stopped and 20 seconds while it was running, and a similar task that occurred randomly with a mean time between failures of 1000 seconds. I assumed that weavers could respond to a stopped loom without delay as long as they were not already working on another loom.

18 The equation estimated over 8 points was $y = a\left(k^{\frac{-1-\sigma}{\sigma}} + b^{\frac{-1-\sigma}{\sigma}}\right)^{\frac{-\sigma}{1-\sigma}}$ with a estimated at 3.47 (0.05), b at 4.21 (0.06) and σ at 0.11 (0.02) with an R^2 of 0.9998 (standard errors in parentheses).

19 I did two sets of simulations. One set used a single stochastic and a single deterministic process where the duration and frequency parameters matched the range of the main weaving tasks seen on the nineteenth century looms. I used this ahistorical data to "stress test" my estimates at extreme values. A second set used the actual parameters for up to the seven different tasks for several of the benchmark mills. In all cases, I assumed that weavers could respond to a stopped loom without delay as long as they were not already working on another loom. I fit the data to the CES specification in (8), keeping the parameters a and b constant.

technology or other factors.

To further support this conclusion, I also ran regressions using data on monthly output from a weaving room at Lawrence Company Mill No. 2 in Lowell from 1834 through 1855. These data were originally developed by Lazonick and Brush (1985, see also Bessen 2003). Using these data, I fit a CES specification similar to one used by David and Van de Klundert (1965),

(8) $$y = a(t)\left(k^{\frac{-1-\sigma}{\sigma}} + b(t)^{\frac{-1-\sigma}{\sigma}}\right)^{\frac{-\sigma}{1-\sigma}}, \qquad a(t) \equiv a_0 e^{zt}, \;\; b(t) \equiv b_0 e^{gt}$$

where a represents neutral technical change, b represents labor productivity and σ is the elasticity of substitution. This specification assumes a constant rate of neutral technical change, z, and a constant rate of labor augmentation, g. I estimated this production function using Non-Linear Least Squares, excluding months where water power was known to be insufficient. I also excluded the first six months of operation of the mill because learning-by-doing strongly affected productivity (David 1975). The estimates are shown in Table 4. The estimate of the elasticity of substitution over the entire period is 0.142, closely corresponding to the estimates from the simulation runs. The table also shows separate regressions for the first and second decades of the sample. The elasticity of substitution does not appear to change significantly over this period.

These estimates also correspond well with Asher's (1972) findings. Asher estimates the elasticity of substitution for the entire US cotton industry (not just weaving) from 1850 – 1900 using a CES production function with constant rates of capital- and labor-augmenting technical change. He obtains estimates of the elasticity of substitution ranging from 0.04 to 0.15. Thus my parameter estimates and model generate an elasticity of substitution that corresponds well to empirical estimates.[20]

To calculate the contribution of factor substitution in (6), I use σ = 0.14, $s_K = 0.42$ in (6) and the average of the initial and final values of X_l and X_k. I do this calculation between the Boston Manufacturing Company in 1819 and the two mills with Northrop looms in 1902-3. The changes in the weaver time required to produce a yard of cloth attributable to changes in relative factor prices between 1819 and 1902 is $\Delta^w W = -0.5$; the change in the loom time requirement is $\Delta^w I = 1.7$, both calculated using the Dollar-David unskilled wage. Using the Layer weaver wage series, these values are $\Delta^w W = -0.6$ and $\Delta^w I = 2.1$.

20 Also, Cain and Patterson (1986) find that the elasticity of substitution for the textile industry as a whole was not significantly different from zero from 1850 to 1919.

Residual

Using the estimates of loom idle time, *I*, and weaver watch time, *W*, from the simulations (see Table 2) and the just-calculated changes attributable to loom-labor substitution, it is straightforward to calculate the residual changes. Between the powerlooms at BMC in 1819 and the Northrop looms in 1902-3, weaver watch time decreased 10.6 minutes per yard; loom idle time increased 0.5 minutes per yard. Using the two estimates for the contribution o factor substitution, this means that residual factors account for a reduction in weaver time per yard produced from 10.0 minutes to 10.1 minutes. Residual factors account for a reduction in loom idle time per yard of from 1.2 minutes to 1.6 minutes.

Decomposition of productivity changes

Table 5 summarizes these changes in the loom and labor requirements between 1819 and 1902-3 according to equation (7). The top panel shows the decomposition of the changes in the loom and labor requirements from the handloom to the average of two mills using Northrop looms in 1902-3. The first row shows the reductions directly attributed to inventions, ΔZ_l and ΔZ_k, taken from Table 3. The second row shows the reduction attributed to loom-labor substitution just calculated, $\Delta^w W$ and $\Delta^w I$. The third row shows the residuals. The fourth row sums the previous three rows to obtain the total change in the weaver time requirement and loom time requirement per yard.[21]

The bottom panel shows the decomposition of the changes in loom and labor requirements between the Boston Manufacturing Company (BMC) in 1819 and those two mills using Northrop looms in 1902-3.

How much of the reductions in weaver and loom requirements can be directly attributed to inventions? A lot. From the handloom to the Northrop loom, inventions accounted for a 28.3 minute reduction in weaver time per yard and a reduction in loom time per yard of 24.8 minutes. Comparing these figures to the total reduction of weaver time per yard of 38.9 minutes and a reduction of loom time per yard of 24.3 minutes, inventions directly account for 73% of the reduction in weaver time and virtually all of the reduction in loom time per yard. From the first powerlooms at BMC to the Northrop looms, inventions directly accounted for about one third of the reduction in weaver time per yard (5.2 minutes of a total of 15.9) and about all of the improvement in loom time required per yard.

21 I attribute the effect of loom labor substitution observed for the powerlooms from 1819 to 1902-3 to the handloom as well, although a handloom weaver could only operate a single loom herself. Similarly, I assume that the effect of residual factors was the same between the two types of looms in 1819 and the looms in 1902-3. The sums in the fourth row differ slightly from the corresponding changes in actual loom and labor requirements in Table 2 because I save used estimate of loom idle time and weaver watch time from the simulations.

How much of this change can be attributed to movements along the production function, that is, to the substitution of looms for labor? Only 1-2% of the reduction in the labor requirement from the handloom to Northrop loom appears to arise from factor substitution (3-4% from BMC). And, of course, greater capital intensity increased the loom requirement, reducing capital productivity.

Clearly, a substantial part of the reduction in the labor requirement arises neither from the direct impact of inventions nor from the effect of factor substitution. The change in the residuals between the Boston Manufacturing Company and the Northrop looms are substantial as shown in the third row of Table 5. This accounts for 25-26% of the reduction in the labor requirement between the handloom and the Northrop loom (10.0 to 10.1 yards per minute of 38.9). If, instead, one looks just at the reduction from the Boston Manufacturing Company to the Northrop looms, then two thirds of the reduction in weaving time per yard can be attributed to the residual change in W (as reduction of 10.0 to 10.1 yards per minute out of a total reduction in weaver time of 15.8 minutes per yard).

The large impact of the change in weaver watch time on labor productivity can be seen in Figure 4. Figure 4 shows the portion of time each weaver spent actively performing a task on a loom, where by "actively performing" I mean performing the tasks listed in Table 1 as opposed to the relatively passive task of watching the looms. I calculate this portion as

$$1 - \frac{W}{X_l} \quad .$$

During the early years, weavers only actively performed tasks about 25 – 30% of the time; by the early twentieth century, weavers at some mills were actively performing tasks 80% of the time. Clearly this is a large and economically significant difference. Something must have prevented the early mills from assigning more looms per weaver to increase the portion of time that the weavers actively worked.

Could this apparently large difference be a statistical artifact? Perhaps early powerloom weavers took longer to complete their tasks or they performed them less reliably, causing more frequent errors. This seems at odds with the data, however. If task durations were substantially larger, then the predicted output rates in Table 2 would have been substantially lower than the actual output rates. Similarly, substantial increases in task frequency are at odds with Table 2. Weavers performed two significant tasks while the looms were running (and so are not reflected in the output rate), but the historical evidence suggests that neither of these took very long.[22] The relatively large values of W during the early years of the nineteenth century do not appear to be statistical artifacts.

22 Moreover, as discussed above, the estimated effect for the adjustment of warp tension was confirmed by regression analysis.

Interpreting the residuals

What might explain the large drop in *W* and the smaller drop in *I* after taking into account factor substitution?

Technological change is, of course, a prime candidate. The various inventions in Table 3 reduced the frequency of loom stoppages and this might have changed both the frequency of loom idle time and weavers' difficulty monitoring the looms. By my estimates, a powerloom at the Boston Manufacturing Company in 1819 was stopped every 2.6 minutes on average; a Northrop loom at the benchmark mills in the early 1900s stopped every 33 or 34 minutes. Thus inventions reduced the frequency of stoppages on each loom, likely accounting for the reduction in loom idle time observed in the residual.

Could these changes in the frequency of stoppages also explain the drop in time that weavers spent watching the looms? Note that the weavers were not simply idle during this time; they were *monitoring* the looms and the frequency of stoppages might affect the intensity of monitoring. An essential part of their job was to watch for defects in the cloth and errors in the operation of the loom. There were more than a dozen different defects in the cloth that could arise if the loom was not working perfectly (Draper 1907, pp. 165-8) and the weaver had to be alert to these and also to breaking threads, empty shuttles etc. so that remedial action could be taken. In many cases, the longer it took to notice an error, the longer it took to fix because the loom had to be backed up or because one error could cause another, multiplying the severity. Consequently, the weaver's ability to anticipate and to detect errors quickly affected her productivity. Moreover, this was not always easy to do, because many parts of the loom moved faster than the eye could see and many of the cloth defects were subtle to detect, especially in poorly lit factories. And it was likely difficult to maintain a high level of alertness ten or twelve hours a day without some significant resting time.

If errors occurred less frequently, then weavers would not require as much "buffer" time to notice and respond to errors and the portion of time they spent resting after fixing each error would be less. However, changes in technology made conditions more difficult for the weavers, not less. While the frequency of stoppages per *loom* dramatically decreased, the stoppages per *weaver* actually increased because the weavers were tending that many more looms. Of all the benchmark companies, weavers at the Lawrence Company in 1835 spent the greatest portion of their time watching the looms; weavers spent the least time watching at the three mills with plain looms in 1901-3. Yet the weaver at the Lawrence Company in 1835 had to tend to a loom stoppage only once every 2.5 minutes on average while a plain loom weaver in 1901-3 had to tend to a loom stoppage every 0.5 minutes. Thus the weaver in 1901-3 had to monitor loom stoppages that were five times more frequent yet that weaver actually spent substantially *less* time—one third the time—monitoring the looms.

Could the inventions in Table 3 have reduced monitoring time in some other way? Only one of the inventions would have affected the visibility of errors: the weft fork stopped the loom when the weft ran out or broke, making the error easier to monitor. However, a rough calculation suggests that the weft fork could not have saved as much as one minute per yard of monitoring time and would have been offset by the higher frequency of stoppages with more looms.[23] This is consistent with the data from the benchmark mills. Weavers spent about the same portion of their time watching the looms at the Lawrence Company in 1855, which did not have the weft fork, as the weavers at the Boott Company mill in 1876, who had the weft fork.

Thus changes in technology, if anything, likely increased the difficulty of monitoring the looms overall. Technology cannot explain the dramatic drop in the share of time weavers spent watching the looms. An alternative explanation is that later weavers were able to spend less time monitoring these more frequent stoppages because the later weavers exerted more effort and/or had greater skills at monitoring than did earlier weavers. That is, labor quality improved.

The importance of labor quality is suggested by the difficulty that the mills in Lowell had when they tried to switch from two looms per weaver to three looms per weaver in response to depressed markets in 1842. According to Montgomery, a mill manager, it was thought that most weavers, even experienced ones, could not keep up with three looms (Montgomery 1843, p. 132). So the mills had to reduce loom speeds by 15% when they first started using three looms. The productivity data for the Lawrence Co., Mill No. 2 show that the loom remained at the lower speeds for over a year, by which time the weavers had apparently acquired the skills necessary to keep up with three looms at the original speed. This change is evident in Table 2 where the value of W was cut in half between 1835 and 1845.[24]

Evidence on human capital for weavers also supports the view that weaver skills increased during the century. Bessen (2003) finds that the "learning curves" for individual weavers at the Lawrence Company were sharply steeper during the 1840s and 1850s than during the 1830s. Using a calculation based on foregone earnings, he found that these learning curves corresponded to a human capital

23 The time spent backing up the loom was roughly the same as the time it took the weaver to notice the error (the monitoring time), get to the loom and stop it. From Table 3, the total weaver time saved per yard was 1.1 minutes. Only a fraction of this could have been monitoring time. This is consistent with the data. The Lawrence Company mill had a watch time of 2.0 minutes per yard in 1855 with about 4 looms per weaver without the weft fork; Boott Mills had a watch time of 1.1 mintues per yard in 1876 with about 6 looms per weaver with the weft fork.

24 Moreover, there is no evidence of significant changes in the looms during this period. See footnote 25.

investment per trained weaver of $162 during the later period but only $47 during 1833-6. This suggests that a substantial portion of the increase in weaver productivity shown in Figure 4 between 1835 and 1855 was realized in part through greater weaver skills. Indeed, both historians and contemporary observers have noted that the looms experienced relatively little technological change during these decades, despite the substantial growth in labor productivity shown in Table 2.[25] Moreover, the contribution of human capital to weaver productivity after 1855 is supported by the relative increase in weaver's wages: from 1860 to 1900, weavers' daily wages increased 31% relative to the unskilled wage, suggesting a growing skill level.[26]

My interpretation that weaver quality appeared to increase substantially over the course of the nineteenth century also corresponds to Clark's findings on international differences in weaving (1987, 2000). Clark finds that some nations (e.g., the U.S. and U.K.) deployed many more looms per weaver at the beginning of the twentieth century than others (e.g., India, China, Japan). As Clark discusses, all these nations used more or less the *same* looms, almost all supplied by U.K. manufacturers, except for the U.S., where the looms were similar. Since the looms also ran at about the same speeds, the differences in looms per weaver correspond to differences in the portion of time spent monitoring. Using a process of elimination, Clark argues that workers in the higher productivity nations simply worked harder. However, although Clark considers experience as a factor, he does not consider learning on the job.[27] Lazonick and Brush (1985), echoing a suggestion made earlier by Ware (1931) and Josephson (1949), argue that the change to an immigrant labor supply during the 1840s and 1850s allowed mill owners to extract greater effort from the weavers.

To summarize, I find that a substantial part of the reduction in the time that a weaver required to produce a yard of cloth cannot be accounted for by the direct or indirect effects of technology nor by the effect of the substitution of looms for labor. Improved labor quality does, however, provide a

25 The looms at the Lawrence Company were not replaced during this period and were only retrofitted with one significant improvement (an automatic friction adjustment to the warp tension) that accounts for little of the productivity increase (see Table 4, McGouldrick 1968, Lazonick and Brush 1985). Gibb (1950), Jeremy (1973) and Strassman (1959) stress the remarkable improvements made in the early decades relative to later decades. Draper (1907), Hayes (1879) and Harriman (1900) note the improvements made at the end of the century after a period of relative stagnation. Habakkuk (1962) argues that historians ascribe "the absence of technical progress in the American textile-machine industry between 1840 and 1870 to the softening effect of abundant demand."

26 Using David and Solar (1977), the unskilled wage index increased from 100 to 140. Layer's (1955) estimate of daily earnings for cotton mill operatives increased from .675 to 1.098, but weaver's wages increased from 95% of this in 1860 to 107% of the 1900 figure. I use the starting date of 1860 because by this time the majority of new hires were immigrants. Earlier, the labor supply was mainly Yankee and these girls had substantially better employment alternatives than the immigrants, e.g., as school teachers.

27 Experience is not necessarily a good proxy for learning because most of the learning appears to take place during the first year and because in order to learn to handle many looms, the weaver must be assigned many looms during the learning period.

plausible explanation. My data here cannot distinguish whether this consisted of greater worker effort or from learning on the job, or—most likely—from a combination of these factors. In any case, both interpretations fit the notion that the quality of weavers was greater in the US and UK in 1900 compared both to the weavers in other countries in 1900 and compared to the weavers in the US during the early nineteenth century.

Sources of Technical Bias

At least since Hicks (1932), many economists have observed the large increase in capital labor ratios accompanying rapid labor productivity growth and, aware of the limited substitution of capital for labor, have concluded that this provides evidence of labor-saving technical change. Such might seem to be the case for weaving as well. The engineering production function provides the means to identify the sources of the bias in technical change.

Given the assumption of constant returns to scale, a Hicks neutral technical change corresponds to a shift in the isoquants that leaves the ratio of the required weaver time to the required loom time unchanged (Blackorby et al. 1976). Since loom time equals weaver time for the handloom, the net bias of technical change over the nineteenth century can be determined by comparing changes in the required weaver time, ΔX_l, to required loom time, ΔX_k. If technical change decreased the weaving time per yard more than it decreased the loom time per yard, then the net technical change was labor-saving.

Table 6 shows a simple accounting of the differences in changes in ΔX_l and ΔX_k., using the values from Table 5 from the handloom to the Northrop loom. The net change, even aside from factor substitution is strongly labor-saving. The time required for a weaver to produce a yard of cloth fell 38.9 minutes while the time required for a loom to produce a yard fell only 24.3 minutes, a difference of 14.6 minutes per yard.

However, decomposing this shift into the terms found in equation (7) yields a surprise. Contrary to assumptions of Hicks and others, only a small part of this increase can be attributed to the labor-saving bias of inventions. Instead, inventions exhibit only a small direct labor-saving bias of 3.5 minutes per yard. Moreover, this ignores the indirect effect of technology on the frequency of loom stoppages. Taking the residual shift in loom idle time into account (1.2 – 1.6 minutes per yard), the net labor-saving effect of inventions was only 1.9 – 2.3 minutes per yard. Instead, most of the apparent technical bias appears to arise from the improvement in labor quality as reflected in the decrease of W after taking factor substitution into account. As I noted above, Habakkuk recognized that factor prices could influence the choice of technology through worker training rather than through inventions per se.

However, most other discussion of directed technical change or "induced innovation" has tended to assume that the main effect concerned inventions. The intuition behind this theory is that firms weigh the cost of developing new technology against the cost saving potential of the technology. When wages are relatively high, the cost reductions from saving labor will exceed the cost reductions from saving capital, all else equal, so technical change will tend to be biased toward labor-saving inventions.

This notion is appealing, but the evidence here suggests that, at the very least, the way things actually worked in cotton weaving was more complicated. First, note in Table 3 that almost every task was automated to some degree during the nineteenth century. As Salter (1960) argued "any advance that reduces total cost is welcome; whether this is achieved by saving labor or saving capital is irrelevant." This means that technological considerations necessarily played a strong role in determining the technical bias of inventions.

The effect of an invention on the technical bias depended on the nature of that invention: whether it automated tasks that were performed while the loom was running or while the loom was stopped or whether the invention increased loom speed. These differences are shown in Table 3. Inventions that automated tasks performed while the looms were running were purely labor-saving because they only affected the weaver time requirement, X_l. But inventions that automated other tasks reduced loom time and labor time equally. And inventions that increased loom speed were purely capital-saving because they only affected the loom time requirement, X_k. Given that inventors attacked all sorts of opportunities for improvement, it is not clear that factor prices necessarily affected their net profit calculations very much.

In particular, the breakdown in Table 3 shows that different types of inventions had different effects on the bias. Note that most of the labor-saving shift came from the initial powerloom while most of the counterbalancing capital-saving shift came from increases in loom speed. This is significant because these were very different sorts of inventions. The powerloom automated weaving tasks, so this development was highly specific to the field of weaving. These inventions drew on the general vocabulary of machine elements, including cranks, cams, pulley wheels, etc., but they were specific to the textile weaving industry. On the other hand, much of the improvement in loom speed arose from beneficial developments in other fields. As described in the Appendix, there were improvements in power transmission, in water turbines and steam engines and improvements in machine construction associated with the development of machine tools and other advances in machining. In other words, much of the capital-saving arose from “general purpose technologies.” This meant that inventors developing these technologies would look to reap profits from a wide range of industries in addition to textile weaving. The development costs of the capital-saving inventions were therefore spread over many industries as well. The share of development cost for capital-saving inventions that were amortized to the textile weaving industry might well have been substantially less than the development costs of the industry-specific labor-saving inventions. This means that even if the basic intuition is correct that inventors compared profit against development cost, high relative wages might not lead to a labor-saving bias. Because the development costs of capital-saving inventions were spread over many industries while the development costs of labor-savings inventions had to paid for by weaving alone, factor prices might have played only a secondary role in this calculation.

On the other hand, factor prices might very well have influenced *labor quality*, as Habakkuk suggested. Bessen (2003) found that high wages relative to prices was important in the mills’ decisions to invest in greater human capital development in the 1840s, which enabled an increase the number of looms per weaver.

In summary, Table 6 illustrates that evidence of a rising capital-labor ratio does not imply that inventions are labor-saving. The source of the bias might well be changes in labor quality rather than inventions. Moreover, because of technological constraints, inventions might not be particularly labor-saving even if factor prices influence the choice of inventions that are developed and adopted.

Conclusion

Economists have long recognized that economic growth has historically involved both an increase in output per worker and an increase in capital per worker. Some have explained this relationship with a story about “more machines”: increased capital accumulation led to rising wages relative to capital costs, causing firms to substitute capital for labor along the production possibilities frontier, as in the transitional dynamics of the neoclassical growth model. Indeed, the traditional view sees nineteenth century growth driven by capital accumulation much more than by technical change. Others have favored a “better machines” story, where labor-saving inventions increase both the output per worker and the capital per worker. Some have further argued that factor prices influence the development of inventions, so that rising relative wages induce this labor-saving bias in technical change. Prospective inventors presumably calculate the returns that they will earn on a successful invention; when wages are relatively high, the returns might be greater from labor-saving inventions, so, all else equal, they direct more inventive activity toward saving labor than saving capital.

However, it has proven difficult to disentangle these explanations empirically using aggregate data. This paper uses detailed data about the production function and inventions to parse these explanations for nineteenth century cotton weaving. I find that very little of the capital deepening and labor productivity growth that took place in weaving can be attributed to factor substitution. That is, economic growth in weaving was hardly a story of “more machines.”

However, it was not a simple story of “better machines,” either. The engineering production function analysis suggests that about a quarter of the growth in labor productivity arose from better quality labor. Skilled weavers at the end of the century took less time to monitor the looms than did weavers in the early part of the century, suggesting that the later weavers had better skills and/or they worked harder than the weavers early in the century. This view is supported by a range of secondary evidence. In other words, economic growth in weaving was a story of “better machines and better workers.”

This increase in labor quality is important because I also find that it contributes substantially to the apparent technical bias. In fact, I find that the inventions implemented over the course of the century only account for a small part of the bias in technical change. Contrary to what has been widely assumed, they were only modestly labor-saving.

Moreover, my engineering analysis suggests a reason *why* weaving inventions did not exhibit a strong labor-saving bias despite rising relative wages: capital-saving inventions benefited substantially from improvements in general purpose technologies while labor-saving inventions did not. Some inventions were labor-saving because they automated weaving tasks, but these inventions were necessarily specific to the textile industries. Other inventions were capital-saving because they permitted the looms to run faster. These inventions included improvements in power generation, power transmission, and machine construction. These improvements were valuable to many different industries, however. This difference is significant because it meant that factor prices were not the only considerations involved in a prospective inventor’s calculation of his return on development cost. While high relative wages might generate greater returns from a labor-saving invention within one industry, the general purpose nature of capital-saving inventions meant that these inventions might generate greater returns over *many* industries. Alternatively, the portion of development cost attributed specifically to the cotton weaving industry might be much less for a capital-saving invention than for a labor-saving invention. Thus given this mix of different biases for different types of inventions, there is no guarantee that inventions in weaving would be labor-saving overall even if the technical bias is determined by inventors' profitability calculations.

These findings regard only one industry, however, they might have broader significance for several reasons. First, because the cotton textile industry was so central to economic development, aggregate explanations need to be reconciled with these results. Second, this example makes clear that care must be taken in interpreting aggregate trends. Growing capital intensity is not necessarily evidence that capital accumulation drives growth nor is it necessarily evidence that inventions are labor-saving. Finally, the general purpose technologies used in cotton were also used in many other industries. These technologies might also have imparted capital-saving biases in other industries, perhaps offsetting industry-specific labor-saving biases. This hints at a possible rich relationship between capital deepening and productivity growth.

Appendix 1. Derivation of (5)

Under the assumption that factors are paid their marginal products, profit maximization provides a simple relationship between changes in the relative factor price, *w* (the wage divided by the cost of capital), and changes in *I* and *W*. Let $\hat{k}$ be the profit maximizing value of *k* for a given *w*. Then using (2),

$$\frac{d\ln X_l}{d\ln w} = -\frac{d\ln y}{d\ln w}$$

Further, since *y* is a function of *k* and $\hat{k}$ is a function of *w*,

$$\frac{d\ln X_l}{d\ln w} = -\frac{d\ln y}{d\ln w} = -\frac{d\ln y}{d\ln k}\,\frac{d\ln \hat{k}}{d\ln w} = -s_K\sigma, \qquad \sigma \equiv \frac{d\ln \hat{k}}{d\ln w},\ \ s_K = \frac{d\ln y}{d\ln k} \quad .$$

Similarly,

$$\frac{d\ln X_k}{d\ln w} = \frac{d\ln(k/y)}{d\ln w} = \frac{d(\ln k - \ln y)}{d\ln k}\,\frac{d\ln \hat{k}}{d\ln w} = (1-s_K)\sigma \quad .$$

Appendix 2. Major inventions

Aside from the mechanization realized by the first power looms, the major inventions that influenced nineteenth century productivity are, briefly:

- The "protector" (also called "stop rod" and "frog-and-dagger") automatically stopped the loom if it detected that the shuttle was not where it was supposed to be immediately after the pick. This prevented many "smashes," where a shuttle stuck in the cloth is struck by the reed, possibly breaking hundreds of threads. First patented by Gorton in 1791 (Barlow 1878, p. 264) this was employed in looms from 1796 in the U.K. This device was likely employed in most early U.S. power looms.

- Handloom weavers used a device to keep the sides of the cloth, called “temples,” from pulling in. These had to be reset frequently. A self-acting (automatic) temple developed by Ira Draper was successfully employed in Waltham in 1825 (Hayes 1879, p. 42, Jeremy 1973).
- Automatic let-off adjustments adjusted the tension on the warp which would naturally change as the diameter of the warp remaining on the beam diminished, reducing the time a weaver needed to spend making this adjustment. An early friction-based mechanism was employed in Lowell in 1835 (Lazonick and Brush 1985 p. 88, Montgomery 1840, p. 103). Later improvements included the “Bartlett” and “Roper” letoff motions, however, while these offered some advantages, they were not universally adopted and many weavers preferred the friction mechanisms at the end of the nineteenth century (Hawkesworth 1896, Draper 1903).
- The “weft fork” detected whether the bobbin had run out of yarn or the weft yarn had broken; if so, it stopped the loom. Prior to this invention, the loom would continue to run and weavers would have to take time to back it up (possibly hundreds of picks). Although first invented in the 1830s (Barlow 1878, p. 262), it was apparently not widely used in the US (mainly in new looms) until the 1870s (Burke 1876, Hayes 1879, p. 42, Draper 1907, p. 28).
- A significant number of inventions allowed increases in machine speed. In general, two sorts of factors limited machine speed: the cost of energy[28] and greater risk of damage to cloth, machine and weaver at higher speeds. Energy costs decreased sharply over time especially with improvements in steam engines and water turbines installed after 1870 (Crafts 2004, Atack et al. 1980).[29] But while lower energy costs might have made faster speeds economical, they were accompanied by critical complementary inventions that reduced the associated increase in machine errors (e.g., flying shuttles), machine wear and tear, and risk of injury to weavers. In 1828, Moody increased loom speeds by changing the power delivery from English-style gearing to belt drives (Gibb 1950, pp. 76-8).[30] Several contemporary observers attribute increased loom speeds after 1860 to the friction brake, which reduced machine wear and tear when the loom was stopped (Fox 1894, Hayes 1879, Watson 1863). Yet the friction brake was surely

28 Lyons (1987) suggests that energy costs increased as the square of loom speed, so these could increase rapidly beyond a certain point.

29 In 1840, Temin (1966a) estimates that about 85% of cotton mills used water power. In 1870 67% of power supplied to cotton mills was water power; by 1905, only 24% was (Copeland 1912, p. 28, fn. 2).

30 In private correspondence, John Lyons suggests that energy efficiency might also have been increased by improvements in the shafts used to transmit the power.

complemented by reduced power costs that made it more economical to run at higher speeds. Also important was a general improvement in the sturdiness of loom construction that permitted machines to run at higher speeds with fewer errors or accidents. The early looms were built mainly of wood (Montgomery 1840, p. 110); later looms were mostly constructed of metal and benefited from the development of machine tools that reduced the cost of better quality construction (Chapman and Butt 1988).[31] Other improvements facilitating faster loom speeds in the latter half of the century include the parallel picker motion (which propelled the shuttle more accurately and with less power required) and shuttle guards (which protected against shuttles flying out). Atack et al. (2008) find that labor productivity was higher at steam-powered mills in all industries during this period, but they are unable to distinguish to what extent steam permitted faster machine speeds and to what extent steam plants were newer and thus had more productive vintages of equipment.[32]

- The Northrop loom, developed by the Draper Company, introduced several improvements, most notably, it automatically replaced the bobbin, threading the shuttle, when the previous weft ran out or broke. Although the Northrop looms had a number of additional improvements over time (see Mass 1989, p. 904), for the mills of 1902-3, I assume that just these functions were automated.

Several other inventions that did not appear to have a substantial impact on nineteenth century coarse cloth productivity were the precision take up motion (which allowed more precise control of the number of picks per inch, thus improving cloth quality, but not changing the productivity of coarse cloth production), the Barber warp tying machine (introduced in 1904), and warp stop motions (which stopped the machine when warp threads broke). While warp stop motions were deployed during the latter nineteenth century at some mills, much of this production was in fine cloths (Harriman 1900). Moreover, where it was employed in coarse cloth production, productivity gains appear to have been largely offset by the added labor needed to draw and dress the warp (Young 1902).[33]

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31 McGouldrick's (1968, p. 240-1) index of machinery cost per spindle declined from $27.97 in 1827 to $9.58 in 1886.

32 New mills and renovated mills likely used the latest loom technology, while older mills that did not upgrade their power supplies likely used older loom technology as well. When water-powered mills in Lowell, for example, upgraded their equipment, they supplemented their water power with steam engines to provide power during those times of the year when water power was insufficient. For example, I find that mills powered exclusively by water in 1879 had about the same output per loom as mills in 1835 (see Figure 3); steam-powered mills had greater output per loom and mills powered by a combination of steam and water had an intermediate output per loom. It seems very likely that most of the mills powered exclusively by water power did not use the weft fork, which would have increased utilization. On the other hand, Boott Cotton Mills, Mill No. 1 *did* use the weft fork in 1876, and it did have higher output per loom (Burke 1876). It also had an improved power system then.

33 Young (1902) reports on a variety of mills, some using warp stops and some not, for the reasons mentioned. Warp stops

References

Acemoglu, Daron. 2003. “Labor- and Capital-Augmenting Technical Change,” Journal of the European Economic Association, 1, pp. 1–37.

Acemoglu, Daron. 2007. “Equilibrium Bias of Technology,” Econometrica, 75, No. 5, pp. 1371–1409.

Acemoglu, Daron. 2009. “When Does Labor Scarcity Encourage Innovation?,” MIT Working Paper 09-07.

Ahmad, Syed. 1966. “On the Theory of Induced Innovation,” Economic Journal, 76, pp. 344-357.

Allen, Robert C. 2009. The British Industrial Revolution in Global Perspective, Cambridge: Cambridge University Press.

Antras, Pol. 2004. “Is the U.S. Aggregate Production Function Cobb-Douglas? New Estimates of the Elasticity of Substitution,” Contributions to Macroeconomics, v. 4, no. 1.

Arrow, Kenneth, David Levhari and Eytan Sheshinski. 1972. “A Production Function for the Repairman Problem,” Review of Economic Studies, 39, pp. 241-9.

Asher, Ephraim. 1972. “Industrial Efficiency and Biased Technical Change in American and British Manufacturing: The Case of Textiles in the Nineteenth Century,” Journal of Economic History, 32, pp. 431-442.

Atack, Jeremy, Fred Bateman and Robert Margo. 2008. “Steam Power, Establishment Size, and Labor Productivity Growth in Nineteenth Century,” Explorations in Economic History, 45, pp. 185-198.

Atack, Jeremy, Fred Bateman, and Thomas Weiss. 1980. “The Regional Diffusion and Adoption of the Steam Engine in American Manufacturing,” Journal of Economic History, 40, pp. 281-308.

Barlow, Alfred. 1878. The History and Principles of Weaving by Hand and by Power. London: S. Low, Marston, Searle & Rivington.

Berndt, Ernst R. and Mohammed S. Khaled. 1979. “Parametric Productivity Measurement and Choice Among Flexible Functional Forms,” Journal of Political Economy, 87, pp. 1220-1245.

Berndt, Ernst, Charles Kolstad and Jong-Kun Lee. 1993. Measuring the Energy Efficiency and Productivity Impacts of Embodied Technical Change, Energy Journal, 14, pp. 33-55.

Berndt, Ernst R. and David O. Wood (1982). "The Specification and Measurement of Technical Change in US Manufacturing," Chapter 7 in John R. Moroney, ed., Advances in the Economics of Energy and Resources, Vol. 4, Greenwich, CT: JAI Press, pp. 199-221.

Bessen, James. 2003. “Technology and Learning by Factory Workers: The Stretch-Out at Lowell, 1842,” Journal of Economic History, 63, pp. 33-64.

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required threading each warp thread through a loop. This took time and also increased the likelihood of warp breaks; mills using warp stops had to dress the warp more heavily to counter this tendency.

Binswanger, Hans P. 1974. "The Measurement of Technical Change Biases with Many Factors of Production," American Economic Review, 64, pp. 964-976.

Blackorby, Charles, C. A. Knox Lovell and Marie C. Thursby. 1976. "Extended Hicks Neutral Technical Change," Economic Journal, 86, pp. 845-852.

Bourne, John. 1865. Handbook of the Steam Engine, London: Longman, Green, Longman, Roberts and Green.

Brown, Murray and John S. De Cani. 1963. "Technological Change and the Distribution of Income," International Economic Review, Vol. 4, No. 3 (Sep., 1963), pp. 289-309.

Burke, 1876. Transactions of the National Association of Cotton Manufacturers, No. 21, p. 8-9.

Cain, Louis P. and Donald G. Paterson. 1986. "Biased Technical Change, Scale, and Factor Substitution in American Industry, 1850-1919," Journal of Economic History, 46(1), pp. 153-164.

Champernowne, David. 1963. "A Dynamic Growth Model Involving a Production Function,"in F. A. Lutz and D. C. Hague (editors) The Theory of Capital, New York: Macmillan.

Chapman, Stanley and John Butt. 1988. "The Cotton Industry, 1775-1856," in Feinstein, Charles H. and Sidney Pollard, eds., Studies in Capital Formation in the United Kingdom, 1750-1920," Oxford: Clarendon Press.

Chenery, Hollis B. 1949. "Engineering Production Functions," Quarterly Journal of Economics, 63, No. 4, pp. 507-531.

Clark, Gregory. 1987. "Why Isn't the Whole World Developed? Lessons from the Cotton Mills," Journal of Economic History 47, pp. 141-173.

Clark, Gregory. 2007 *A Farewell to Alms*. Princeton: Princeton University Press.

Clarke, Richard N. and Lawrence Summers. 1980. "The Labour Scarcity Controversy Reconsidered," *Economic Journal,* 90, pp. 129-139.

Copeland, Melvin T. 1912. The Cotton Manufacturing Industry of the United States, Cambridge: Harvard University.

Crafts, Nicholas. 2004. "Steam As A General Purpose Technology: A Growth Accounting Perspective," Economic Journal, 114, pp. 338-51.

David, Paul. 1975. *Technical Choice, Innovation and Economic Growth*. Cambridge: Cambridge University Press.

David, Paul and Van de Klundert, Th. 1965. "Biased Efficiency Growth and Capital-Labor Substitution in the U.S., 1899–1960," American Economic Review, 55, pp. 357–393.

David, Paul A. and Peter Solar, (1977). "A Bicentenary Contribution to the History of the Cost of Living in America," Pages 1-80 in Volume 2 of Research in Economic History , Greenwich: JAI Press, Inc.

Diamond, Peter, Daniel McFadden, and M. Rodriguez. 1978. "Measurement of the elasticity of factor substitution and bias of technical change," In: Fuss, Melvyn and Daniel MacFadden, (Eds.), Production Economics: A Dual Approach to Theory and Applications, vol. 2. Contribution to Economic Analysis, North Holland.

Draper, George Otis. 1895. "The Present Development of the Northrop Loom," Transactions of the National Association of Cotton Manufacturers, No. 59, p. 88.

Draper, George Otis. 1907. Labor Saving Looms, 3rd edition. Draper Corporation.

Draper, William F. 1903. "Continued Development of the Northrop Loom," Transactions of the National Association of Cotton Manufacturers, No. 74, p. 158.

Dublin, Thomas. 1993. *Women at Work: The Transformation of Work and Community in Lowell, Massachusetts, 1826-1860*, 2nd edition. New York: Columbia University Press.

Feller, Irwin. 1966. "The Draper Loom in New England Textiles, 1894-1914: A Study of Diffusion of an Innovation," Journal of Economic History, 26, pp. 320-347.

Fellner, William. 1961. "Two Propositions in the Theory of Induced Innovations," The Economic Journal, 71, pp. 305–308.

Ferguson, C. E. 1965. "Substitution, Technical Progress, and Returns to Scale," The American Economic Review, Vol. 55, No. 1/2 (Mar. 1, 1965), pp. 296-305 .

Fish, Charles H. 1896. "Test Showing Power Requirements to Drive Various Widths and Makes of Looms," Transactions of the National Association of Cotton Manufacturers, No. 60, pp. 179-80.

Fogel, Robert W. 1967. "The Specification Problem in Economic History," *Journal of Economic History*, 27, pp. 283-308.

Fox, Thomas William. 1894. *The Mechanism of Weaving*, London: Macmillan and Company.

Gibb, George. 1950. *The Saco-Lowell Shops: Textile machinery building in New England 1813-1949*. New York: Russell & Russell.

Gilroy, Clinton G. 1844. The Art of Weaving by Hand and by Power. New York: George D. Baldwin.

Habakkuk, H. J. 1962. *American and British Technology in the Nineteenth Century*, Cambridge, England: Cambridge University Press.

Harley, C. Knick. 1999. "Reassessing the Industrial Revolution: a Macro View," in Mokyr, Joel, ed., *The British Industrial Revolution: An Economic Perspective*, Boulder, CO: Westview Press.

Harriman, Henry I. 1900. “The Harriman Automatic Loom,” Transactions of the National Association of Cotton Manufacturers, No. 68, p. 318.

Harvard Business School, Baker Library Historical Collections, Records of the Lawrence Company.

Hawkesworth, Alfred, 1896. “Looms and Loom Fixers; Weavers and Weaving Rooms,” Transactions of the National Association of Cotton Manufacturers, No. 61, p. 290.

Hayami, Yujiro and Vernon W. Ruttan, 1970. “Factor Prices and Technical Change in Agricultural Development: The United States and Japan, 1880–1960.” The Journal of Political Economy, 78, pp. 1115–41.

Hayes, John L. 1879. American Textile Machinery, Cambridge: University Press.

Hicks, John. 1932. *The Theory of Wages*. London: Macmillan.

Hsieh, Chang-Tai. 2002. “What Explains the Industrial Revolution in East Asia? Evidence from the Factor Markets” American Economic Review, 92(3), pp. 502-526.

Jeremy, David J. 1973. “Innovation in American Textile Technology during the Early 19th Century,” Technology and Culture, 14, pp. 40-76.

Jeremy, David. 1990. *Technology and Power in the Early American Cotton Industry: James Montgomery, the Second Edition of His “Cotton Manufacture” and the Justitia Controversy about Relative Power Costs*, Diane Publishing.

Jorgenson, Dale W. and Barbara Fraumeni. 1981. “Relative Prices and Technical Change,” in Ernst R. Berndt and Barry C. Fields, eds., Modeling and Measuring Natural Resource Substitution, Cambridge, MA: MIT Press, pp. 17-47.

Josephson, Hannah. 1949. *Golden Threads; New England Mill Girls and Magnates*. New York: Russell & Russell.

Kalt, Joseph P. 1978. “Technological Change and Factor Substitution in the United States: 1929-1967,” International Economic Review, Vol. 19, No. 3 (Oct., 1978), pp. 761-775 .

Kennedy, Charles. 1964. “Induced Bias in Innovation and the Theory of Distribution,” Economic Journal, 74, pp. 541–547.

Kim, J. I. and Lau, L. J. 1994. “The sources of economic growth in the East Asian newly industrialized countries,” Journal of Japanese and International Economics, 8, pp. 235-71.

Klump, Rainer, Peter McAdam and Alpo Willman. 2007. “Factor Substitution And Factor-Augmenting Technical Progress In The United States: A Normalized Supply-Side System Approach,” The Review of Economics and Statistics, February 2007, 89(1): 183–192.

Landes, David. 1969. The Unbound Prometheus: Technological Change And Industrial Development In Western Europe From 1750 To The Present, London: Cambridge University Press.

Layer, Robert G. 1951. Papers, Baker Library Harvard Business School.

Layer, Robert G. 1955. *Earnings of Cotton Mill Operatives, 1815-1914*, Cambridge, MA: Committee in Research in Economic History.

Lazonick, William and Brush, Thomas. 1985. “The 'Horndal Effect' in Early U. S. Manufacturing,” Explorations in Economic History 22, pp. 53-96.

Levhari, David and Eytan Sheshinski. 1970. “A Microeconomic Production Function,” Econometrica, Vol. 38, No. 3 (May, 1970), pp. 559-573.

Liu, Yucan and C. Richard Shumway, 2009. “Induced Innovation in U.S. Agriculture: time-series, direct econometric, and nonparametric tests,” American Journal of Agricultural Economics, 91(1), pp. 224-36.

Luft, Harold S., 1971. “New England Textile Labor in the 1840’s From Yankee Farmgirl to Irish Immigrant,” graduate seminar paper, Harvard.

Lyons, John S. 1987. “Powerloom Profitability and Steam Power Costs: Britain in the 1830s,” Explorations in Economic History, 24, pp. 392-408.

Macmillan’s Magazine. 1862. “Cotton Weaving and Lancashire Looms,” May-October 1862, v. 6, p. 451.

Mass, William. 1989. “Mechanical and Organizational Innovation: The Drapers and the Automatic Loom,” Business History Review, 63(4), pp. 876-929.

May, J. D. and M. Denny, “Factor-Augmenting Technical Progress and Productivity in U.S. Manufacturing,”International Economic Review, 20, pp. 759-774.

McCloskey, Donald. 1981. “The Industrial Revolution: A Survey,” in R. C. Flous and C. N. McCloskey, eds., *The Economic History of Britain Since 1700*, V. 1., Cambridge: Cambridge University Press.

McGouldrick, Paul F. 1968. *New England Textiles in the Nineteenth Century*, Cambridge: Harvard University Press.

Montgomery, James. 1840. *A Practical Detail of the Cotton Manufacture of the United States of America*, First Edition. Glasgow: John Niven.

Montgomery, James. 1843. *A Practical Detail of the Cotton Manufacture of the United States of America*, Second Edition. In Jeremy, David (1990) *Technology and Power in the Early American Cotton Industry: James Montgomery, the Second Edition of His “Cotton Manufacture” and the Justitia Controversy about Relative Power Costs*, Diane Publishing.

Moroney, John R. and John M. Trapani, 1981. “Alternative Models of Substitution and Technical Change in Natural Resource-Intensive Industries,” in Ernst R. Berndt and Barry C. Fields, eds., Modeling and Measuring Natural Resource Substitution, Cambridge, MA: MIT Press, pp. 48-69.

Nelson, Richard R. and Howard Pack. 1999, "The Asian Miracle and Modern Growth Theory," Economic Journal, 109, pp. 416-436.

Nickless, Pamela J. 1979. "A New Look at Productivity in the New England Cotton Textile Industry, 1830-1860." Journal of Economic History 39, pp. 889-907.

Nordhaus, William. 1973. "Some Skeptical Thoughts on the Theory of Induced Innovation," Quarterly Journal of Economics, 87, pp. 208–219.

Nourse, Henry S. 1903. "Some Notes Upon the Genesis of the Power Loom in Worcester County," Proceedings of the American Antiquarian Society, v. 16, October 1903.

Olmstead, Alan L. and Paul Rhode, 1993. "Induced Innovation in American Agiculture: A Reconsideration," The Journal of Political Economy, 101(1), pp. 100-118.

Olmstead, Alan L. and Paul Rhode, 2008. "Biological Innovation and Productivity Growth in the Antebellum Cotton Economy," Journal of Economic History, 68(4), pp. 1123-71.

Panik, Michael J. 1976. "Factor Learning and Biased Factor-Efficiency Growth in the United States, 1929-1966," International Economic Review, Vol. 17, No. 3 (Oct., 1976), pp. 733-739 .

Pearl, D. J. and John L. Enos. 1975. "Engineering Production Functions and Technological Progress," Journal of Industrial Economics, 24, No. 1, pp. 55-72.

Rodrik, Dani. 1997. "TFPG Controversies, Institutions, and Economic Performance in East Asia," NBER Working Paper 5914.

Rothbarth, Edwin. (1946) "Causes of the Superior Efficiency of U.S.A. Industry as Compared to British Industry," *Economic Journal*, 56, pp. 383-90.

Salter, W. E. G. 1960. Productivity and technical change, Cambridge: Cambridge University Press.

Samuelson, Paul. 1965. "A Theory of Induced Innovations Along Kennedy-Weisacker Lines," Review of Economics and Statistics, 47, pp. 444–464.

Sato,Ryuzo. 1970. "The Estimation of Biased Technical Progress and the Production Function," International Economic Review, 11, pp. 179-208.

Smith, Vernon L. 1957. "Engineering Data and Statistical Techniques in the Analysis of Production and Technological Change: Fuel Requirements of the Trucking Industry," Econometrica, 25, No. 2, pp. 281-301.

Sokoloff, Kenneth. 1984. "Was the Transition from the Artisanal Shop to the Nonmechanized Factory Associated with Gains in Efficiency? Evidence from the U.S. Manufacturing Censuses of 1820 and 1850," Explorations in Economic History, 21, pp. 351-382.

Solow, Robert M. 1956. "A Contribution to the Theory of Economic Growth," Quarterly Journal of Economics, 70, pp. 65-94.

Strassmann, W. Paul. 1959. Risk and technological innovation, Ithaca, N. Y.: Cornell University Press.

Swan, Trevor. 1956. "Economic Growth and Capital Accumulation," Economic Record 32, pp. 334-61.

Temin, Peter 1966a. "Steam and Waterpower in the Early Nineteenth Century," *Journal of Economic History*, 26, pp. 187-205.

Temin, Peter. 1966b. "Labor Scarcity and the Problem of American Industrial Efficiency in the 1850's," *Journal of Economic History*, 26, pp. 277-298.

Toevs, Alden L. 1980. "Input Substitution and Biased Technological Change in Resource-Intensive Manufacturing Industries," in John R. Moroney, ed., Advances in the Economics of Energy and Resources, Vol. 3, Greenwich, CT: JAI Press, pp. 221-251.

U. S. Congress, House, United States Tariff Commission. 1912. Cotton Manufactures, 62d Cong., 1st session, House Doc. 643, p. 490-3.

U. S. Department of Commerce, Bureau of Foreign and Domestic Commerce, W. A. Graham Clark. 1908. "Cotton Textile Trade in the Turkish Empire, Greece and Italy," Special Agent Series No. 18.

U. S. Department of Commerce, Bureau of Foreign and Domestic Commerce, W. A. Graham Clark. 1908. "Cotton Fabrics in Middle Europe, Germany," Special Agent Series No. 24.

U. S. Department of Commerce, Bureau of Foreign and Domestic Commerce, W. A. Graham Clark. 1914. "Cotton Goods in Japan and their Competition on the Manchurian Market," Special Agent Series No. 86.

U. S. Department of Commerce, Bureau of Foreign and Domestic Commerce, Ralph Odell. 1916. "Cotton Goods in China," Special Agent Series No. 107.

Ure, Andrew. 1836. *The Cotton Manufacture of Great Britain*, London: Charles Knight.

Uttley, T. W. 1905. *Cotton Spinning and Manufacturing in the United States of America*, Manchester: University Press.

Walmsley, Herbert Edward. 1893. *Cotton Spinning and Weaving: A practical and theoretical treatise*, Manchester: Abel Heyward and Son.

Ware, Caroline. 1931. *The Early New England Cotton Manufacture*. Boston and New York: Houghton Mifflin.

Watson, John. 1863. *The Theory and Practice of the Art of Weaving by Hand and Power*. Glasgow: George Watson.

Wibe, Sőren. 1984. "Engineering Production Functions: A Survey," Economica, 51, pp. 401-11.

Wilkinson, Maurice. 1968. "Factor Supply and the Direction of Technological Change," The American Economic Review, Vol. 58, No. 1 (Mar., 1968), pp. 120-128.

Wills, John. 1979. “Technical Change in the U.S. Primary Metals Industry,” Journal of Econometrics, 10, pp. 85-98.

Wright, Carroll D. 1880. Report on the Factory System of the United States, Census of Manufactures, v. 2, pp. 52-4.

Young, Alwyn. 1995. “The tyranny of numbers: confronting the statistical realities of the East Asian growth experience,” Quarterly Journal of Economics, 110, pp. 641-80.

Young, Thomas M. 1902. The American Cotton Industry. New York: Charles Scribner’s Sons.

Yuhn, Ky-hyang. 1991. “Economic Growth, Technical Change Biases, and the Elasticity of Substitution: A Test of the De La Grandville Hypothesis,” The Review of Economics and Statistics, Vol. 73, No. 2, (May, 1991), pp. 340-346.

Zeira, Joseph. 1998. “Workers, Machines, and Economic Growth,” Quarterly Journal of Economics, 113(4), pp. 1091-1117.

Table 1. Frequency and Duration of Power Loom Tasks

Tasks	Duration (minutes)	Occurrence (yards)	T_i/R_i (min./yd.)
Tasks performed while machine running			
Replace empty bobbin[a]			
plain loom	0.20	0.5	0.38
Northrop loom (fill magazine; self-threading bobbin)	0.13	0.5	0.25
Adjust warp tension			
before 1835	0.15	0.5	0.28
with friction, Bartlett and Roper let-off motions	"	5.3	0.03
Tasks performed while machine stopped			
Fix smashes (assisted by helpers)[b]	60	1200	0.05
Adjust temples[c]	0.5	0.2	3.00
Replace empty shuttle[d]	0.20	0.5	0.38
stop loom and back it up (prior to weft fork)		0.5	0.6 – 1.3
Fix broken weft	0.20	2.0	0.10
stop loom and back it up (prior to weft fork)		2.0	0.2 – 0.3
Fix broken warp end[e]	0.5	3.3 - 5	0.10-0.15
Remove cloth[f]	4.0	60	0.07
Clean and oil[g]	--	--	--
Replace warp[h] (warp beam size changed over time)			
1810-36	60	240 yds	0.25
1838-80		320 yds	0.19
1880-1903		691 yds	0.09

Notes: Estimates without specific sources are based on interviews and measured times with Rick Randall at the Lowell National Historical Park and Mike Christian at the American Textile History Museum.
a assume weft delivered by other personnel (Draper 1895; Harriman 1900; Uttley 1905)
b estimate from smash assistants per loom (Uttley 1905)
c (Jeremy 1973)
d (Draper 1895); time to stop and backup loom is calculated as 4**k**picks/min/60 seconds.
e (Draper 1903; Draper 1907) Lower frequency of breaks after 1900 from improvements in warp preparation (Draper 1907)
f (Draper 1903, Uttley 1905). Duration could be as much as 30 min./day for 8 looms (Draper); length is typical piece size
g assume performed by other labor or after hours (Draper 1903, Uttley 1905)
h (Barlow 1878, Burke 1876, Draper 1907, Montgomery 1840, Young 1902). Duration could be as little as 15 min. (Young), but could also be several hours (Randall). Task might not involve weaver.

Table 2. Performance at Benchmark Mills

Mill	Year	Looms/ weaver	Output rate (yds./ weaver-minute): Actual	Output rate (yds./ weaver-minute): Simu-lated	Loom requirement (minutes/yd.): Loom time	Loom requirement (minutes/yd.): Idle time	Weaver requirement (minutes/yd.): Weaver time	Weaver requirement (minutes/yd.): Watch time
		k	y	$\hat{y}$	X_k	I	X_l	W
Handloom[a]	1819	1	0.03		39.6		39.6	
Boston Mfg. Co.[b]	1819	1.8	0.06	0.07	29.2	0.4	15.9	10.9
Lawrence Co., Mill 2[c]	1835	1.8	0.12	0.12	15.2	0.4	8.3	6.2
″	1845	2.7	0.18	0.18	15.1	0.7	5.7	3.3
″	1855	3.4	0.22	0.21	15.8	1.1	4.6	2.0
Boott Mills, Mill No. 1[d]	1838	2.0	0.14	0.14	14.6	0.3	7.3	5.2
″	1876	5.7	0.42	0.40	13.6	1.4	2.4	1.1
5 steam powered mills[f]	1879	6.0	0.42		14.4		2.4	
6 water powered mills[e]	1879	5.1	0.31		16.4		3.2	
Fall River Ironworks[g]	1901	8	0.69	0.63	11.6	1.3	1.5	0.3
Merrimack Mfg.[h]								
plain looms	1901	8	0.63	0.63	12.7	1.2	1.6	0.4
Northrop looms		18	1.27	1.34	14.2	1.0	0.8	0.3
Pacific Mills[i]								
plain looms	1903	8	0.61	0.58	13.0	1.2	1.6	0.4
Northrop looms		18	1.31	1.31	13.7	0.8	0.8	0.2

Yards/worker-minute includes labor time of assistants to weavers. W and $\in$ are calculated as residuals after estimating times to perform tasks. Simulation results with fractional values of k were calculated by linearly interpolating the two closest integer values.

[a] hypothetical estimate based on 50 picks/minute at 80% utilization (Gilroy 1844, Marsden 1895, Draper 1907)

[b] Waltham, MA (1820 Census of Manufactures, Jeremy 1973); Looms per worker estimate is taken from Lawrence Co.

[c] Lowell, MA (payroll records, Lazonick and Brush 1985, Montgomery 1840)

[d] Lowell, MA (Burke 1876); In 1876 has weft fork & renovated power supply. Assumed 150 picks/min.

[e] US print cloth mills powered only by water (Wright 1880)

[f] US print cloth mills powered only by steam (Wright 1880)

[g] Fall River, RI (Young 1902); Young reports that this mill had an exceptionally low rate of warp breaks (probably because of additional preparatory processing), so I halved the frequency for warp breaks at this mill.

[h] Lowell, MA (Young 1902); Following Young and Uttley, in calculating W, I assumed that weavers did not fix smashes and remove cloth on the Northrop looms.

[i] Lawrence, MA (Uttley 1905)

Table 3. Changes in loom and weaver requirements from weaving inventions

Tasks	Invention	Date first used in US	Decrease in loom time $-\Delta Z_k$	Decrease in weaver time $-\Delta Z_l$
Tasks performed while machine running				$-\Delta T_j/R_j$
Weaving (shed, pick, batten, let off warp, take up cloth)	Initial power loom	1814	--	23.1
Adjust warp tension	Automatic let-off adjustment	1835 + later	--	0.3
Replace empty bobbin	Northrop loom (reduces duration)	1895	--	0.1
	Shuttleless loom	1959	--	--
Tasks performed while machine stopped			$-\Delta T_j/R_j$	$-\Delta T_j/R_j$
Fix smashes	Protector (stops loom when shuttle not in the box, reducing frequency of smashes)	1814	--	--
Adjust temples	Self-acting temple	1825	3.0	3.0
Replace empty shuttle	Weft fork (reduces time to back up loom)	1870s	0.9	0.9
	Northrop loom	1895	0.4	0.4
Fix broken weft	Weft fork (reduces time to back up loom)	1870s	0.2	0.2
	Northrop loom	1895	0.1	0.1
Fix broken warp	Warp stop (not widely adopted for coarse work before 1900)	--	--	--
Remove cloth, clean	--			
Replace warp	Larger warp beams	various	0.2	0.2
	Warp tying machine; larger beams	1904+	--	--
Changes to machine speed			$-\Delta (1/s)$	
	Initial power loom	1814	9.1	--
	Belt drive & associated improvements	1828	9.9	--
	Steam power/water turbine, friction brake, shuttle guards, parallel picking motion	1870-1900	1.0	--
Total direct effects			24.8	28.3

Note: Changes are in minutes per yard of standard cloth. Weft fork is evaluated for the Lawrence Co., Mill No. 2, in 1855.

Table 4. CES Production Function Estimation

Monthly data for Lawrence Co. Mill No. 2, Upper Weave Room, 1834-55.

Dependent variable: ln *y*	1834 - 1855	1834 - 1845	1846 - 1855
σ	0.142 (0.069)	0.159 (0.110)	0.144 (0.144)
a_0	1.400 (0.052)	1.471 (0.127)	1.203 (0.214)
z	0.005 (0.004)	-0.004 (0.009)	0.019 (0.020)
b_0	2.036 (0.125)	1.809 (0.248)	2.558 (0.938)
g	0.018 (0.006)	0.039 (0.020)	0.003 (0.028)
Number of observations	224	111	113
Adjusted R-squared	0.915	0.800	0.766

Note: Non-linear least squares estimation; asymptotic standard errors in parentheses.

Table 5. Sources of Change in Loom and Labor Requirements from 1819 to 1902

Handloom to Northrop loom	ΔX_l	Percent	ΔX_k
Direct effect of inventions, ΔZ_l, ΔZ_k	-28.3	73%	-24.8
Loom-labor substitution, $\Delta^w W$, $\Delta^w I$	-0.5 to -0.6	1 to 2%	1.7 to 2.1
Residual, M_l, M_k	-10.0 to -10.1	25 to 26%	-1.2 to -1.6
TOTAL CHANGE	-38.9		-24.3
Boston Manufacturing to Northrop loom			
Direct effect of inventions, ΔZ_l, ΔZ_k	-5.2	33%	-15.7
Loom-labor substitution, $\Delta^w W$, $\Delta^w I$	-0.5 to -0.6	3 to 4%	1.7 to 2.1
Residual, M_l, M_k	-10.0 to -10.1	64 to 65%	-1.2 to -1.6
TOTAL CHANGE	-15.8		-15.2

Source: Figures in minutes per yard. Data from Tables 2 and 3 plus calculation of factor substitution in text. "Total Change" figures are the sums of differences; these might differ from differences calculated from actual performance in Table 2 because of slight differences between actual and predicted performance.

Table 6. Sources of labor-saving shift in isoquants from the handloom to the Northrop Loom, 1902-3

Sources	$-\Delta X_k$	$-\Delta X_l$	Labor-saving shift $\Delta X_k - \Delta X_l$	
Loom-labor substitution, $\Delta^w I$, $\Delta^w W$	-1.7 to -2.1	0.5 to 0.6	2.2 to 2.7	
Shift in isoquants				
Inventions, ΔZ_{lk}, ΔZ_l	24.8	28.3	3.5	
Tasks performed while running				23.5
Tasks performed while stopped				0.0
Speed changes				-20.0
Residual terms, M_l, M_k	1.2 to 1.6	10.0 to 10.1	8.4 to 8.9	
TOTAL	24.3	38.9	14.6	

Source: Data from Table 3 plus calculation of factor substitution in text. In minutes per yard.

Figure 1. Technical Change and Factor Substitution on the Unit Isoquant

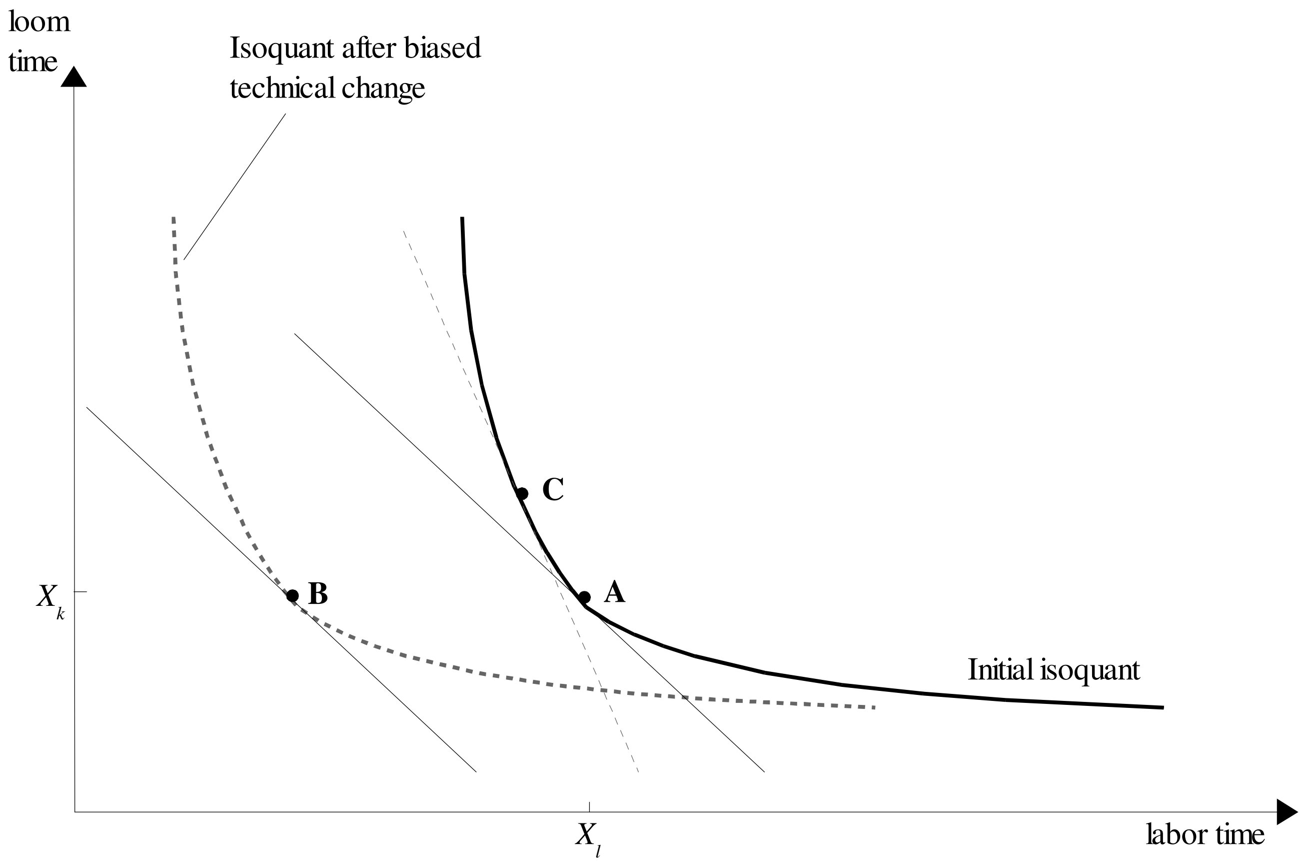


Figure 2. Weaving production function

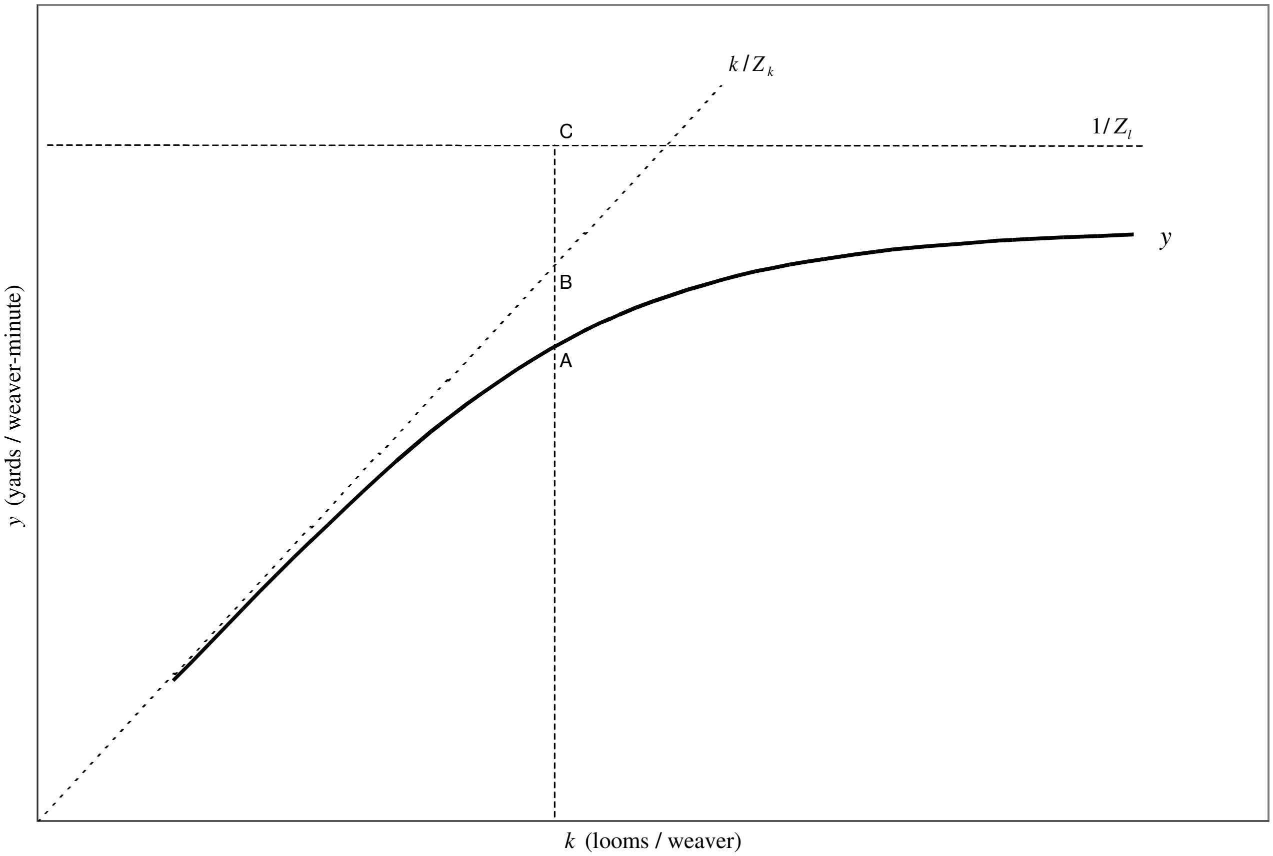


Figure 3. Production function simulations

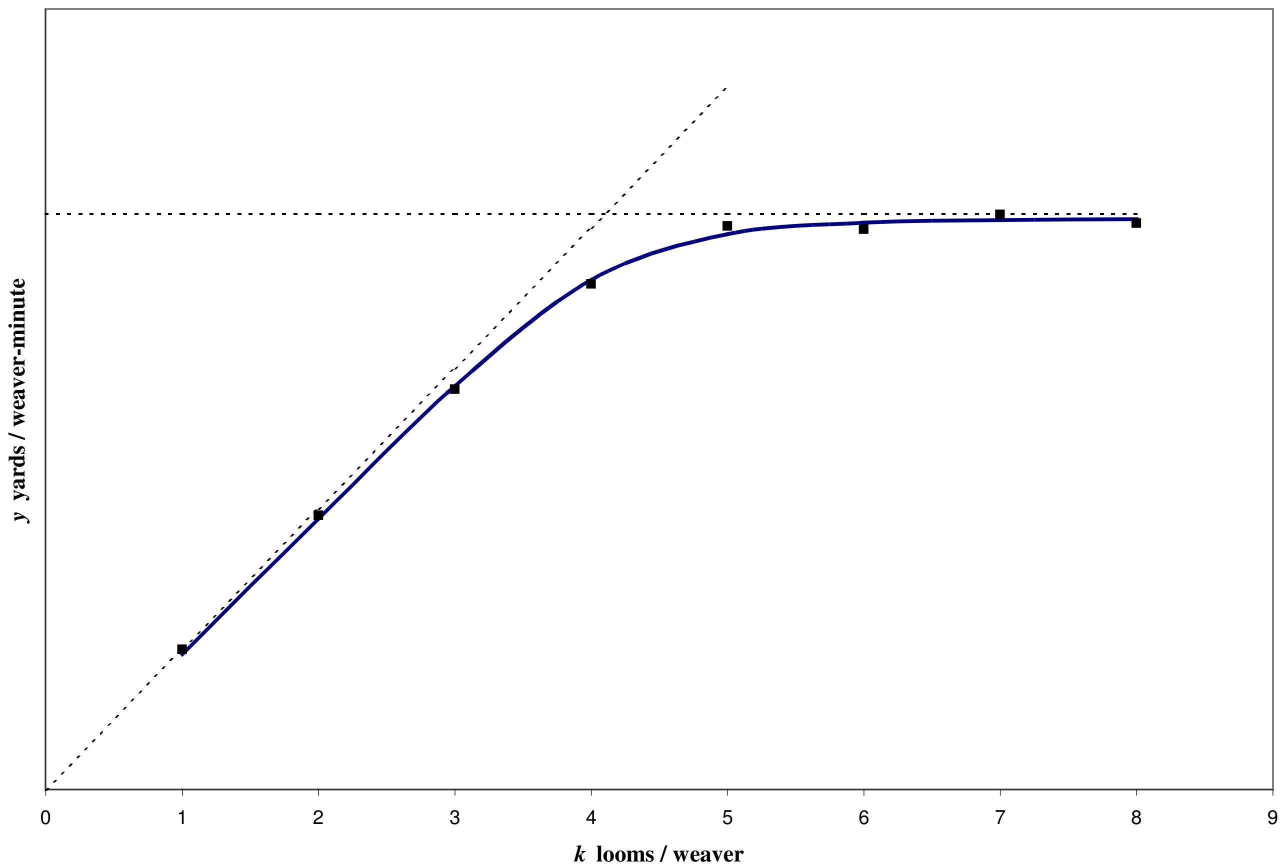
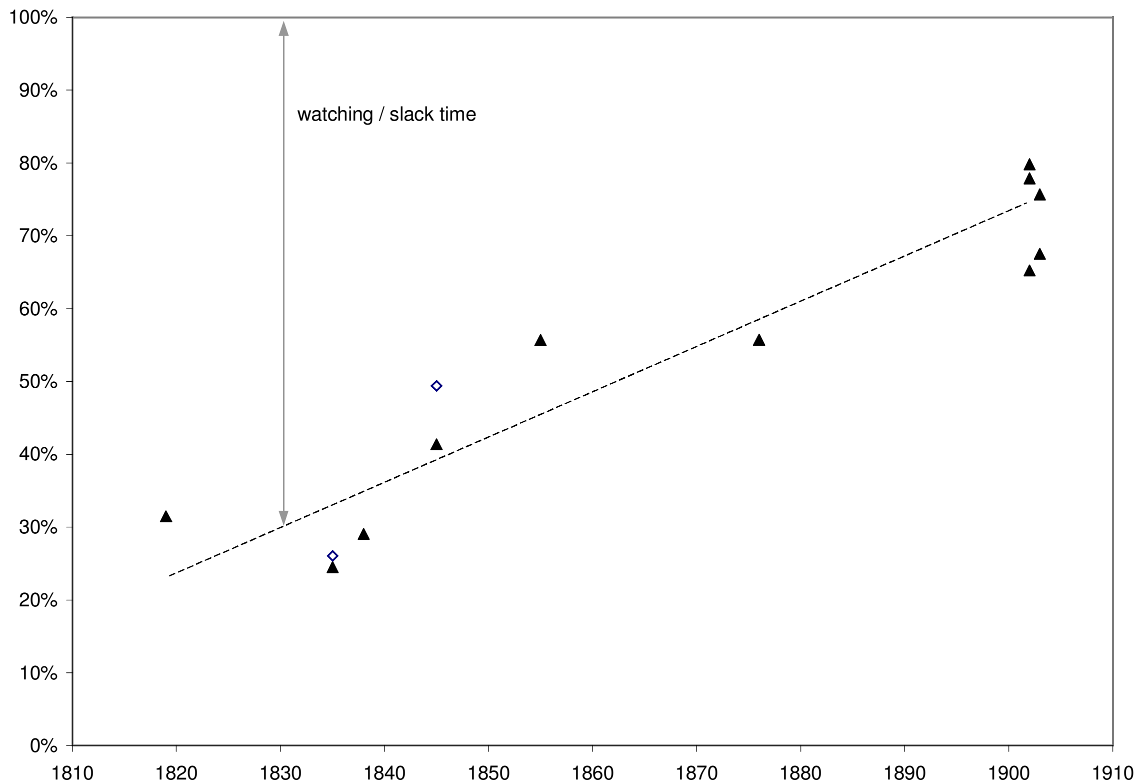


Figure 4. Portion of work time required for a skilled weaver to perform weaving tasks



Note: The data points represent the estimated portion of the time a skilled weaver would require to actively performing tasks under the conditions used at different mills. These calculations assume a skilled weaver. Skills and effort exerted might have been less in earlier years, so that some portion of the slack time might be attributed deficient skills or a lower level of effort. While the weavers were not actively performing tasks, they walked between the looms checking for defects, stoppages or other problems. The dots shown in outline for 1835 and 1845 are calculated for the Lawrence Co., Mill No. 2 only for experienced workers only (weavers on piece rate who had more than six months experience and operated 2 and 3 looms respectively).