Technological Breakthroughs and Productivity Growth*

by

Harald Edquist[1] and Magnus Henrekson[2]

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Abstract: This study consists of an examination of productivity growth following three major technological breakthroughs: the steam power revolution, electrification and the ICT revolution. The distinction between sectors *producing* and sectors *using* the new technology is emphasized. A major finding for all breakthroughs is that there is a long lag from the time of the original invention until a substantial increase in the rate of productivity growth can be observed. There is also strong evidence of rapid price decreases for steam engines, electricity, electric motors and ICT products. However, there is no persuasive direct evidence that the steam engine producing industry and electric machinery had particularly high productivity growth rates. For the ICT revolution the highest productivity growth rates are found in the ICT-producing industries. We suggest that one explanation could be that hedonic price indexes are not used for the steam engine and the electric motor. Still, it is likely that the rate of technological development has been much more rapid during the ICT revolution compared to any of the previous breakthroughs.

Keywords: Electrification; General purpose technologies; ICT revolution; Productivity growth; Steam power.

JEL *Classification*: N10; O10; O14; O40.

[1]Institute for Research in Economic History
Stockholm School of Economics
P.O. Box 6501
S-113 83 Stockholm
SWEDEN
Phone: +46-8-736 92 59
Fax: +46-8-31 32 07
e-mail: Harald.Edquist@hhs.se

[2] Research Institute of Industrial Economics

P.O. Box 55665
S-102 15 Stockholm
SWEDEN
Phone: +46-8-665 45 02
Fax: +46-8-665 45 99
e-mail: Magnus.Henrekson@iui.se

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Non-technical summary

According to many observers we currently experience a technological revolution based on a breakthrough in information and communication technology (ICT). This revolution has already profoundly impacted on the way we lead our lives and produce goods and services. Moreover, significantly higher rates of productivity growth have recently been observed compared to the 1970s and 1980s, in particular in the United States. This tendency is discernible in several other countries too, but on closer inspection it appears that it may only be true for the sectors producing the new technology.

Measuring productivity in ICT-producing industries, where technology changes rapidly, is very complicated. In order to measure productivity correctly over time it is necessary to estimate the price change of different products. One of the major difficulties with measuring prices in industries with rapidly changing technologies is the problem of correctly estimating quality improvements. In order to deal with this problem many statistical agencies use so-called hedonic price indexes. Such indexes have been criticized for creating the impression of rapidly falling prices, resulting in overstated productivity figures for ICT-producing industries.

The ICT revolution is of course not the first in human history. Inventions like steam power and electricity had equally dramatic or perhaps even more dramatic effects standards of living and ways of life. But this does not show up in the productivity statistics! But the use of hedonic price indexing is a new invention, much more recent than the steam engine and the electric motor. So what would happen if we took a new look at these historical episodes with our “hedonic” glasses on?

We argue that hedonic price indexes also would have large effects on how we perceive earlier technological breakthroughs. We compare the impact of the ICT revolution with two other major technological breakthroughs, namely the steam engine and electrification. In particular, we examine the patterns of productivity growth after each breakthrough and we distinguish between sectors producing and using the new technology. We show that it takes a long time from the moment of the original invention until a substantial increase in the rate of productivity growth can be observed. For steam engine it took about 140 years, while it only took 40–50 years for electrification and the ICT revolution.

We also find evidence of rapid price decreases for steam engines, electricity, electric motors and ICT products. This indicates rapid productivity growth in the industries *producing* the new technology. However, we cannot find any direct evidence that the steam engine producing industry in the UK and the electric machinery industry in the US had particularly high productivity growth rates. For the ICT revolution the highest productivity growth rates were found for the ICT-producing industries throughout the six countries that we investigate (Finland, France, Germany, Sweden, the UK and the US).

There is thus, no clear evidence of any particular productivity growth pattern after major technological breakthroughs. We suggest that one explanation could be that hedonic price indexes are not used for the steam engine and the electric motor. Still, it is likely that the rate of technological development has been much more rapid during the ICT revolution compared to any of the previous breakthroughs. On the other hand, this is not to say that the steam engine or the electric motor did not change our lives more than the computer, it may just be that it took a little longer.

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1. Introduction

According to many observers (e.g., Castells 1996, 1997; Greenwood 1997; Litan and Rivlin 2001) we have just experienced a technological revolution based on a breakthrough in information and communication technology (ICT). This revolution has already profoundly impacted the way we lead our lives and produce goods and services. Moreover, significantly higher rates of productivity growth were observed in the latter half of the 1990s compared to the 1970s and 1980s, in particular in the United States. This tendency was discernible in several other countries too, but on closer inspection it appears that it may only be true for the sectors producing the new technology. Still, towards the very end of the last millenium the ICT revolution carried high hopes for a new era, ”a new economy”, entailing a permanent upward shift in long-term productivity growth rates. Or as one extremely influential policymaker at the time put it: ”the recent acceleration in labor productivity is not just a cyclical phenomenon or a statistical aberration, but reflects – at least in part – a more deep-seated, still developing, shift in our economic landscape” (Greenspan 1999, p. 3).

Throughout human history there have been a number of important technological breakthroughs. Schumpeter (1939) argued that new products and technologies, giving rise to “gales of creative destruction”, would have a large impact on the economy for several decades. But how can we distinguish truly revolutionary changes from other changes? Bresnahan and Trajtenberg’s (1995) concept of a General Purpose Technology (GPT) is useful in this context. They argue that whole eras of technical progress are driven by a few GPTs, characterized by pervasiveness, inherent potential for technical improvements and innovational complementarities giving rise to increasing returns to scale. GPTs are believed to play a decisive role for long-term productivity development as the new technology is diffused throughout different sectors of the economy (Helpman and Trajtenberg 1998). More specifically, Lipsey, Bekar and Carlaw (1998) maintain that a GPT has the following four characteristics: (1) wide scope for improvement and elaboration; (2) applicability across a broad range of uses; (3) potential usefulness in a wide range of products and processes; and (4) strong complementarities with existing or potential new technologies.

However, as noted by David and Wright (2003), based on these criteria Lipsey *et al.* (1998) come up with a list of GPTs that is so lengthy that the term revolutionary becomes grossly devalued. Hence, the GPT framework has limitations when it comes to distinguishing revolutionary technologies from new technologies of lesser importance. Moreover, it can be argued that the GPT framework also suffers from ex post bias. A clear set of criteria to distinguish among all possible technologies and not simply an ex post definition of the technologies that matter would be highly useful, but such an analysis is beyond the scope of this paper.

The GPT framework can be compared with the broader concept of techno-economic paradigm (TEP) (Perez 1983; Freeman and Soete 1987). According to Freeman (1987) a TEP is a systematic relationship among products, processes, organizations and institutions that coordinate economic activity. Changes of TEPs are pervasive changes in technology affecting many branches of the economy and giving rise to entirely new sectors. A characteristic of this type of technical change is that it affects the input cost structure and the conditions of production and distribution for almost every branch of the economy. The definition of a GPT is more precise than the definition of a techno-economic paradigm. However, the TEP literature clearly distinguishes between “deeper conceptual breakthroughs” and subcategories that presuppose the deeper change (e.g., the steam engine vs. railways and steamships, the internal combustion engine vs. motor vehicles and the integrated circuit vs. personal computers and the Internet).

By using the criteria suggested by the GPT and TEP perspectives on technological breakthroughs and focusing on the period since the eve of the Industrial Revolution in the UK, we reach the conclusion that the number of innovations that can rival the ICT revolution in importance is exceptionally small. Arguably, there are only three innovations that qualify: the steam engine, the internal combustion engine, and electrification.

But what impact does a major technological breakthrough have on the economy, notably on the level and rate of growth of productivity? How long does it take before the new technology has spread throughout the economy, fundamentally altering modes and patterns of production and consumption? The purpose of this paper is to explore these questions. In particular, we intend to explore whether each breakthrough is unique in its effects or whether one can detect a general pattern. We will compare the effects of three technological breakthroughs, namely the steam power revolution, electrification, and the ICT revolution.[1] Our paper is purely empirical and we have no pretension to make any conceptual or theoretical contribution to the GPT or TEP literature. The questions above are very broad, and more specifically we address the following questions:

(i) Have these technological breakthroughs been important for productivity growth?

(ii) What similarities and dissimilarities are there between technological breakthroughs?

(iii) What similarities can be found in the pattern of productivity growth after the breakthroughs and do they differ across countries?

(iv) Is productivity growth different in sectors *producing* the new technology compared to sectors *using* it?

Most studies that compare technological breakthroughs use either a macroeconomic perspective based on quantitative data or a microeconomic perspective based on qualitative data. We believe that the questions above must be analyzed with a combination of different perspectives, including the micro, macro, and industry levels. By combining these three perspectives and analyzing three major technological breakthroughs, it will be possible to gain new knowledge on the impact of different technological breakthroughs on productivity growth.

The paper is organized as follows. Section 2 consists of a methodological discussion related to our investigation. In sections 3–5 we examine each technological breakthrough in detail and investigate its impact on productivity growth. Finally, we analyze our results from all three breakthroughs in order to find answers to the above questions. Our results show that it takes a long time from the moment of the original invention until a substantial increase in the rate of productivity growth can be observed. For the steam engine this was about 140 years (90 if the Watt steam engine is treated as the original innovation), while it was 40–50 years for electrification and the ICT revolution. We also find evidence of rapid price decreases for steam engines, electricity, electric motors and ICT products. This indicates rapid productivity growth in the industries producing the new technology. However, we cannot find direct evidence that the steam engine producing industry in the UK and the electric machinery industry in the US had particularly high productivity growth rates. For the ICT revolution the highest productivity growth rates were found for the ICT-producing industries throughout the six countries that we investigate.

2. Methodological Discussion

For the steam engine and electrification we will use secondary sources covering primarily Germany, Sweden, the UK and the US. For the ICT revolution we will present evidence from six different countries: Finland, France, Germany, Sweden, the UK and the US. Our

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[1] We do not examine the impact of the internal combustion engine. The reason for this omission is purely pragmatic. The body of literature is meager and the introduction of the internal combustion engine largely coincides with electrification.

investigation rests on empirical data mostly drawn from quantitative research. This raises issues concerning sources, concepts and productivity measurement. Before we delve into these matters it should be stressed that it is extremely hard, perhaps infeasible, to come up with “sharp” tests of causal effects from new GPTs to significant productivity growth, in particular concerning GPTs introduced long ago. There are long lags involved, the real world is exceedingly complex and general patterns are unlikely to repeat themselves from one GPT to the next in closely similar fashions. Instead we have to content ourselves with exploratory analyses with the aim of documenting whether identified patterns are consistent with fairly loosely formulated hypotheses.

2.1 Sources

For the ICT revolution we use primary data taken from the OECD Structural Analysis industrial database (STAN) (OECD 2003b) to analyze sectoral productivity in manufacturing for six countries.[2] The inclusion of Germany, France and Finland gives us a more complete picture of productivity development for Western European countries. Given that we include the three largest countries in Europe and two countries from northern Europe with a high degree of specialization in ICT-producing industries, we judge that our results can be seen as reasonably representative for the most recent breakthrough.

For the steam engine we primarily focus on the UK productivity development, while most of the evidence about electrification comes from the US. This is almost wholly due to data constraints. We are aware that this limitation may exclude important parts of the complex process of technological development and its implications for productivity growth. It is evident that technological processes may have evolved differently across countries, not least as a result of sizeable institutional differences.

Another limitation of our study is that we primarily, but not exclusively, focus on the impact of the new GPT on productivity in manufacturing, despite the fact that a large part of overall technological change takes place outside manufacturing. Difficulties in measuring productivity in the service sector and the ensuing lack of data force us to accept this limitation.

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[2] For the US we also use data from the Bureau of Economic Analysis (2004) and the Bureau of Labor Statistics (2005).

2.2 Data quality and measurement issues

We will present estimates both of labor productivity growth and total factor productivity (TFP) growth.[3] The data presented for earlier technological breakthroughs should be used with caution. Nevertheless, the available data make it possible to gain a better understanding of the general patterns of productivity development. Mokyr (1993) argues that if it is true that in modern industrial societies, the construction of national income statistics gives rise to theoretical and data problems, for 18th-century Britain the problems are much greater and national income estimates can only be "controlled conjectures". Nonetheless, growth cannot be analyzed without them. Hence, when we write that "the growth rate *was* x percent" during a certain period this always mean estimated to be x percent by the cited author(s) given all the limitations of the study in question. As long as numerous independent sources are used and the data are viewed with these caveats in mind, we deem that the quality and accuracy of productivity data for earlier technological breakthroughs is sufficiently high to warrant conclusions about productivity development and the diffusion of the technology in the economy.

Another issue concerns the use of hedonic price indices.[4] The hedonic approach to price measurement is used to take quality changes into account. It redefines goods in terms of their characteristics so that modified or new models do not open up a new product category, but simply represent a new combination of characteristics (Scarpetta *et al.* 2000). There are no consistent hedonic price indices available for steam power and electrification.[5] For the ICT revolution hedonic price indices are used to adjust quality change in output for some countries. France, Sweden and the US use hedonic adjustments for some ICT products, while Finland, Germany and the UK do not (Scarpetta *et al.* 2000). Cross-country comparability of output and productivity could thus be impaired in sectors with rapidly falling prices such as the computer industry.

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[3] Labor productivity is usually based on data of value added and labor input. TFP estimates are based on data for value added, employment, hours worked, capital stock, and factor shares. TFP accounts for the effect of capital input on productivity, but the measure is derived on the assumption that the marginal products of labor and capital are equal to their respective market prices and that production is characterized by constant returns to scale.
[4] A hedonic price index is any price index that makes use of a hedonic function. A hedonic function is a relation between the prices of different varieties of a product, such as the various models of personal computers, and the quantities of characteristics in them (Triplett 2004). Hedonic price indices are further discussed in section 6.2.
[5] Section 4.3 includes estimates of hedonic price indices for electric motors based on Edquist (2005a).

3. The steam engine

3.1 The early development of the steam engine

The first widely used steam engine was invented by Thomas Newcomen in 1712. The Newcomen engine was mostly used in mining and consumed relatively large amounts of coal. It took several decades for the steam engine to become modified for productivity enhancing use and to diffuse among countries and industries. In 1765 James Watt developed the separate condenser (patented in 1769). Watt realized that if the main cylinder could be kept hot all the time, and condensation occurred in a separate cold vessel, fuel-savings could be fourfold (Mokyr 1994). The fuel-saving innovation made it possible to use the steam engine at locations where coal was scarce (Nuvolari and Verbong 2001). Thanks to Watt's innovation the steam engine could become an important power source in factories (Robertson 1955).

However, the Watt steam engine had serious limitations and it was not until reliable high pressure boilers were developed and put to effective use in the 1840s (the Lancashire boiler; Crafts 2004) that steam power could be deployed on a large scale in factories and transportation (railways and sea vessels). A further important improvement was the introduction of the Corliss engine in the early 1860s (Rosenberg and Trajtenberg 2004).[6] In particular, the switch to steam ships hinged crucially on the introduction of high-pressure steam and in fact steam ships did not replace sailing ships to any great extent until the late 1800s.

3.2 The diffusion of the steam engine

Table 1 presents crude estimates of total steam power capacity in 15 different countries in 1840–96.[7] According to *Table 1* the US and the UK had the highest steam power capacity in 1840 totaling 760,000 and 620,000 horsepower, respectively.[8] Thus, these two countries accounted for more than 80 percent of the total world steam power capacity in 1840. At that point other large European countries, such as France and Germany, had a modest steam power capacity in relation to the UK and the US. However, the growth rate of steam power capacity was higher between 1840 and 1896 for all other countries included in *Table 1*. Germany had the highest annual growth rate in steam power capacity (9.9 percent p.a.). Hence, most countries caught up with the UK and the US during the second half of the 19th century.

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[6] The Corliss engine had more advanced valves that allowed a much greater fuel efficiency and a uniform and uninterrupted flow of power.

[7] The steam power capacity estimates in *Table 1* include capacity of fixed, railway and shipping steam power.

[8] The standard unit for measuring power capacity is horsepower, where one unit is equivalent to a rate of 550 foot-pounds per second.

TABLE 1 ABOUT HERE

In 1896 the US and UK share of world steam power capacity had decreased to 48 percent. Nevertheless, the UK had the highest capacity per inhabitant in 1896/97. *Table 1* shows that the steam power capacity per 100 inhabitants in 1896/97 was 34 horsepower for the UK compared to 25 for the US. The corresponding figures for France and Germany were 15 horsepower. Portugal, Russia and Italy had the lowest capacity per 100 inhabitants (see *Table 1*). Hence the catch up was far from complete.

In manufacturing, the steam engine was first adopted in the UK, but the initial adoption was slow. According to Nuvolari and Castaldi (2003) the total number of steam engines installed in British mining and manufacturing in 1800 was only 2,191. The price difference between steam power and waterpower remained high. However, the cost disadvantage was gradually overcome by the mobility advantage and the increased efficiency of new generations of steam engines (Atack *et al.* 1980).

The initial adoption of steam power in US manufacturing was even slower. According to Atack *et al.* (1980) there was only one manufacturing plant using steam power in the US before 1776 compared to 130 in Britain. In 1838 the total steam power capacity in US manufacturing was 36,100 horsepower (Atack *et al.* 1980). A crude estimate of the corresponding figure for the UK was 350,000 horsepower (Tann 1988). These figures, although crude, suggest that by the 1840s the UK was far ahead of the US in steam power capacity in manufacturing. But once adoption gained momentum in the US it became rapid. By 1869 the total power capacity in US manufacturing had increased to 1,216,000 horsepower. Around 1820 waterwheels probably outnumbered steam engines by 100 to 1 in the US, but by 1870 this difference had narrowed to about 5 to 4 (Atack *et al.* 1980). These figures indicate that the breakthrough in the diffusion of the steam engine in the US manufacturing took place in the middle of the century. Fenichel (1966) shows that by 1899 steam accounted for four-fifths of total primary power capacity in US manufacturing.[9]

[9] Primary power means the work done by “prime movers” which convert energy of nature directly into the energy of motion.

3.3 The steam engine and productivity growth

3.3.1 Steam power development in the UK

One way to investigate the impact of the steam engine on productivity growth is to analyze how TFP developed during the period when the steam engine was introduced in manufacturing. Most evidence indicates that the growth in output and TFP in the UK did not increase until the beginning of the 19th century (see *Table 2*). This was more than 35 years after the invention of Watt's steam engine and 90 years after Newcomen's engine. Crafts (2004) argues that productivity growth did not increase substantially until the 1850s (see *Table 2*).

TABLE 2 ABOUT HERE

But can the increase in TFP and labor productivity growth in the UK be ascribed to the introduction of the steam engine? Several studies suggest that the impact of steam power on TFP growth was quite small (see Von Tunzelmann 1978 and Crafts 2004). Moreover, there are few indications that the steam engine had a substantial productivity-enhancing effect initially. One way of measuring the contribution of new technology is to use the concept of social savings. Social savings are usually measured as the gain in consumer surplus from the fall in costs due to new technology.[10] Estimates of social savings are invariably small for the steam engine. Von Tunzelmann (1978) estimates that the savings from using Watt's engines over Newcomen's in 1800 were approximately 0.11 percent of national income.

Crafts (2004) analyses the impact of steam engines on British labor productivity growth by using the growth accounting framework that Oliner and Sichel (2000) developed to assess the impact of ICT on US labor productivity growth.[11] *Table 3* reports Crafts' estimates of the contribution of stationary steam engines, railways and steamships to British labor productivity growth in 1760–1910. *Table 3* shows that the impact of steam technology on labor productivity growth, measured as the increase in steam power capital in all sectors as a share of total income and TFP growth in the steam power industry as a share of total output, was 0.01–0.02 percentage points per year throughout the period 1760–1830.[12] During 1830–50, the contribution of steam technology increased to 0.2 percentage points of the annual labor

[10] This approach was applied to railroads in Fogel's (1964) famous study.

[11] Oliner and Sichel (2000) identify the contribution from ICT to labor productivity growth as three types of ICT capital deepening (computer hardware, software and communication equipment) weighted by the shares of these types of capital in income and through TFP growth in the ICT-producing industry weighted by its share in gross output.

[12] Crafts (2004) does not calculate the rate of technical change in steam power as a TFP residual, instead he estimates the TFP as the aggregate social savings determined by the reductions in steam power costs.

productivity growth of 1.65 percent (see *Table 3*).[13] In 1850–1910 the contribution of steam increased to 0.31–0.41 percentage points.[14]

TABLE 3 ABOUT HERE

The increase in the contribution of steam technology to labor productivity growth during the second half of the 19th century was to a great extent due to the large investments in railways during the period. For example, in 1830–1850 railways contributed 0.16 percentage points to labor productivity growth, while the contribution from stationary steam engines was estimated to be a mere 0.04 percentage points. It is important to point out that the railway industry was not *producing* steam engines, but rather *using* steam power technology. Moreover, it was not until after 1850 that the contribution of steam technology to labor productivity growth increased. However, the contribution from the stationary steam engine producing industry never exceeded 17 percent of total labor productivity growth.

Crafts' (2004) estimates show that the steam engine had little influence on labor productivity growth in the period 1760–1850. This suggests that 140 years after Newcomen's steam engine and 85 years after Watt's steam engine, no substantial TFP growth had taken place within the steam power *producing* industry. However, after 1850 steam technology started to contribute more to labor productivity growth. This time period coincides with the introduction of the high pressure steam engine. Steam engine capacity also increased rapidly during this period. In 1830 total steam power capacity in the UK was 160,000 horsepower compared to 2.06 million in 1870 and 9.65 million in 1907 (Kanefsky 1979; Crafts 2004). Hence, capacity in terms of horsepower grew by 5.5 percent p.a. in the 1830–1907 period.

Crafts' growth accounting approach also has shortcomings. Field (2006a) argues that the key message of the social savings approach is that in the absence of new technology the saving flows would have been invested elsewhere. This would have resulted in economic growth, although not quite as large. According to Fogel (1964) this meant canals and river dredging in the hypothetical absence of the railroad.[15] Fogel estimated that in 1890 GNP was 4 percent higher as a result of the railroad. The approach used by Crafts includes the portion of the effect of capital deepening on labor productivity that is the consequence of the accumulation of particular steam engine capital goods. As pointed out by Field (2006a) the message of the

[13] The average annual labor productivity growth of 1.65 percent refers to the years 1931–73.
[14] Annual labor productivity growth in Britain averaged 1.65 percent in 1873–1899 and 0.85 percent in 1899–1913 (see *Table 2*).

Fogel approach is that in the absence of the steam engine, capital would have been accumulated in a slightly inferior range of capital goods. As a result, the growth accounting approach used by, *inter alia*, Crafts (2004) and Oliner and Sichel (2000) may overestimate the impact of the new technology.

However, it is also possible to argue that the growth accounting approach underestimates the impact of the steam engine, since it does not take account of spillover effects from the steam power *producing* industry to steam power *using* industries.[16] It is possible that increased flexibility and reliability due to the introduction of the steam engine in the production process could have generated substantial productivity growth in manufacturing industries using the new steam power technology. Nuvolari and Castaldi (2003) maintain that if the steam technology stimulated the generation of further technical or organizational innovations in sectors applying the new GPT, its economic impact cannot be appropriately assessed by means of growth accounting and social savings.

Table 3 indicated that the stationary steam engine producing industry did not have a large impact on aggregate productivity growth in 1760–1910 (see *Table 3*). However, the steam engine may have had an impact on productivity in other sectors of the economy. Even though aggregate TFP growth was low in the UK it seems that some sectors experienced very high growth rates thanks to the introduction of the steam engine in their production processes. *Table 4* shows that steam power was used intensively in a few industries only. Throughout the period 1800–1907 mining, textiles, and metal manufactures accounted for more than 50 percent of the steam industrial power (Nuvolari and Castaldi 2003). However, important sectors including agriculture and the service sector excepting transport were in fact very slow at adopting the steam engine (Crafts 2004). This might be the reason why productivity growth stemming from the steam engine did not result in high aggregate productivity growth in the UK during this period.

TABLE 4 ABOUT HERE

So which industries experienced the highest productivity growth? McCloskey (1981) estimates total factor productivity growth for a number of individual industries. McCloskey's figures have been widely criticized. Harley (1993) claims that McCloskey exaggerated productivity

[15] The approach assumes that aggregate saving flows would have been largely unaffected by the absence of the particular innovation under study.

growth in several industries (cotton, wool, and shipping). In *Table 5* the average annual TFP growth for different industries in 1780–1860 are presented based on both McCloskey (1981) and Harley (1993). The figures indicate that productivity estimates for different industries must be analyzed with caution. Nevertheless, it is possible to draw some conclusions. It is, for example, evident that the textile industry had a high rate of productivity growth during this period. The textile industry was also an intensive user of steam power (see *Table 4*).

TABLE 5 ABOUT HERE

An important issue is how productivity increased in the sector producing steam engines.[17] By the size of the output shares for production of steam it is clear that the steam power producing industry was small compared to the rest of the economy. Crafts (2004) argues that in the period 1800–1840 there were few innovations in the steam power producing industry and the costs of steam engines did not fall. The subsequent period of rapid innovation resulted in large cost reductions. One of these innovations was the automatic variable cut-off mechanism of the Corliss steam engine that resulted in substantial improvement in fuel efficiency in the mid 19th century (Rosenberg and Trajtenberg 2004). Hence, the price of steam power had approximately halved by the mid-1850s and in 1910 the annual cost of steam horsepower had fallen by approximately 80 percent compared to the beginning of the 19th century (Crafts 2004). These observations suggest rapid productivity growth in the steam engine producing industry after 1850.

3.3.2 Steam power development in other countries

As already noted considerable time elapsed before the steam engine diffused in the US. According to Robertson (1955) the British sought to prevent export of the steam engine abroad. By 1838 only 5 percent of the total power used in US manufacturing was generated by steam engines. Rosenberg and Trajtenberg (2004) argue that it was not until around 1850 when the Corliss engine was introduced in the manufacturing process, that steam started having a substantial impact on productivity growth in the US. As in the UK, textiles, primary metals and machinery industries were the key industries in the process of industrialization. The fraction of power generated from steam increased in the textile and primary metals industries from 1/4 in

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[16] We define spillovers as increases in labor productivity in the using sectors beyond what one would expect from the capital deepening effect alone. In other words, spillover effects are the contribution to TFP growth in the using sectors resulting from the introduction of the new technology.

[17] The estimates of TFP growth in the steam engine producing industry is based on an incomplete data set and should therefore be analyzed with caution.

1870 to 1/3 in 1910. However, by then another key technology had started to change the production process in manufacturing.

For Finland, France, Germany, and Sweden we have been unable to uncover sufficient data to accurately investigate the impact of steam power on productivity growth. From a macroeconomic perspective the productivity and growth increases took place later in these countries compared to the UK (Fisher 1992). For the period 1820–70 GDP per capita growth in Germany was 0.7 percent p.a. The corresponding figures for Sweden and France were 0.7 and 0.8 percent p.a., respectively (Maddison 1991). However, it has not been possible to investigate the importance of steam power for this development.

3.4 Concluding remarks on the development of steam power

Aggregate productivity growth did not accelerate until after 1850 in the UK, i.e. 140 and 85 years after Newcomen's and Watt's steam engines were invented. Hence, one cannot detect an effect on TFP until quite long after the invention had been made. Crafts and Mills (2004) note that "the contribution of steam power to industrial output and labor productivity was at its strongest *after* 1870". One interpretation of this is that the real potential of steam technology did not materialize until the high pressure steam engine had been invented. From this invention until sizable productivity effects could be detected no more than 20–40 years elapsed.

Furthermore, most of the productivity increases for the period appeared in sectors that were *using* the steam engine intensively, i.e. textiles and railways. The cost of steam power fell rapidly after 1840 as a result of a series of technical improvements of the original design. Notably, this opened the way for intensive use of the steam engine in the transportation sector. This may indicate a high productivity growth in the steam engine *producing* industry after all. However, the output of the steam engine producing industry remained less than 1 percent of total output in the UK throughout the 1760–1860 period. This could be one reason why the detectable effects of the steam engine producing industry remained small until the mid 19th century.

4. Electrification

We now switch the main focus from the role of the steam engine in British manufacturing to the US electrification process. The focus on US manufacturing is governed by data availability.

To the greatest extent possible we also present complementary evidence from other countries, notably Sweden and the UK.

The invention of the dynamo was crucial for the 19th century electric industry. The principle behind the dynamo – the theory of electromagnetic induction – was discovered by Michael Faraday in 1831 (Byatt 1979). However, it took over forty years until the dynamo could be used commercially. The basic technological innovations raising energy efficiency in electricity generation to levels permitting commercial application occurred during 1856–1880 (David 1991). In 1867 a number of inventors came up with the idea of using an electromagnetic field energized by the dynamo itself. The Gramm dynamo was based on this principle and was able to generate electricity inexpensively enough for the commercial use of electric lightning. Other inventions such as the Swann-Edison lamp in 1879 and the Edison central generating station in New York and London in 1881 were also important for the diffusion of electricity. Moreover, innovations such as transformers and alternators made it possible to use alternating current instead of direct current, which substantially lowered costs for transmitting electricity.

4.1 Diffusion of electricity

Electric energy in the 19th century was produced by prime movers driven primarily by falling water (hydroelectric power) or by steam (thermal power).[18] Electricity is not a prime mover, but rather a form of energy that is easy to transport from the power source to the end user, which gives rise to efficiency and flexibility gains. The process of electrification began in the 1880s both in Europe and the US (Goldfarb 2005; Hughes 1983; Byatt 1979; Landes 1969). In the beginning, application was largely limited to lightning. Later, electrification spread to tramways and railways. Innovations such as the electric motor eventually came to revolutionize manufacturing. The large-scale use of motors in manufacturing started around 1900 in the UK. By 1907 electric motors in factories consumed about half of the total amount of electricity produced, and by 1912 factories used three times as much electricity as did traction (Byatt 1979).

The industries of other large European countries, such as Germany and France, were also rapidly electrified in the late 19th and early 20th century (Milward and Saul 1977). According to Landes (1969) the most striking achievements occurred in Germany. In 1907 the capacity of

[18] According to Du Boff (1979) a prime mover is an engine that utilizes the potential energy of nature and directly converts it into energy of motion. Modern mechanical prime movers are the steam engine, the steam turbine, the hydro turbine, the internal combustion engine and the jet turbine.

electric generators in Germany and the UK was roughly the same.[19] However, in 1925 the total capacity of German electric generators was 13,288,800 horsepower compared to 8,510,000 for the UK. Moreover, German companies such as Siemens & Halske and Allgemeine Elektrizitäts-Gesellschaft (AEG) became world leading manufacturers of electric equipment (Hughes 1983). In 1913 the German electric machinery industry was twice as big as that of Britain and only slightly smaller than in the US (Landes 1969).

In the US, electricity was first used as a commercial power source in 1882. The use of electricity in manufacturing increased slowly. In 1899, 4 percent of the total primary horsepower capacity in manufacturing used energy from purchased or firm-generated electric power. This had risen to 21 percent in 1909, 50 percent in 1919 and 75 percent in 1929 (Woolf 1984). *Table 6* presents figures from Du Boff (1979) for total primary capacity in manufacturing divided into non-electric capacity and electric motor capacity. The figures indicate that the rapid expansion of purchased and firm-generated electricity was somewhat more modest compared to what Woolf argues. Still, the expansion of primary and secondary electric motors was rapid.[20] Moreover, the adoption of electricity was very uniformly distributed across manufacturing industries (Jovanovic and Rousseau 2005).

TABLE 6 ABOUT HERE

Table 7 compares electrification in five manufacturing industries in the UK and the US. Even though the figures are not fully comparable some conclusions may be drawn. The figures point to large differences in the electrification process across industries in both countries. Industries such as engineering, shipbuilding and vehicles and chemicals were electrified much more rapidly compared to cotton textiles and coal mining. In iron and steel, coal mining, and cotton textiles Britain lagged behind the US. Byatt (1979) documents that these industries were slow in adopting electric motors in their production processes compared to both the US and Germany. Moreover, according to estimates by Broadberry (1997), the US/UK relative labor productivity level in the cotton industry increased from 151 in 1909/07 to 174 in 1914/12.

TABLE 7 ABOUT HERE

[19] Landes (1969) estimates are based on the industrial censuses in Germany and the UK in 1907. According to these estimates, the capacity of electric generators in the UK and Germany was 2,341,900 and 1,830,000 horsepower respectively. However, the British figures are based on capacity of engines and motors, while the German the power produced in regular operation.

[20] Primary electric motors are those driven by electricity purchased from utilities outside the manufacturing plant. Secondary motors are driven by electricity from generators and prime movers within the plant itself. They represent no addition to power available for use, since some of the plant's own power generating capacity must be employed to generate their electric energy (du Boff 1979).

Why did Britain lag behind both Germany and the US in adopting electric motors in manufacturing? It appears that mining and textile industries that were early in adopting the steam engine in their production processes in Britain were much slower in adopting electricity compared, for example, to chemicals and engineering, or shipbuilding and vehicles (see *Table 7*). One possible explanation for this is that the large investments in steam engines made those industries reluctant to invest in new electric technology. This suggests that technological choices are often path dependent and are not always socially optimal. Similar evidence from other areas supports this view (see David 1985). It is interesting to note that the US textile industry quickly switched from steam to electricity. In fact, Jovanovic and Rousseau (2005) find that the industries that quickly switched to electricity had been heavy users of steam. One parallel that comes to mind is the Gerschenkron (1952) thesis that “relative backwardness” may facilitate economic growth, since it is easier to imitate the technologically leading countries. Similarly, a new GPT may be more readily adopted in a country where the previous GPT has not yet become so deeply entrenched.

In Sweden, electricity started to be used in lightning in 1876. In 1885 there existed 111 dynamos with a capacity of 1036 horsepower (Hjulström 1940). The diffusion of electricity was rapid in Swedish industries. Sweden was also successful in innovation that permitted electricity to be transmitted over long distances without substantial power losses (Schön 1990). Initially, the primary source of electricity was steam power; in 1885 82 percent of the electricity produced came from steam power and the remainder from hydropower. In 1900 the relationship was largely reversed and 60 percent of the electricity was produced by hydropower (Hjulström 1940).

Swedish manufacturing rapidly adopted electricity in the production process. *Figure 1* shows the development of Swedish electric motor capacity in the manufacturing and handicraft industry. It is evident that Swedish manufacturing was electrified very rapidly at the beginning of the 20th century. From 1906 to 1937 the power capacity of electric motors increased more than twenty fold. Which industries were then electrified most rapidly?

FIGURE 1 ABOUT HERE

Table 8 shows that electric motor capacity increased in all industries throughout the period investigated. For the period 1913–1931 the most rapid expansion took place in wood and cork with a capacity increase of 452 percent. Food manufacturing, leather, furs and rubber products, and Non-metallic mining and quarrying also experienced increases exceeding 300 percent in their electric motor capacity in 1913–1931. The growth was slowest in textiles, wearing apparel and made-up textile goods – which is in accordance with the findings for the UK presented earlier.

TABLE 8 ABOUT HERE

4.2 Electricity and productivity growth

4.2.1 Productivity development in the US

Table 9 presents estimates of the compound annual growth rate of labor and TFP growth in the US non-farm business sector 1889–1948. Productivity growth is measured from peak to peak over the business cycle. According to Field (2003) choosing business cycle peaks for beginning and end points largely controls for the variations in capacity utilization that occur over the business cycle. The results show that labor and total factor productivity growth was high during the period 1889–1901. In 1901–19 productivity growth slowed down and it did not start to increase until the 1920s. It is unlikely that electrification had a sizable effect on productivity growth in 1889–1901. For example, in 1899 only 4 percent of the total primary horsepower capacity in manufacturing used energy from purchased or firm-generated electric power (see section 4.1).

TABLE 9 ABOUT HERE

Table 10 presents estimates of compound annual labor and TFP growth in US manufacturing for different periods. The estimates are based on Kendrick (1961) and Field (2006b).[21] These show large increases in both labor productivity and TFP growth in manufacturing for the period 1919–1929. The estimated growth rate in labor productivity and TFP was 5.5 and 5.1 percent, respectively. As in the case of the steam engine several decades elapsed from the installation of the first power station producing electricity until there is evidence that electrification had a substantial impact on productivity growth within manufacturing. Why did productivity growth in manufacturing increase some 40–50 years after the introduction of the first commercial electric power stations? And which manufacturing industries experienced the highest productivity growth during this period?

[21] Kendrick (1961) provides estimates of TFP growth rates within manufacturing for the benchmark years 1929, 1937 and 1948. According to Field (2006b), 1937 is not a peak of the business cycle. Field has therefore calculated TFP growth rates within manufacturing for the subperiods 1929–41 and 1941–48. His calculations are

TABLE 10 ABOUT HERE

David (1991) argues that it took considerable time for the manufacturing sector to adopt the new technology and use it efficiently. According to David electrification paved the way for a thorough rationalization of factory construction designs and internal layouts of production. One such rationalization was the shift from shafts to wires in the production system (Devine 1983). Before electricity was introduced, the production process was built around a large power source, such as a waterwheel or a steam engine. The power source turned iron and steel “line shafts” via pulleys and leather belts. Often all machines in an entire factory were linked to a single power source through these line shafts. The entire network of line shafts rotated continuously no matter how many machines were actually in use. If one line shaft broke, production stopped in the entire factory. It is evident that production systems built around a single power source were very energy consuming and lacked flexibility.

The first electric motors used in production just replaced steam engines and continued to turn long line shafts. But, it was soon discovered that large energy savings could be realized if a group of machines were driven from a short line shaft turned by its own electric motor. A further step was to connect a single electric motor to each machine. This unit drive innovation used less energy than the line shaft drive. Yet, the most important economic impact of the unit drive system was the increased production process flexibility that it entailed. Machines could be run only when needed. Moreover, machines could be organized in a natural sequence for manufacturing. In this way the unit drive offered an opportunity to obtain greater output per unit of inputs (Devine 1983).

The reorganization of production processes around a new technology turned out to be time consuming. David (1991) maintains that it was not until half of the factory mechanical drive capacity had been electrified that productivity growth in manufacturing began to increase. In addition, David and Wright (2003) point out in some detail that in order for electric power to gain full momentum a number of political and institutional changes were also necessary.

Table 11 shows the ratio of primary electric motor capacity to total primary capacity in US manufacturing. The data support David’s hypothesis that it was not until the end of the 1920s that half of the mechanical drives had been electrified. To support his hypothesis David shows

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based on Kendrick’s estimates for output and labor input combined with capital input data from the Bureau of Economic Analysis.

that there is a correlation between the change in the rate of productivity growth from 1909–19 to 1919–29 and the ratio of secondary electric motor capacity in 1929 to that capacity in 1919. A simple linear (OLS) regression of 15 industries confirms that the increase in secondary motor capacity accounts for approximately 25 percent of the variation in productivity growth from 1909–1919 to 1919–1929.[22] In subsequent work David and Wright (1999) provide more compelling evidence in support of the view that the productivity surge in the 1920s can be attributed to the diffusion of a new GPT rather than to multiple, largely unrelated sources.

TABLE 11 ABOUT HERE

An interesting observation can also be made for the production of electricity and for electric machinery. Woolf (1984) finds that there was a substantial increase in the rate of productivity growth in the sector *producing* electricity. In 1902 7.3 lbs of coal was needed to generate one kilowatt hour of electricity. In 1917 the figure had fallen to 3.4 lbs and by 1932 only 1.5 lbs were needed. *Table 12* presents figures from Kendrick (1961) on compound annual labor and TFP growth in different manufacturing industries in the US. According to these estimates the substantial productivity increase did not appear in the industry *producing* electric machinery. For the period 1919–1929 annual TFP growth in US manufacturing was 5.1 percent, while TFP growth in electric machinery was only 3.5 percent per year.[23] The change in TFP growth from 1909–1919 to 1919–1929 for manufacturing and electric machinery is 4.9 and 3.2 percentage points, respectively. Hence, productivity growth increased substantially in the sector producing electricity, but not in the sector producing electric machinery. The productivity effects were materialized in sectors using electric machinery rather than in sectors producing it.[24]

TABLE 12 ABOUT HERE

4.2.2 Evidence for other countries

Table 7 indicates that the UK lagged behind the US in the electrification of many important industries. According to Byatt (1979) the UK industry was very slow in investing in electric motors. The UK also lagged behind the US in terms of productivity growth. Floud (1994) estimates that annual TFP growth in the British economy decreased from 1.4 percent in 1856–

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[22] David's regression results are based on TFP estimates adjusted for energy inputs based on Woolf (1984). However, David's OLS regression is still significant when we run the regression with productivity estimates based on Kendrick's (1961) two input approach (available upon request).

[23] The compound annual labor productivity growth was 5.4 percent in US manufacturing, but only 3.9 percent in Electric machinery (see *Table 12*).

[24] Kendrick (1961) provides estimates at the industry level from 1899. Therefore, it is possible that productivity increased in Electric machinery before 1899.

1873 to 0.5 percent in 1873–1913. Labor productivity growth was slower in the UK relative to most other industrialized countries for the period 1913–1950 (Maddison 1991). Why then was the UK slower in adopting electricity?

Byatt (1979) argues that investments in electric motors had an impact on the UK economy, but not to the same extent as in the US. One reason for the late adoption of electricity in the UK could have been that other energy sources were cheaper than electricity. The UK had the most developed applications of steam as a power source and it was probably therefore more costly to invest in electricity. The evidence indicating that sectors with well-developed steam capabilities were slow in investing in electricity supports this explanation.

Table 13 shows annual labor productivity growth for 12 German manufacturing and handicraft industries in 1925–38.[25] The estimated total annual labor productivity growth in German manufacturing and handicraft was 2.5 percent in 1925–38.[26] Labor productivity was particularly high in metal producing, metal processing and chemical industries in the late 1920s. However during the 1930s, the rate of labor productivity growth decreased considerably in the metal producing and metal processing industries, while it remained relatively high in the chemical industry. However, throughout the period 1925–38, the chemical and metal processing industry had the highest annual labor productivity growth at 4.9 and 3.4 percent, respectively.

TABLE 13 ABOUT HERE

When it comes to productivity development in Sweden it appears that Sweden followed the US pattern. Schön (2000) shows that labor productivity growth in Swedish manufacturing increased from 1.5 percent p.a. in 1896–1910 to 2.9 percent in 1910–1935.[27] *Table 14* shows labor productivity growth for different industries in the Swedish manufacturing and handicraft industries in 1913–39. As in the US, labor productivity growth accelerated in 1919–1929. Chemicals and chemical products and power, lightening and waterworks experienced the highest rates of productivity growth in 1919–1929. However, as indicated in *Table 8*, electric motor capacity did not increase the most in these industries. Thus, one cannot establish a clear correlation between labor productivity growth and the increased use of electric motors for different industries within Swedish manufacturing during the years 1919–1929.

[25] The figures in *Table 13* are based on estimates by Hoffmann (1965). The reliability of Hoffmann's estimates for the period 1850–1913 have been questioned (see Fremdling (1995) and Burhop and Wolff (2005)). Therefore, we only report estimates for the period 1925–38.
[26] Hoffmann (1965) does not present any comparable figures for the period 1914–24.

TABLE 14 ABOUT HERE

Finland's productivity growth was similar to the US and Sweden during electrification. According to Jalava and Pohjola (2005) annual labor productivity growth in the Finnish non-residential business sector increased from 1.9 percent in 1900–1913 to 3.1 percent in 1920–38. Moreover, they estimate that the use of electrical capital goods contributed 1.2 percentage points of the 4.5 percent growth in value added in 1920–38 compared to 0.4 percentage points of the 3.0 percent growth in value added in 1900–13. Hence, the contribution of electrical capital goods increased from 13 percent of total value added growth in 1900–13 to 27 percent in 1920–38.

4.3 Price development of electric motors

We noted above that compound annual TFP growth in US manufacturing was 5.1 percent, while TFP growth in electric machinery was only 3.5 percent in 1919–1929. This suggests that the industry actually producing the electrical equipment was not able to take advantage of its own technology to the same extent as other industries. *Table 15* shows the price development for a number of different electric motors (in terms of SEK/horsepower) produced by the Swedish company Luth & Rosen during the 1920s.

TABLE 15 ABOUT HERE

According to *Table 15* the price of 3–15 horsepower electric motors fell rapidly in Sweden during the 1920s. On average prices fell by approximately 70 percent from 1919 to 1929. CPI calculations by Myrdal (1933) and Johansson (1967) indicate that total price deflation during this period was 37 percent. Hence, the real price of electric motors decreased substantially,[28] which is a clear indication of productivity gains in the electric motor producing industry in Sweden.[29] These results call the productivity findings for US Electric machinery into question. It is reasonable to presume that the industry producing the electric motor also should be the industry that most rapidly understood how the electric motor could be used efficiently in the production process. Moreover, the increase in demand for the electric motor should have

[27] Schön (2000) defines labor productivity as real value added per hour worked.
[28] Our own investigation of the price of a 20 horsepower electric motor produced by ASEA for the Swedish market show that the nominal price for this motor did not increase at all for the period 1914 to 1935 (ASEA 1914 and ASEA 1935). Total price inflation during this period was about 35 percent, which provides further evidence of a substantial fall in real prices of electric motors.

resulted in increased production and thereby allowed the industry to benefit from economies of scale.

Table 15 indicates that the price per horsepower fell more rapidly for electric motors with more than 5 horsepower. Moreover, a 15 hp electric motor in Sweden was much cheaper in 1929 compared to a 7.5 hp motor in 1919 both in nominal and real terms. To the extent that companies were buying electric motors with higher capacity during the 1920s, the real price of motor capacity installed fell even more than what is indicated by the price change of each motor category. Finally, it is likely that the quality of an electric motor increased during the 1920s in terms of reliability, duration etc. Ordinary price indexes do not take such quality improvements into account. Edquist (2005a) constructs hedonic and matched model price indexes for electric motors in Sweden for the period 1900–35.[30] He finds that during the 1920s, PPI-deflated hedonic and matched model price indexes decreased by 4.8 and 3.7 percent per year, respectively. *Table 16* shows the estimated labor productivity growth for Electric machinery based on the hedonic and matched model price indexes estimated by Edquist (2005a).[31] According to *Table 16*, annual labor productivity growth in the Swedish electric machinery industry in 1920–29 was 12.1 and 10.8 percent when hedonic and matched model deflators were used. Therefore, there is strong evidence that productivity growth in the Swedish electric motor producing industry was very high during the 1920s. However, it is still a puzzle why productivity did not increase more in US Electric machinery during the 1920s.

TABLE 16 ABOUT HERE

4.4 Concluding remarks on electrification

Evidence from the electrification process shows that productivity growth did not increase in US manufacturing until the 1920s, i.e. 40 years after the first electric power stations were established. Similar patterns can be observed in Sweden and Germany. Electrification took place in all the investigated countries in the 1880s. However, British manufacturing was slow in adopting the new technology, especially in industries that had a well-developed production system based on steam power technology.

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[29] It is important to point out that a price decline does not necessarily mean that productivity gains have been made. A price decline could also be due to increased competition in a specific market.

[30] The hedonic and matched model price indexes are based on prices and characteristics collected for slip-ring electric motors with 1–100 horsepower. Thereby, it is assumed that other electric motors would have a similar price development.

[31] Labor productivity has been defined as production value per person employed. Unfortunately it has not been possible to calculate labor productivity based on value added which implies that only single deflation is used to calculate productivity.

In the US there was high productivity growth in the sectors producing electricity, but not in the industry producing electric machinery. Thus, it appears that the productivity effects were largely materialized in sectors *using* electric machinery rather than in sectors *producing* it. One possible explanation to these findings is that quality improvements were insufficiently considered when productivity was measured in the producing industries. As we will see below, this stands in contrast to contemporary estimates of productivity in ICT-producing sectors where a large part of productivity increases may be attributed to assessed improvements in quality.

5. The ICT revolution

5.1 Background

In 1947 Bardeen, Brattain, and Shockley invented the transistor. The transistor became the basis for numerous electronic innovations. Many of these innovations formed what is called the **I**nformation and **C**ommunications **T**echnology (ICT) sector. During recent decades the ICT sector has undergone a technological revolution. The development of numerous innovative technologies has given rise to a plethora of new products providing the basis for development within the ICT sector. Communication satellites in the 1960s, fiber optic cables in the 1970s and cellular telephones first introduced during the 1980s are significant examples of such product innovations. The Internet is yet another innovation that is believed by many to be a crucial driver of future economic growth (e.g., Litan and Rivlin 2001 and Lipsey *et al*. 1998).

In this section we investigate the economic impact of the ICT sector on productivity in the US and five European countries (Finland, France, Germany, Sweden, and the UK). The selection of countries was governed by data availability, but there is strong reason to believe that the conclusions for these countries are readily applicable to other European countries on a similar income level. The following questions will be discussed in depth: (1) What effect has ICT investments had on aggregate productivity growth? (2) In which industries can we find increased productivity growth? (3) Have there been any spillover effects from ICT-producing to the ICT-using industries?

5.2 What is ICT?

Before analyzing the economic impact of the ICT sector it is important to define ICT. We adhere to OECD’s definition. For a manufacturing industry to be defined as an ICT industry, the manufactured products (OECD 2002b): (1) must be intended to fulfill the function of information processing and communication including transmission and display; and (2) must use electronic processing to detect, measure, and/or record physical phenomena or to control a physical process. For a service industry, products must be intended to enable the function of information processing and communication by electronic means.

Productivity measurements within the service sector give rise to several measurement problems.[32] Therefore we have chosen to focus on manufacturing (see *Table 17*). For certain industries, the OECD definition of ICT-producing industries has been at a very disaggregated level. Therefore it is not possible to calculate value added and labor productivity at the disaggregated level used in *Table 17*. The following industries are defined as ICT-producing: Office, accounting and computing machinery (ISIC 30), Electric machinery and apparatus (ISIC 31), Radio, television and communication equipment (ISIC 32) and Medical, precision and optical instruments (ISIC 33).

TABLE 17 ABOUT HERE

5.3 The ICT Revolution and productivity growth

Despite heavy investments by firms in computers and other ICT technology in the 1970s and 1980s, productivity growth slowed down in most countries. The first oil crisis has been pointed out as one of the explanations for the productivity slowdown (Hulten 2001).[33] Nevertheless, the slowdown has remained a puzzle for economists, especially since it occurred when firms started to invest in computers that were believed to have a major positive effect on productivity.

During the 1990s, ICT investments were extremely large. During 1990–1996, US investments in computers rose by 28.3 percent per year (Jorgenson and Stiroh 1999). Sichel (1999) reports that the annual increase for computer investments during 1996–1998 was 41.8 percent. Calculations also show that ICT accounted for about half of the increase in real capital in the US during the period 1990–1996 (Andersson 2001). The available data for OECD countries show that ICT investments rose from less than 15 percent of total non-residential investment in the business sector in the early 1980s, to between 15 and 35 percent in 2001 (OECD 2004).

[32] When measuring productivity in the service sector, it is difficult to determine whether quality improvements for produced services have occurred. This problem is further discussed in section 6. Moreover, many statistical agencies do not use any consistent method to measure prices in the service sector.
[33] The difficulty for the oil hypothesis has been explaining why low productivity growth rates persisted in the 1980s after oil prices collapsed.

Did these investments have any substantial impact on productivity growth in different countries?

In *Table 18*, we present data for the average annual growth rate of labor productivity for the six economies we study, as well as average labor productivity growth for the EU countries.[34] It is evident that the US is the only country that experienced a significant increase in the growth rate of labor productivity in the late 1990s and early 2000s. None of the other economies shows a similar increase in productivity growth during the late 1990s. We can also see that average labor productivity growth in EU countries decreased substantially during the second half of the 1990s. In this respect, development in the EU on the whole has been the opposite of what has occurred in the US.

TABLE 18 ABOUT HERE

During 2001, the US and most EU countries experienced an economic slowdown. Falling growth rates called the narrow “new economy” concept into doubt. Many observers have associated the concept with bankruptcies among dotcoms and other firms. However, productivity growth in the US remained high, despite the general downturn in the economy (Council of Economic Advisers 2002). *Table 19* shows that growth in labor productivity as well as TFP growth increased considerably during the period 1995–2001 compared to 1973–1995. Figures in *Table 19* are based on a model that takes the effects of the business cycle on productivity into consideration. According to these calculations, structural labor productivity growth increased by 1.7 percentage points between the periods 1973–1995 and 1995–2001.[35] The corresponding figure for structural TFP growth is 1.07 percentage points, i.e. a tripling of the pace in the 1973–1995 period.

TABLE 19 ABOUT HERE

The productivity performance of the US economy has intensified the debate about the effect of ICT on productivity throughout the whole economy. Research results have shown that investments in ICT play an increasingly important role for productivity growth. In recent years, however, several researchers have pointed out that a dramatic increase in productivity has only been experienced in a few industries (Jorgenson and Stiroh 2000; Gordon 2000).

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[34] The selection of 1996 as the initial year for the last period follows other productivity studies of the “new economy” such as Oliner and Sichel (2000) and Nordhaus (2001). The choice of final year is governed by data availability.

5.4 Productivity growth: Industry evidence

Has ICT influenced productivity growth in the whole economy, or has productivity growth accelerated in just a few industries? To make an in-depth analysis, we present results from productivity calculations at the sectoral level for manufacturing. We begin by presenting detailed information for the US (*Tables 20* and *21*).[36] For the other countries, we present information for those three industries with the highest rate of productivity growth in 1996–2000/01. *Table 20* indicates that the compound annual labor productivity growth rate increased considerably in US manufacturing in 1996–2000. Compound annual labor productivity growth increased from 3.7 percent in 1990–1995 to 4.5 percent in 1996–2000.

TABLE 20 ABOUT HERE

Labor productivity growth increased in 13 out of 20 of the industries between 1990–1995 and 1996–2000. This could indicate a spillover effect from ICT-*producing* to ICT-*using* industries.[37] However, a closer inspection reveals two industries in the US with much higher growth rates in labor productivity in the 1990s: Office, accounting and computing machinery (OAC) (ISIC 30) and Radio, television and communication equipment (RTC) (ISIC 32). The compound annual productivity growth rate for these two industries in 1996–2000 was 31.1 and 20.8 percent, respectively.

In *Table 20* labor productivity is defined as production value per person engaged. Intermediate inputs are not deducted from the production value, which implies double-counting of intermediate inputs. Production value may therefore be a poor measure of output when industry trends are analyzed (Bailey 1986). *Table 21* presents estimates of compound annual productivity growth for different US manufacturing industries in 1990–2003 defined as value added per person employed.[38] *Table 21* confirms the result that the highest productivity growth

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[35] The structural labor productivity growth is defined as labor productivity growth minus the growth which is due to business cycle effects.

[36] In *Table 20* labor productivity is calculated for the period 1980–2000 and is defined as production value per person engaged. The reason is that value added deflators were not available for all industries in the STAN database. In *Table 21* labor productivity is calculated for the period 1990–2003 and labor productivity is defined as value added per person employed. *Table 21* is based on figures from Bureau of Economic Analysis (2004) and Bureau of Labor Statistics (2005).

[37] We define spillovers as increases in labor productivity in the using sectors beyond what one would expect from the capital deepening effect alone. In other words, spillover effects are the contribution to TFP growth in the using sectors resulting from the introduction of the new technology.

[38] The productivity estimates are based on Bureau of Economic Analysis (2004) and Bureau of Labor Statistics (2005). The BEA and BLS use the North American Industry Classification Standard (NAICS) instead of the International Standard for Industry Classification (ISIC) used by OECD (2003b). This implies that the estimates in *Table 20* and *21* cannot be directly compared.

took place in the industry producing computers and communication equipment in 1990–2003. The compound annual productivity growth for Computer and electronic products (NAICS 334) was 26.6 percent in 1996–2003.[39]

TABLE 21 ABOUT HERE

Results for the five European countries show much less evidence of spillovers to the rest of the economy. First, as already shown, there is no detectable increase in aggregate productivity growth compared to the mid 1990s. Second, compared to the US, there is little evidence of spillovers within manufacturing. *Table 22* reports the three industries with the highest rates of labor productivity growth during 1996–2000/01.[40] In France, Sweden and Finland there were two ICT-producing industries that had the highest annual productivity growth. However, for Finland and Sweden OAC (ISIC 30) is not among the three sectors with the highest productivity growth. Instead, electric machinery and apparatus (ISIC 31) had the second highest labor productivity growth in Finland and medical, precision and instruments (ISIC 33) in Sweden.

TABLE 22 ABOUT HERE

In Germany, OAC (ISIC 30) had the highest productivity growth for the period 1996–2000. However, RTC (ISIC 32) ranks only third, with an annual productivity growth of 14.0 percent. For the UK OAC (ISIC 30) holds first place, but there are no data available for electric machinery and apparatus (ISIC 31) and RTC (ISIC 32).

In all European countries investigated, an ICT-producing industry had the highest productivity growth. For Finland, France and Sweden the industry with the second highest growth was also ICT-producing. In Germany RTC had the third highest labor productivity growth. The comparison for the UK is incomplete, because of lack of data for some industries.

5.5 Spillovers to the rest of the economy

Aggregate data show that the US had very high aggregate productivity growth during the second half of the 1990s relative to the preceding twenty-year period. However, more disaggregated data for manufacturing shows that high productivity growth rates were experienced in just a few industries, notably in the ICT-*producing* industries, while

[39] Computer and electronic products (NAICS 334) include computers and communication equipment.

productivity growth in ICT-*using* industries remained at levels similar to previous periods. Gordon (2000) argues that the productivity revival in the US occurred primarily within durable goods production and particularly in the ICT-producing industries. Should we then expect spillover effects to ICT-using industries in manufacturing and non-manufacturing? Evidence from the two earlier breakthroughs suggests that the large productivity gains were not realized until long after the introduction of the new GPT.

David (2001) points out that the increase in TFP growth in the US in the 1920s was very evenly distributed across industries. In contrast, it appears that most of the productivity growth during the 1990s was very unevenly distributed across industries, most of it taking place in ICT-producing industries. Harberger (1998) makes a distinction between a "yeast-like" process of growth characterized by evenly distributed growth throughout most of the economy and a "mushroom-like" process with productivity growth in just a few sectors. David (2001) argues that the patterns of TFP growth were starting to move from a "mushroom-like" process to a "yeast-like" process in the late 1990s.

Recent studies of productivity performance and ICT suggest that ICT has had substantial impact on productivity in a wide range of different industries and not only in the ICT-producing industries. Stiroh (2002) and Van Ark *et al*. (2002) distinguish between ICT-producing industries, intensive ICT-using industries and less intensive ICT-using industries.[41] Stiroh (2002) finds that in the US, the ICT-producing and the intensive ICT-using industries accounted for all of the productivity revival (after 1995) that can be attributable to the direct contributions from specific industries. Oliner and Sichel (2000) also attribute a crucial role to the manufacture of computers, but they do not find that it accounts for all of the productivity increase. They estimate that use of ICT equipment together with improved production technology for computers account for approximately two-thirds of the increase in productivity growth in the US.[42]

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[40] Information for Finland and Sweden is from 1996–2001 and for the UK from 1996–1999.

[41] Stiroh (2002) defines an intensive ICT-using industry as an industry with above median ICT share of capital services in 1995. Van Ark *et al*. (2002) largely base their distinction of ICT intensive and less ICT intensive industries on the definition provided by Stiroh (2002).

[42] As pointed out in section III the growth accounting framework used by Oliner and Sichel includes the portion of the effect of capital deepening on labor productivity that is the consequence of the accumulation of particular ICT capital goods. Field (2006a) argues that this is problematic since capital would have been accumulated in slightly inferior capital goods in the absence of ICT. Moreover, the growth accounting approach does not take spillover effects into account. Nevertheless, according to Oliner and Sichel (2000) TFP growth in computer production and computer related semiconductor production alone accounts for one fourth of the increase in labor productivity growth 1996–99 compared to 1991–95.

Europe lags the US in terms of productivity growth. Still, it appears as though productivity growth has increased in the ICT-producing industries also in Europe even though the pattern is somewhat different. Within manufacturing RTC (ISIC 32) has had astounding productivity growth in several countries, while computer manufacturing played a larger role in the US. The phenomenal growth in RTC is particularly pronounced in Sweden and Finland.

Which sectors have accounted for increased productivity growth noticeable at the macro level in the US and why has not aggregate productivity growth increased in Europe? It appears that parts of the economy outside of manufacturing in the US have had a higher increase in productivity than corresponding sectors in Europe. McKinsey Global Institute (2001) maintains that the greater part of the increase in productivity in the US economy is concentrated in three sectors in addition to the ICT sector (semiconductors included): retail trade, wholesale trade and financial services.

Table 23 shows that both the US and most EU countries experienced rapid increases in labor productivity in ICT-producing industries. According to van Ark *et al.* (2002) the contribution of these industries to aggregate productivity growth was slightly lower in the EU compared to the US. Moreover, the largest difference appears to have taken place in ICT-using services. According to Van Ark *et al.* the differential between the US and Europe is heavily caused by different productivity development in retailing, wholesale trade and financial Services. Estimates show that 0.90 percentage points out of a total productivity growth differential of 1.1 percentage points between the US and Europe in the late 1990s emanated from these industries.

TABLE 23 ABOUT HERE

Table 23 also shows that ICT-producing manufacturing and the ICT-using service sector were larger in the US compared to the EU, measured as a share of GDP. The ICT-producing manufacturing sector had a share of 2.6 percent of total GDP in the US compared to 1.6 percent in the EU. The ICT-using service sector share of total GDP was 26.3 percent in the US compared to 21.1 percent in the EU. Thus, the sectors where productivity growth increased most during 1995–2000 were relatively larger in the US.

5.6 Concluding remarks on the ICT revolution

The transistor was invented in the late 1940s, but computers and cellular phones did not become consumer products until the 1980s. Aggregate labor productivity growth increased in the US in the latter part of the 1990s. However, aggregate labor productivity growth did not increase to the same extent in the EU countries. Nonetheless, labor productivity growth was much faster in the ICT-*producing* industries compared to ICT-*using* industries for the US and for the five European countries that we have investigated for the period 1996–2001. Moreover, the aggregate productivity gap between the US and the EU was mainly due to productivity differences in retailing, wholesale trade and financial services. One possible reason for this could be that the US has been faster than Europe in implementing institutional and political changes that facilitate the exploitation of the economic potential of the new GPT (Litan and Rivlin 2001).

6. Summary and conclusions

We have examined three technological breakthroughs and the development of subsequent productivity growth. We will now summarize and draw some conclusions from our investigation. Moreover, we discuss some measurement issues concerned with comparing productivity growth in different countries and for different time periods.

6.1 Patterns of productivity growth after major technological breakthroughs

When comparing technological breakthroughs it is important to keep in mind that every new technology has unique characteristics. Few technologies fulfill the requirements for being classified as a GPT or TEP. The three technological breakthroughs investigated here are different from each other. The interdependence between different technologies can also be highly complex. For example, electricity replaced the steam engine in the industrial production process, but the steam engine was also important initially as a primary source for producing electricity. Furthermore, the ICT revolution presupposed the existence of an extensive electricity network. These examples imply that technological breakthroughs cannot be analyzed solely as individual cases.

We have shown that some major technological breakthroughs have impacted importantly on productivity growth in manufacturing, but also on aggregate productivity. It also appears that the impact of different key technologies has differed substantially across countries and industries. However, one major similarity for all three technological breakthroughs is that the productivity effects took place a considerable time after the initial innovation. David (1990, 1991) argues that when considering technological paradigm shifts, with the potential to create the core of a new technological regime, a time scale of 40–50 years may be necessary for the full impact of productivity growth to become evident in the conventional indicators. Our findings for the steam engine and the ICT revolution support David’s view. However, it took much longer from the time when the steam engine was invented until it had an impact on productivity growth (some 140 years) than for the electricity breakthrough and the ICT revolution, where 40–50 years elapsed before increases in manufacturing productivity growth rates could be observed. These findings suggest that it is not the technological invention that directly affects growth, but rather the additional innovations made to improve the new technology that is important for productivity growth (this will be discussed further below). Why does the process of additional innovation take so long? And what is the character of these innovations?

Even though there are similarities between the productivity pattern following major technological breakthroughs, there are also important differences among them. The steam engine did not have a substantial impact on aggregate productivity growth in the UK until the 1850s, i.e. 140 years after Newcomen’s original invention. The steam engine was not adopted by all sectors in the economy, but it was intensely used in a few key industries such as textile, coal mining and transportation. These industries also appear to have had a higher than average productivity growth (McCloskey 1981; Harley 1993). There is no clear evidence that the productivity growth associated with the steam engine in the UK took place in the industries *producing* the new technology. However, even though there are no direct statistical observations of high productivity growth in the steam engine producing industry, the price of steam power decreased substantially around 1850. This is a strong indirect indication of high productivity growth in the steam engine producing industry.

Both quantitative and qualitative studies have provided evidence that electrification had a substantial but delayed influence on productivity growth in US manufacturing. Moreover, there was an increase in productivity in the electricity-producing sector. However, increased productivity growth was not discernible in the sector producing electric machinery. Kendrick (1961) suggests that compound annual TFP growth was 3.5 percent per year in the industry producing electric machinery in the 1919–1929 period, while manufacturing as a whole had a TFP growth of 5.1 percent p.a. during that period. This suggests that the productivity effects took place in sectors *using* electric machinery rather than in sectors *producing* it.

David (1991) pointed out the relationship between increases in the rate of productivity growth and investments in electric motors. The same results cannot be found for Sweden. Moreover, even if there were substantial investments made in machinery with electric motors there was no substantial productivity increase in this particular industry. This is a major difference compared to the ICT revolution, where productivity increased by far the most in ICT-producing industries**.** In section 4 it was shown that there was a substantial fall in real prices of electric motors during the period 1919–1929. Unlike the ICT revolution there are no consistent hedonic price indices for the periods covering earlier technological breakthroughs, which suggests that the productivity effects from earlier technological breakthroughs may be underestimated.

For the ICT revolution we have seen large increases in the productivity growth for the sector *producing* ICT technology during the 1990s. However, it has not been possible to find evidence of spillover effects to other manufacturing industries. One of the reasons for the high labor productivity growth for the ICT-producing industries could be that hedonic price indices are used when deflating the value added for these industries. Still, this cannot be the whole explanation, since there are some countries with high productivity growth in the ICT-producing industries that do not use hedonic price indices, i.e. Finland, Germany, and the UK.[43] Despite the productivity increase in the ICT-producing industries it is only in the US that aggregate productivity growth has been at a significantly higher level compared to earlier periods. The increase in the productivity growth differential between the US and the EU in 1995–2000 can mostly be explained by differential productivity growth in retailing, wholesale trade and financial services.

Another interesting point is the difference between the intensity of ICT use among ICT-using sectors. The major difference in productivity growth between the EU and the US has arisen in service industries with a high ICT intensity. Evidence from the steam engine revolution suggests that the industries using steam power technology intensely were those that had the highest productivity growth increases. The same pattern was observed for the US economy during electrification; productivity growth increases took place disproportionately in sectors that increased their use of electric motors in the production process.

6.2 Measurement errors

For the six countries studied we have shown that a large share of aggregate productivity growth in manufacturing during the latter half of the 1990s occurred in ICT-*producing* industries. A crucial assumption behind this result is that there are no systematic measurement errors.

[43] Hedonic price indices are thoroughly discussed below.

However, there are a number of problems with measuring production and productivity and these problems are likely to have increased in recent decades.[44]

First, most countries in our investigation use double deflation to arrive at value added in fixed prices. Double deflation implies that the value of gross output and intermediate inputs are deflated separately with an output price index and an intermediate input price index, respectively. However, Finland has not introduced double deflation in their national accounts, which implies that inputs are not deflated separately. If double deflation were introduced in the Finnish national accounts, productivity for different industries would change. This especially holds for industries that are using inputs with rapidly shifting prices, like ICT products. Output of the ICT-producing industry is largely an input for other industries. This implies that the deflation of production value and value added in the ICT-producing industry greatly affects the distribution of productivity growth between ICT-producing and ICT-using industries.

Second, it is almost impossible to construct completely true deflators for the ICT sector (Brynjolfsson and Hitt 2000), where technology changes rapidly. Nordhaus (1997) argues that capturing the impact of new technologies on living standards is beyond the practical ability of official statistical agencies. The quality of the goods that we consume today is much higher compared to the quality of “the same” goods a decade ago. Countries use different methods to account for the rapid quality changes that take place. Sweden, the US, and France – but not Finland, Germany and the UK – use hedonic price indices for some of the ICT products. This has so far resulted in larger estimated quality improvements and thus volume increases (Pilat and Lee 2001).

Different methods for capturing quality improvements can have a large effect on productivity. Edquist (2005b) shows that productivity levels in the ICT-producing industry in Germany, Sweden, and the US change substantially depending on which country’s value added price deflator that are used. Since there are no consistent hedonic price indices for the industries producing steam engines and electric machinery, it is likely that if quality adjustments had been made for their output, recorded productivity growth would have been higher for those industries as well.

Edquist (2005a) constructs hedonic and matched model price indices for electric motors in Sweden for the period 1900–35. He finds that during the 1920s, PPI-deflated hedonic and

[44] This problem was noticed by the so-called Boskin Commission (see Boskin *et al*. 1997), which calculated that the annual inflation rate in the US during the preceding quarter-century was overestimated by slightly more than

matched model price indexes decreased by 4.8 and 3.7 percent per year, respectively. This is a strong indication of high productivity growth in the industry producing electric motors in 1919–29. Moreover, the difference between the hedonic and matched model price indices is only 1.1 percentage points. One reason for this is that the same quality characteristics are used for the hedonic and matched model price indices, i.e. speed, power and maximum voltage. It is likely, that productivity growth in electric machinery would have been considerably lower if these quality aspects were not taken into account.

Third, the recent technological shift has given rise to enormous intangible investments in new business and production systems, personnel training, etc. Brynjolfsson and Yang (1997) estimate that each dollar invested in computer hardware is associated with intangible investments of 10 dollars. These intangible investments are usually treated as current costs and not as investments, which reduces value added and the growth rate (in the medium term).

Fourth, an increasing share of production consists of services where deflation is often more difficult than for goods, since a larger share of the value depends on intangible characteristics (degree of accessibility, customer adaptation, delivery time, etc.). Van Ark and Smits (2002) argue that new product applications based on electricity were mainly concentrated to manufacturing, while the real challenge for ICT is to change the production processes in services. Research on the finance and health care sectors in the US has shown that measurement problems have led to underestimates of productivity growth (e.g., Cutler 2004).[45] Thus, there are measurement problems that can cause both an underestimate of aggregate productivity growth, and an overestimate of increases in ICT production.

6.3 Concluding remarks

Our empirical investigation of three different technological breakthroughs suggests that it takes a long interval from the time of the original invention until a substantial increase in the rate of productivity growth can be observed. For the steam engine this period was about 140 years (85 years if the Watt steam engine is treated as the original innovation), while it was around 40–50 years for electrification and the ICT revolution. On the other hand, if we consider the high-pressure steam engine as the innovation that paved the way for the real steam engine

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one percentage point.

[45] Intuitively it is easy to understand that it can be particularly difficult to discriminate between price increases and volume in health care. When a new, more expensive drug replaces an existing drug, how should the cost increase be divided between increased effectiveness and increased prices? Perhaps the improved effectiveness is so great that there is actually a decrease in price, or the improvement is so marginal that almost all of the cost increase should be treated as a price increase.

revolution, then the time lag from innovation to greater rates of productivity growth is no longer for the steam engine than for the two subsequent technologies that we examine.

From the theoretical literature on GPTs as well as from our investigation it seems as though both *innovational complementarities* and *technological dynamism* are crucial for productivity growth. This implies, that an invention by itself would have little effect on an economy if there is no scope for the users of the new technology to improve their own technologies, and if continuous innovational efforts would not increase the efficiency by which the generic function is performed. For example, innovations that made the steam engine more efficient had to occur before it was introduced in the industrial production process. Moreover, before electricity could be used in manufacturing several types of electric machines had to be invented.

A further explanation for the delayed productivity effects is that it takes time to develop organizational innovations, i.e. systems that permit organizations to use new technology efficiently. At first the new technology may often just be performing the same function as the old technology, and in this process a great deal of existing productive capital will be "creatively destroyed" which further tends to delay the point where positive productivity effects at the more aggregate level can be observed (Greenwood 1997). Political decisions may also be called for before the full potential of the new GPT can be reaped. There may be strong vested interests tied to the old GPT, which manage to block reforms that would facilitate the deployment of the new GPT.

Concerning the pattern of productivity growth after major technological breakthroughs we find evidence of rapid price decreases for steam engines, electricity, electric motors, and ICT products. This indicates rapid productivity growth in the industries producing the new technology. However, we cannot find strong direct evidence that the steam engine producing industry and electric machinery had particularly high productivity growth rates. For the ICT revolution the highest productivity growth rates has been found for the ICT-producing industry. There is thus no clear evidence of any particular productivity growth pattern after major technological breakthroughs. We argue that one explanation for the high productivity growth rates in the ICT-producing industries could be that no hedonic price indexes were used for the steam engine and the electric motor. Further research is called for to investigate the impact on productivity growth if hedonic price indexes are used for steam engines or electric motors. Another explanation could be that the technological development of semiconductors and integrated circuits could not be matched by the steam engine or the electric motor. There is simply no equivalent to “Moore’s law” for other technological breakthroughs than the ICT revolution.

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Tables and figures

Table 1 Crude estimates of steam power capacity in different countries 1840–1896 (thousands of horsepower)

Countries	*Thousands of Horsepower*							*Annual growth rate*	*Per 100 inhabitants*
	1840	*1850*	*1860*	*1870*	*1880*	*1888*	*1896*	*1840–1896*	*in 1896/97*
Austria	20	100	333	800	1,560	2,150	2,520	9.0	6
Belgium	40	70	160	350	610	810	1,180	6.2	18
Denmark	n.a.	n.a.	10	30	90	150	260	n.a.	11
France	90	370	1,120	1,850	3,070	4,520	5,920	7.8	15
Germany	40	260	850	2,480	5,120	6,200	8,080	9.9	15
Italy	10	40	50	330	500	830	1,520	9.4	5
Netherlands	n.a.	10	30	130	250	340	600	n.a.	12
Norway	n.a.	n.a.	10	40	90	180	410	n.a.	20
Portugal	n.a.	n.a.	10	30	60	80	170	n.a.	3
Russia	20	70	200	920	1,740	2,240	3,100	9.4	3
Spain	10	20	100	210	470	740	1,180	8.9	7
Sweden	n.a.	n.a.	20	100	220	300	510	n.a.	10
Switzerland	n.a.	n.a.	90	140	230	290	580	n.a.	19
UK	620	1,290	2,450	4,040	7,600	9,200	13,700	5.7	34
US	760	1,680	3,470	5,590	9,110	14,400	18,060	5.8	25
The World	1,650	3,990	9,380	18,460	34,150	50,150	66,100	6.8	n.a

Note: The steam power capacity figures include capacity of fixed, railway and shipping steam power. The figures of steam power per 100 inhabitants are based on steam power capacity in 1896 and population figures in 1897. n.a. = not available.

Source: Mulhall (1899) and authors' calculations.

Table 2 Growth during the British industrial revolution, 1760–1913 (percent p.a.)

Crafts	*Output*	*Capital stock*	*Labor force*	*Labor productivity*	*TFP*
1760–1780	0.6	0.25	0.35	0.25	0.0
1780–1831	1.7	0.6	0.8	0.9	0.3
1831–1873	2.4	0.9	0.75	1.65	0.75
1873–1899	2.1	0.8	0.55	1.65	0.75
1899–1913	1.4	0.8	0.55	0.85	0.05
Feinstein					
1760–1780	1.1	0.5	0.4	0.7	0.2
1780–1831	2.7	0.7	0.7	2.0	1.3
1831–1860	2.5	1.0	0.7	1.8	0.8

Note: Weights: Crafts: capital 0.4, labor 0.6; Feinstein: capital 0.5, labor 0.5.

Sources: Crafts (2002; 2004).

Table 3 The contribution of steam technology to British labor productivity growth, 1760–1910 (percent p.a.)

	1760–1800	1800–30	1830–50	1850–70	1870–1910
Stationary Steam engines					
Capital deepening	*0.004*	*0.02*	*0.02*	*0.06*	*0.09*
TFP	*0.005*	*0.001*	*0.02*	*0.06*	*0.05*
Total	0.01	0.02	0.04	0.12	0.14
Railways					
Capital deepening	–	–	*0.14*	*0.12*	*0.01*
TFP	–	–	*0.02*	*0.14*	*0.06*
Total	–	–	0.16	0.26	0.07
Steamships					
Capital deepening	–	–	–	*0.02*	*0.05*
TFP	–	–	–	*0.01*	*0.05*
Total	–	–	–	0.03	0.1
Total Steam Technology	**0.01**	**0.02**	**0.20**	**0.41**	**0.31**

Note: The total steam technology contribution is based on the combined impact of capital deepening and TFP growth from stationary steam engines, railways and steamships.

Source: Crafts (2004).

Table 4 Steam power by industry in the UK, 1800–1907

	1800		*1870*		*1907*	
Industry	Number of engines	%	Steam HP (power in use)	%	Steam HP (power in use)	%
Mining	1,064	48.6	360,000	26.2	2,415,841	26.5
Textiles	469	21.4	513,335	37.4	1,873,169	20.5
Metal manufactures	263	12.0	329,683	24.0	2,165,243	23.7
Food and drink trades	112	5.1	22,956	1.7	266,299	2.9
Paper manufactures	13	0.6	27,971	2.0	179,762	2.0
Building trades	12	0.6	17,220	1.3	347,647	3.8
Chemicals	18	0.8	21,400	1.6	182,456	2.0
Public utility (water-works, canals, etc.)	80	3.7	36,000	2.6	1,379,376	15.1
Others	160	7.3	44,375	3.2	309,025	3.4
Total	**2,191**	**100**	**1,372,940**	**100**	**9,118,818**	**100**

Source: Nuvolari and Castaldi (2003).

Table 5 Crude estimates of annual total factor productivity growth for different UK industries, 1780–1860

	McCloskey	*Harley*
Cotton	2.6	1.9
Worsteds	1.8	1.3
Woolens	0.9	0.6
Iron	0.9	0.9
Canals and Railways	1.3	1.3
Shipping	0.5	0.5
Agriculture	0.4	0.7
All others	0.02	0.02

Sources: McCloskey (1981) and Harley (1993).

Table 6 Available horsepower capacity in US manufacturing, 1869–1954 (thousand horsepower)

Year	*Total primary capacity*	*Non-electric capacity*	*Primary Electric motors*	*Secondary electric motors*
1869	2,346	2,346		
1879	3,411	3,411		
1889	5,845	5,845		16
1899	9,811	9,633	178	297
1904	13,033	12,605	428	1,089
1909	18,062	16,393	1,669	2,913
1914	21,565	17,858	3,707	4,684
1919	28,397	19,432	8,965	6,647
1923	32,667	19,426	13,241	8,796
1925	34,359	19,243	15,116	9,976
1927	38,236	19,336	18,900	11,201
1929	41,122	19,328	21,794	12,050
1939	49,893	21,077	28,816	16,011
1954	110,181	35,579	74,602	19,514

Note: Primary electric motors are those driven by purchased electricity. Secondary motors are driven by self-generated electricity and are excluded from total primary power available.

Source: Du Boff (1979).

Table 7 Degree of electrification in six industry groups: Britain and the US, 1904–1924 (percent)

Industry		*1904*	*1907*	*1909*	*1912*	*1919*	*1924*
Cotton textile	UK		5†		6		18
	US	7		19		53	
Iron and steel	UK		8		22		46
	US	12		25		46	
Engineering, shipbuilding	UK		43		74		92
and vehicles	US	32		65		72	
Chemicals and allied	UK		19		31		66
	US	16		42		59	
Coal mining	UK		4‡		20		43
	US	n.a.		20		53	

Note: †All textiles, ‡All mining

Source: Byatt (1979).

Table 8 Electric motor capacity in different Swedish industries (horsepower) and percentage change, 1913–1931

	Electric motor capacity			*Percentage change*		
Industry	*1913*	*1920*	*1931*	*1913–1920*	*1920–1931*	*1913–1931*
Ore-mining and metal industries	158,984	384,699	582,253	142	51	266
Non-metallic mining and quarrying	22,470	56,252	92,535	150	65	312
Wood and cork	27,632	79,292	152,428	287	92	452
Paper and paper products, printing and allied industries	134,355	225,460	580,674	68	158	332
Food manufacturing industries	28,152	64,505	132,365	129	105	370
Textiles, wearing apparel and made-up textile goods	34,708	63,988	98,019	84	53	182
Leather, furs and rubber products	6,165	15,663	26,342	154	68	327
Chemicals and chemical products	13,134	31,691	45,033	141	42	243
Power, lighting and waterworks	6,095	17,461	22,916	186	31	276
Total	**431,695**	**939,011**	**1,732,565**	**118**	**85**	**301**

Note: The percentage change refers to the whole period, not percent p.a.

Source: Hjulström (1940).

Table 9 **Compound annual growth rates of labor and total factor productivity in the US private non-farm economy, 1889–1948**

Period	*Labor productivity*	*TFP*
1889–1901	2.9	2.2
1901–19	1.7	1.1
1919–29	2.3	2.0
1929–41	2.4	2.3
1941–48	1.7	1.3

Note: Labor productivity is defined as output per manhour. LP = labor productivity; TFP = total factor productivity.

Source: Kendrick (1961) and authors' calculations.

Table 10 **Compound annual growth rates of labor and total factor productivity in US manufacturing, 1889–1948**

Period	*Field*		*Period*	*Kendrick*	
	LP	TFP		LP	TFP
			1889–99	1.4	1.1
			1899–1909	1.3	0.7
1889–1919	1.3	0.7	1909–19	1.1	0.3
1919–29	5.5	5.1	1919–29	5.5	5.1
1929–41	2.6	2.6	1929–37	2.0	1.5
1941–48	0.2	–0.5	1937–48	1.5	1.7

Note: Labor productivity is defined as output per manhour.

Sources: Field (2006b), Kendrick (1961) and authors' calculations.

Table 11 **Electric motor capacity/total primary capacity in US manufacturing, 1899–1954 (percent)**

Period	*Electric motor capacity /total primary capacity*
1899	1.9
1904	3.3
1909	9.2
1914	17.2
1919	31.6
1923	40.5
1925	44.0
1927	49.4
1929	53.0
1939	57.8
1954	67.7

Source: Du Boff (1979).

Table 12 Compound annual growth rates of labor and total factor productivity in US manufacturing, 1899–1937

Industry	***1899–1909***		***1909–1919***		***1919–1929***		***1929–1937***	
	LP	TFP	LP	TFP	LP	TFP	LP	TFP
Food	0.6	0.3	0	–0.4	5.2	5.2	0.9	1.5
Beverages	1.3	0.9	–6.6	–5.8	0.5	–0.2	13.5	14.1
Tobacco	1.7	1.2	5.9	4.8	7.0	4.3	7.3	6.1
Textiles	1.4	1.1	1.7	0.9	2.4	2.9	4.3	4.5
Apparel	0.9	0.7	3.3	2.7	3.9	3.9	2.1	2.5
Lumber products	–0.2	–0.4	–1.0	–1.2	2.9	2.5	–0.2	0.4
Furniture	–0.7	–0.8	–0.4	–0.5	4.2	4.1	0.3	0.5
Paper	3.0	2.4	0.5	0.3	4.9	4.5	4.4	4.2
Printing, publishing	3.9	3.8	3.2	3.0	3.7	3.7	2.6	2.6
Chemicals	1.3	0.6	–0.3	–0.7	7.9	7.2	3.0	3.0
Petroleum, coal products	3.0	0.7	1.8	–1.0	8.6	8.2	5.5	2.7
Rubber products	2.5	2.2	7.6	7.1	8.1	7.4	3.4	3.9
Leather products	0.5	0.1	0.9	0.5	2.5	2.9	3.2	3.5
Stone, clay, glass	2.7	2.2	1.0	0.7	6.1	5.6	1.7	2.2
Primary metals	3.7	2.6	–0.4	–0.5	5.6	5.4	–0.9	–1.3
Fabricated metals	2.8	2.3	2.0	1.8	5.0	4.5	0.5	1.0
Machinery, nonelectric	1.8	1.0	0.7	0.7	2.9	2.8	1.9	2.2
Electric machinery	1.3	0.6	0	0.3	3.9	3.5	2.8	3.1
Transportation equipment	1.3	1.1	7.4	6.8	8.7	8.1	–0.2	–0.4
Miscellaneous	1.1	0.8	–0.6	–0.6	5.3	4.5	2.2	2.8
Total Manufacturing	**1.3**	**0.7**	**1.1**	**0.3**	**5.4**	**5.1**	**2.0**	**1.9**

Note: Labor productivity is defined as output per manhour. LP = labor productivity; TFP = total factor productivity.

Source: Kendrick (1961) and authors' calculations

Table 13 Compound annual growth rate of labor productivity in different German industries, 1925–38

Industry	*1925–1929*	*1929–1938*	*1925–1938*
Stone and soil production	6.2	–1.9	0.6
Metal producing industry†	6.6	–0.3	1.8
Metal processing industry†	8.1	1.3	3.4
Chemical industry	6.7	4.1	4.9
Textiles	–0.8	3.5	2.2
Leather production	0.4	1.3	1.0
Clothing industry	–2.4	4.9	2.7
Wood products	0.8	0.9	0.8
Paper products	4.5	0.7	1.9
Food production	1.2	1.4	1.3
Gas, water and electricity	4.5	2.2	2.9
Construction††	–1.6	2.5	1.3
Total	**2.8**	**2.4**	**2.5**

Note: Labor productivity is defined as output per worker. †Employment was only available for the total metal producing and processing industry. It is therefore assumed that the change in employment was the same in these industries in 1925–38. ††Labor productivity estimates for Construction are for the 1926–38 period.

Source: Hoffmann (1965) and authors' calculations.

Table 14 Compound annual growth rate of labor productivity in different Swedish industries, 1913–39

Industry	*1913–1919*	*1919–1929*	*1929–1939*
Ore-mining and metal industries	–2.8	4.3	2.5
Non-metallic mining and quarrying	–3.7	4.7	4.6
Wood and cork	0	0.3	1.0
Paper and paper products, printing and allied industries	–2.2	4.4	2.6
Food manufacturing industries	–0.1	3.0	1.8
Textiles, wearing apparel and made-up textile goods	–1.0	1.7	0.8
Leather, furs and rubber products	–2.8	0.1	0.8
Chemicals and chemical products	–6.3	11.2	3.8
Power, lighting and waterworks	–0.4	7.7	4.9
Total	**–1.7**	**3.8**	**2.0**

Note: Labor productivity is defined as value added per worker.

Sources: Schön (1988), Kommerskollegium (1913–39) and own calculations.

Table 15 Price series of electric motors produced by Luth&Rosén, 1919–1929 (SEK/horsepower)

No of hp Model	3 hp C20	5 hp C21	7.5 hp C50	10 hp C51	15 hp C80	Index‡	CPI	Real index
1919	335	250	232	189	160	100	100	100
1920	319	237	215	175	148	93.5	100.4	93.2
1921	195	143	128	106	89	56.4	86.2	65.4
1922	157	114	100	84	53	42.6	69.8	61.1
1923	110	78	71	58	47	30.9	64.9	47.6
1924	122	86	74	63	48	33.3	64.9	51.3
1925	103	71	54	49	39	26.6	66.0	44.8
1926	103	71	54	49	39	26.6	63.8	41.7
1927	125	86	67	60	48	32.5	63.1	51.5
1928	112	78	61	53	44	29.3	63.4	46.2
1929	111	77	60	54	45	29.3	62.7	46.7

Note: ‡The index is an equally weighted price index of the 5 engines presented in the table above. All motors had the following characteristics: Alternating current, 1500 revolutions per minute, 190–500 V.

Sources: Ljungberg (1990), Myrdal (1933), Johansson (1967) and authors' calculations.

Table 16 Labor productivity growth in Electric machinery in Sweden, 1913–35 (percent p.a)

Year	***Growth rate***	
	Hedonic deflation	Matched model deflation
1913–1919	–7.2	–4.2
1920–1929	12.1	10.8
1930–1935	–2.5	–2.0
1913–1935	3.0	3.8

Note: Labor productivity is defined as production value per person employed.

Source: Edquist (2005a)

Table 17 ICT-producing industries in manufacturing

ISIC 3rd revision	*Economic activity*
30	Office, accounting and computing machinery
3130	Insulated wire and cable
3210	Electronic valves and tubes and other electronic components
3220	Television and radio transmitters and apparatus for line telephony and line telegraphy
3230	Television and radio receivers, sound or video recording or reproducing apparatus and associated goods
3312	Instruments and appliances for measuring, checking, testing, navigating and other purposes, except industrial process equipment
3313	Industrial process equipment

Source: OECD (2002b).

Table 18 Average annual growth of GDP per person employed in selected countries, 1980–2001 (labor productivity)

Country	*1980–89*	*1990–95*	*1996–2001*
Finland	2.5	2.5	1.9
France	2.1	1.3	1.4
Germany	n.a.	2.2	1.6
Sweden	1.6	2.5	1.9
UK	2.2	2.0	1.6
US	1.5	1.2	2.1
EU–15	1.8	2.0	1.3

Note: Calculations for Germany use growth figures beginning in 1992 due to the reunification with East Germany in 1990 and 1991. Figures for the period 1980–1995 have been taken from Scarpetta *et al* and figures for the period 1996–2001 are based on OECD (1998), OECD (2000), OECD (2002a) and OECD (2003a). n.a. = not available

Sources: Scarpetta *et al*. (2000), OECD (1998), OECD (2000), OECD (2002a) and OECD (2003a).

Table 19 Average annual growth rates of labor productivity and TFP in the US, 1973–2001

	1973–1995	*1995–2001*	*Change (percentage points)*
Labor productivity growth rate (percent)	1.39	2.60	1.21
– Business cycle effect	0.02	–0.46	–0.48
= Structural labor productivity	1.37	3.07	1.70
– Capital services	0.72	1.29	0.57
– Labor quality	0.27	0.31	0.04
= Structural TFP	0.37	1.44	1.07

Note: Labor productivity is the average of income- and product-side measures of output per hour worked. TFP is labor productivity less the contributions of capital services per hour (capital deepening) and labor quality. Productivity for 2001 is inferred from data for the first three quarters.

Source: Council of Economic Advisers (2002).

Table 20 Compound annual growth rates of labor productivity in different US manufacturing industries, 1980–2000

Industry	*ISIC*	*1980–89*	*1990–95*	*1996–2000*
Food products and beverages	15	2.7	1.7	1.9
Tobacco products	16	1.5	4.3	0.3
Textiles, textile products, leather and footwear	17–19	2.6	4.0	5.5
Wood and products of wood and cork	20	2.0	–0.2	0.7
Paper and paper products	21	2.5	1.9	1.7
Publishing and printing	22	1.1	–0.3	1.5
Coke, refined petroleum products and nuclear fuel	23	2.7	2.7	3.4
Chemicals and chemical products	24	3.2	2.0	2.5
Rubber and plastic products	25	4.0	2.9	3.3
Other non-metallic mineral products	26	2.4	1.7	1.8
Basic metals	27	2.9	3.5	1.3
Fabricated metal products excl. machinery and equipment	28	1.9	2.4	1.9
Machinery and equipment	29–33	5.2	9.2	10.6
Machinery and equipment, n.e.c.	29	n.a.	3.5	1.7
Office accounting and computing machinery	30	n.a.	24.3	31.1
Electric machinery and computing	31	n.a.	5.7	3.0
Radio, television and communication equipment	32	n.a.	18.3	20.8
Medical, precision and optical instruments	33	n.a.	4.2	3.7
Motor vehicles, trailers and semi-trailers	34	4.4	2.7	3.9
Other transport equipment	35	0.9	0.8	3.5
Manufacturing and recycling n.e.c.	36–37	1.7	2.0	2.9
Total manufacturing	**15–37**	**2.9**	**3.7**	**4.5**

Note: Labor productivity is defined as production value per person engaged.

Source: OECD (2003b) and authors' calculations.

Table 21 Compound annual labor productivity growth in different US manufacturing industries, 1990–2003

Industry	*NAICS*	*1990–95*	*1996–2003*
Food, beverage and tobacco products	311–312	4.0	–0.3
Textile mills and textile product mills	313–314	4.0	3.0
Apparel, leather and allied products	315–316	3.5	10.2
Wood products	321	–3.6	1.2
Paper products	322	0.8	1.1
Printing and related support activities	323	–0.2	1.0
Petroleum and coal products	324	6.6	3.2
Chemical products	325	2.3	3.8
Plastics and rubber products	326	3.7	4.0
Nonmetallic mineral products	327	3.8	2.5
Primary metals	331	3.8	3.5
Fabricated metal products	332	3.1	1.5
Machinery	333	–0.8	2.7
Computer and electronic products	334	19.1	26.6
Electric equipment, appliances and components	335	3.0	4.9
Motor vehicles, bodies and trailers, and parts	3361–3363	4.3	5.1
Other transport equipment	3364–3366, 3369	–2.2	1.8
Furniture and related products	337	2.0	–1.6
Miscellaneous manufacturing	339	1.3	3.6
Total manufacturing	**31–33**	**4.1**	**5.8**

Note: Labor productivity is defined as value added per person employed.

Sources: Bureau of Economic Analysis (2004) and Bureau of Labor Statistics (2005)

Table 22 The three manufacturing industries with the highest compound annual growth rate of labor productivity growth in five European countries 1996–2000/01

Country	*ISIC*	*Growth*
Finland		
Radio, television and communication equipment	32	19.9
Electric machinery and apparatus	31	6.0
Basic metals	27	4.2
France		
Office accounting and computing machinery	30	21.2
Radio, television and communication equipment	32	19.9
Motor vehicles, trailers and semi-trailers	34	10.5
Germany		
Office accounting and computing machinery	30	18.0
Coke, refined petroleum products and nuclear fuel	23	16.9
Radio, television and communication equipment	32	14.0
Sweden		
Radio, television and communication equipment	32	25.0
Medical, precision and optical instruments	33	12.1
Motor vehicles, trailers and semi-trailers	34	6.3
UK		
Office accounting and computing machinery	30	7.5
Motor vehicles, trailers and semi-trailers	34	3.8
Other transport equipment	35	2.7

Note: Labor productivity is defined as value added per person engaged. Figures for Sweden and Finland cover the 1996–2001 period. Figures for Germany and France cover 1996–2000 period and figures for the UK are for the 1996–1999 period. For the UK labor productivity is defined as value added/per person employed.

Source: OECD (2003b) and authors’ calculations.

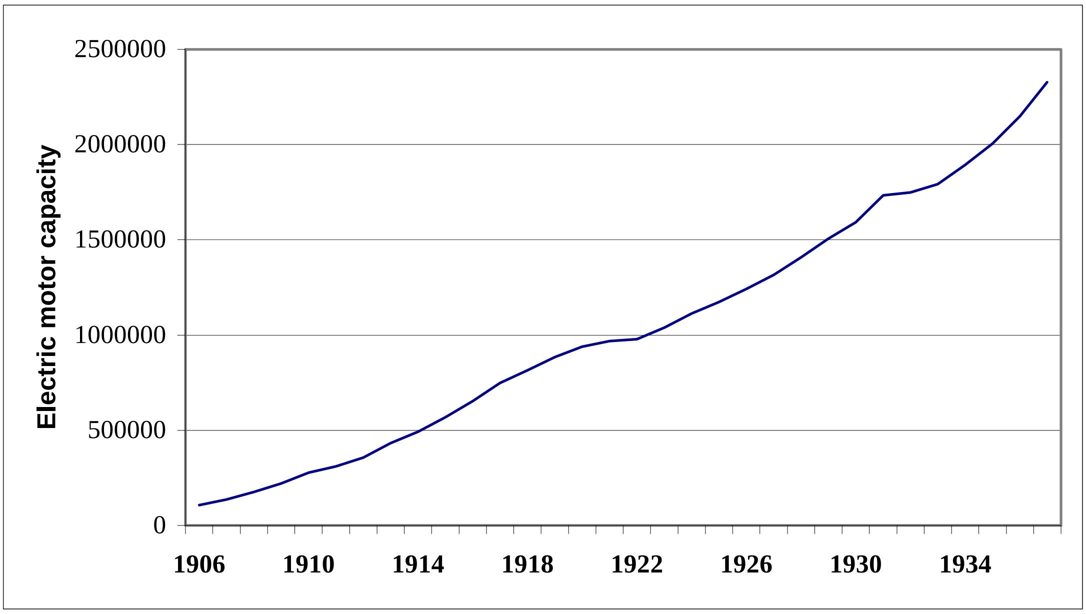
Table 23 Annual labor productivity growth of ICT-producing, ICT-using and non-ICT industries in the EU and the US, 1990–95 vs. 1995–2000 (percent)

	Productivity growth				*GDP share*	
	United States		EU		2000	
	1990–1995	1995–2000	1990–1995	1995–2000	EU	US
Total Economy	1.1	2.5	1.9	1.4	100	100
ICT-producing industries	8.1	10.1	6.7	8.7	5.9	7.3
…ICT-producing Manufacturing	15.1	23.7	11.1	13.8	1.6	2.6
…ICT-producing Services	3.1	1.8	4.4	6.5	4.3	4.7
ICT-using Industries†	1.5	4.7	1.7	1.6	27.0	30.6
…ICT-using Manufacturing	–0.3	1.2	3.1	2.1	5.9	4.3
…ICT-using Services	1.9	5.4	1.1	1.4	21.1	26.3
Non-ICT Industries	0.2	0.5	1.6	0.7	67.7	62.1
…Non-ICT Manufacturing	3.0	1.4	3.8	1.5	11.9	9.3
…Non-ICT Services	–0.4	0.4	0.6	0.2	44.7	43.0
…Non-ICT Other	0.7	0.6	2.7	1.9	10.5	9.8

Note: †Excluding ICT-producing industries. Labor productivity is defined as value added per person employed. EU includes Austria, Denmark, Finland, France, Germany, Ireland, Italy, Netherlands, Spain, Sweden and the United Kingdom, which represents over 90 percent of the EU GDP.

Source: van Ark *et al.* (2002).

Figure 1 Electric motor capacity in the Swedish manufacturing and handicraft industries, 1906–1937 (horsepower)



Source: Hjulström (1940).