Universidad Carlos III de Madrid
www.uc3m.es

Working Papers in Economic History

November 2010 WP 10-13

The role of technology and institutions for growth: Danish creameries in the late nineteenth century

Ingrid Henriksen, Markus Lampe and Paul Sharp

Abstract
We consider the relative contributions of changing technology and institutions for economic growth through the investigation of a natural experiment in history: the almost simultaneous introduction of the automatic cream separator and the cooperative ownership form in the Danish dairy industry from around 1880. Using a new database of statistics from creameries and the tool of stochastic frontier analysis, we find that both institutions and technology were important for the success of the Danish dairy industry and, by implication, the growth and early development of the Danish economy.

Keywords: Creameries, dairies, Denmark, development, economic growth, institutions, technology, stochastic frontier analysis.
JEL Classification: L2, N5, O3, Q1

Ingrid Henriksen: Department of Economics, University of Copenhagen, Øster Farimagsgade 5, DK-1353 Copenhagen K, Denmark.
Email:ingrid.henriksen@econ.ku.dk,
http://www.econ.ku.dk/Faculty_And_Staff/showID.asp?profile_id=32
Markus Lampe: Department of Economic History and Institutions, Universidad Carlos III de Madrid, C/ Madrid, 126, 28903 Getafe, Spain.
Email: mlampe@clio.uc3m.es
http://www.uc3m.es/portal/page/portal/dpto_historia_economica_inst/profesorado/markus_lampe
Paul Sharp: Department of Economics, University of Copenhagen, Øster Farimagsgade 5, DK-1353 Copenhagen K, Denmark.
Email: paul.sharp@econ.ku.dk,
http://www.econ.ku.dk/Faculty_And_Staff/showID.asp?profile_id=1836

UNIVERSIDAD CARLOS III DE MADRID • c/ Madrid 126 • 28903 Getafe (Spain)• Tel: (34) 91 624 96 37
Site: http://www.uc3m.es/uc3m/dpto/HISEC/working_papers/working_papers_general.html

DEPARTAMENTO DE
HISTORIA ECONÓMICA
E INSTITUCIONES

INSTITUTO FIGUEROLA
DE HISTORIA Y CIENCIAS SOCIALES
Universidad Carlos III de Madrid

The role of technology and institutions for growth: Danish creameries in the late nineteenth century[1]

Ingrid Henriksen, University of Copenhagen

Markus Lampe, Carlos III Madrid

Paul Sharp, University of Copenhagen

Abstract: We consider the relative contributions of changing technology and institutions for economic growth through the investigation of a natural experiment in history: the almost simultaneous introduction of the automatic cream separator and the cooperative ownership form in the Danish dairy industry from around 1880. Using a new database of statistics from creameries and the tool of stochastic frontier analysis, we find that both institutions and technology were important for the success of the Danish dairy industry and, by implication, the growth and early development of the Danish economy.

JEL codes: L2, N5, O3, Q1

Keywords: Creameries, dairies, Denmark, development, economic growth, institutions, technology, stochastic frontier analysis

[1] This article was begun while Markus Lampe was a post.doc. funded by the Department of Economics at the University of Copenhagen and was also worked on while Paul Sharp was visiting Carlos III Madrid. Paul Sharp would like to acknowledge generous support from the Carlsberg Foundation, while Markus Lampe appreciates funding by Spain's Ministerio de Ciencia e Innovación (project ECO2008-02089). We also would like to thank Carsten Burhop, Martin Uebele and seminar participants at the University of Copenhagen for valuable comments and suggestions.

1. Introduction

A source of much debate between economists and economic historians working on the relative importance of various contributors to growth is that of whether technological or institutional innovation is of prime importance. Whilst the usual interpretation of the *A* term in a standard neoclassical growth model is as technology, others have recently emphasized a more important role for institutions (see for example Acemoglu et al 2005). We look into this debate from a firm-level microeconomic perspective through the investigation of a natural experiment: the almost simultaneous introduction of the automatic cream separator and the cooperative ownership form in the Danish dairy industry from around 1880.

The story of the emergence and success of Danish creameries at the end of the nineteenth century is well known and is considered to be one of the primary causes of the success of the Danish economy during this period. Two innovations are normally considered to have been the main contributors to this success: one technological, and one institutional. First, the invention of the automatic cream separator in 1878 allowed for butter production on a larger scale than had been possible under previous technologies. In particular, it allowed for the extraction of more cream from the (whole) milk; and for the immediate separation of cream from milk which had been transported over longer distances, without first needing a period of time for the cream to separate by itself, and for the extraction of more milk from the cream. The technology quickly replaced pre-existing technologies in almost all dairies. Second, the cooperative movement emerged as an efficient way to utilize this technology. By solving some of the incentive problems involved in the management of a creamery dependent on many small suppliers, cooperatives allowed for the efficient use of the technology. In doing so they successfully outcompeted rival institutional forms, such as the old estate dairies and private creameries (see Hviid 2006, table 1, based on Bjørn 1982*)*. The technological and institutional determinants of the success are thus clearly interdependent: the invention of the automatic cream separator led to the success of the cooperative movement which in turn allowed for the successful use of the technology. This makes it difficult to know whether the productivity increases were due to better technology (a shift in the production possibility frontier) or better institutions (higher productive efficiency bringing the firm closer to this frontier) or both, although most research has focussed on the institutional explanation (see for example Henriksen 1993 and O'Rourke 2007).

We shed light on this story by quantifying the impact of the institutional and technological innovations using appropriate econometric modelling. We collect data from a large sample of creameries using different technologies and different institutions and quantify the gains from moving to cooperative ownership and from using the automatic cream separators by applying the tool of stochastic frontier analysis.

2. Technology vs. Institutions

Given the extent and importance of the discussion about sources of productivity growth, it is surprising that there are not many more studies comparing the relative impact of technological and organizational innovations. However, it turns out that conducting such an analysis is not so easy in practice, since an (almost) simultaneous technological and institutional shock is seldom observed in economic history, and, besides, rarely is there enough data for a thorough econometric analysis.

Nevertheless, economic historians have had something to say on this subject. In particular, much has been written on a famous example from the English industrial revolution of the great inventions in cotton spinning in late eighteenth century England: Hargreaves' Spinning Jenny, Arkwright's water frame and Crompton's combination of both, the mule; and the accompanying change in labour organization, which is commonly known as 'the rise of the factory'. This seems to be an obvious example to use to help illuminate the debate, and here we briefly survey the evidence that has been collected and demonstrate how much we can learn from this, and the limitations of this example.

A first stumbling block arises when we look at estimates of productivity increases associated with an innovation. For many inventions, large increases in the productivity of individual inputs (e.g., labour and coal) are often cited to have taken place almost immediately and rather dramatically. An example would be from Ayers (1989, pp. 16-17):

> 'Hargreaves's patent specified 16 spindles. The number rapidly increased; by 1784 jennies could handle 80 spindles, and by 1800 the number had risen from 100 to 120. It reached 1,200 by 1832. In effect, the productivity of a single operator was multiplied by 100-fold in the space of a generation and 1,000-fold in two generations.'[2]

Obviously, this is an overstatement since transforming raw cotton into yarn involves more than just increasing the number of spindles per operator, e.g. preparing the fibres for spinning and attaching them to the spinning device. Allen (2009, pp. 184-195) gives a more complete picture of the story and calculates that a 24-spindle jenny in domestic use around 1775 increased labour productivity by a factor of three and reduced total costs by 10.6 percent of total costs and 20.5 percent of transformation costs (net of the value of raw cotton) in comparison to the spinning wheel, since it increased capital costs and did nothing to decrease preparatory costs in the cottage, and supervision and transportation costs between putting-out entrepreneur and the cottage where production took place. Even from this, however, we still do not know how large the decrease in costs from the introduction of centralized production with 80- and more spindle jennies was (which could no longer be operated on the household scale using the

[2] Ayers gives Mann (1958) as source for the spindle numbers and includes a figure on 'Cotton textile productivity measures: output per operator' in which we can appreciate these numbers. Ayers is one of the main sources of the history section of Wikipedia's article on 'Productivity', for he provides numbers for all kinds of innovations in different branches (en.wikipedia.org/wiki/Productivity, assessed 27 October 2010). Compare the following to Attack (1987), pp. 299-300, 308-310, who finds that estimates on labour productivity gains from mechanization in the US published in 1899 (his table 9.3) are in no way reconcilable with his comparisons of TFP in mechanized and non-mechanized firms: 'The failure to realize huge gains in labor productivity that contemporaries expected may have discouraged universal adoption of mechanized production.' (Ibid., p. 309).

spinner's arm as power supply) – the gains from the institutional innovation are thus not really estimated.[3]

Allen calculates that the Arkwright-style Papplewick cotton mill with 2,000 spindles in 1775 did not significantly lower spinning costs in comparison to the 24-spindle domestic jenny (but economized on preparation thanks to the water frame), but decreased remarkably the administration costs, due to centralization in comparison to the putting-out system.[4] This is the radical social change in the production process, eliminating part-time labour and domestic production. If we take the decrease in supervision costs in the Arkwright mill as representative for the transaction cost gains in centralizing production, they decreased by 85 percent and would account for another 10.6 percent decrease in total costs or 23.2 percent if we exclude the raw material costs. From this, we can calculate that mechanized factory production would have produced the same final product 21.6 percent cheaper than spinning-wheel cottage production, or saved 39 percent of the costs of transforming raw cotton into yarn. Of the cost-saving, about 60 percent would be thanks to the invention, and 40 percent thanks to the better organization of production.

Furthermore, we could ask whether the institutional gain is simply due to the larger scale of the factory versus the cottage producer (thanks to increasing returns to scale, cf. Landes 1986), due to a decrease in effective transaction costs (Williamson 1980) or due to more effective supervision, also known as 'factory discipline' (Marglin 1974, Clark 1994). There is no way to assess this directly.

If we were very adventurous we could use Attack's (1987), figure 9.1 (p. 303), which shows that TFP in the production of 'cotton goods' (not just spinning) in the US according to the federal census of manufactures of 1820 was about 40 percent higher in 7-25 employee establishments

[3] Allen (2009), p. 206, mentions them, but does not provide comparable calculations. All his calculations refer to costs in 1784 prices per pound of 16 count cotton (yarn), for higher qualities the gains were probably larger.

[4] But extra material and overhead costs offset much of that gain according to Allen (2009), p. 195.

than in artisan shops and a little more than 50 percent higher for establishments with more than 25-employees, which is in line with the results on cumulative gains of jenny and factory mentioned above.[5] We could furthermore distinguish between technically identical weaving establishments in Britain in 1840, for which Clark (1994) has estimated that 'factory discipline', by allowing a more intensive use of the given fixed and circulating capital, led to about 36 percent higher labour productivity (but paying higher wages) compared to a hypothetical non-disciplined 'freedom mill', decreasing transformation costs of weaving 100 yards of cotton cloth – depending on several assumptions about piece rates in the freedom mill – by 2.2 to 10.6 percent (based on Clark 1994, Table 5, p. 152). Discipline would then account for 32 to 85 percent of the gains from change in the institutional form (15.6 percent transformation cost reduction according to Allen), leaving a broad range of gains for the other parts.

These results are however rather unconvincing, since they depend on observations from individual establishments, strange assumptions, and surveys of different sample sizes from two different countries and subsets of the same industry, spinning and weaving, at two different times, 1760 and 1840. It seems natural, therefore, to look for another example from history.

In this paper we thus look at a comparable case, probably as important for Denmark as the introduction of jennies and factories for Britain, where we actually *can* differentiate between gains from technological change (the steam-driven cream separator), a change in institution (private enterprise vs. cooperatives) and scale (quantity of milk processed). We are not aware of a comparable example which is as well suited for this purpose.

3. Innovation in the Danish dairy industry

The process of producing butter is essentially a two-stage process: the first concerns producing the milk and the second extracting the cream from the milk in order to make butter. We

[5] For on the change in technology/organization between up to 5 and more than 5 employee establishments in the US in 1820 see Sokoloff (1984).

concentrate here on the second stage, at which the main innovations in technology and institutional forms happened. Nevertheless, we can be sure that increased technical efficiency in the second-stage of production (more butter out of the same amount of milk) saved all kinds of resources (cows, milkmaids, land for pasture and fodder and labour for cultivating it) in the first stage.

In analyses of firm level efficiency, a division is usually made between technical and allocative/cost efficiency, and in the following we concentrate exclusively on the former. This is not because cost efficiency is uninteresting – there are certainly reasons to believe that many of the advantages enjoyed by cooperatives were through being able to keep costs down, for example through a more efficient transportation network – but we simply do not have the data on prices of multiple inputs that would be necessary for such an analysis.

Nevertheless, we can learn much from a simple look at the amount of butter produced per unit of milk. Contemporaries were well aware that the milk to butter ratio was one of the key indicators of a creamery's productivity, and it was standard accounting practice to report this statistic. There are a number of factors that could explain differences in this ratio, however, which is the motivation for our formal econometric analysis below.

Differences in the milk/butter ratio can be attributed to two main things: differing returns to scale to different technologies, thus implying different ratios of output to input at different scales of production, and other 'efficiency' differences, which cause production to fall below the possibility frontier of best practice. Another important factor was time, during which the existing technologies were improved.

Returns to scale

Considering returns to scale we observe in our period the movement from one technology to another, so it is sensible to consider what implications this might have. The traditional system for separating cream from the milk is what in Denmark was called the *bøtter*-system, in which the milk was poured into a flat container with a large surface area, the *bøtte*, after which the cream would gradually rise to the surface. Experimentation improved the system gradually. Especially important was the acceleration of the cream separation process through placing the container into a basin with (cold) water, which could be cooled further by the use of preserved crushed ice. From the 1860s this became the most common technology, and in the descriptions of their own technology used by the estates in our dataset we find different combinations of the words *bøtter, vand* (water) and *is* (ice), together with additional terms indicating improvements in the form of the container, such as *Destinonske fade*, a rather more sophisticated version of the standard technology. Clearly, however, we should expect to find decreasing returns to scale to such a technology, since the production process was not easily replicable within the confines of an existing dairy.

With the invention of the automatic cream separator (a centrifuge) in 1878, however, the water- and ice-dairies were very quickly replaced by those using the new technology[6]. Here it was the centrifuge that was the bottleneck in the day-to-day running of the dairy. Time was essential for the skimmed milk to be returned to the dairy farmers in a useful state for the feeding of calves and pigs. However, a study of the most important Danish producer of centrifuges, the Burmeister & Wain machine factory, demonstrates that this bottleneck was becoming wider over time. The technical capacity of the largest centrifuges, here measured in kilograms skimmed per hour, was growing quickly over time from 240 in 1880 to 800 in 1885. At the same time, the price of a machine of a given size was declining measured in fixed prices (Pedersen 1999, p. 367). Moreover, it is clear that early creameries made an allowance for easy future expansion when they were built. A contemporary account giving a sample of designs of some early centrifuge dairies of various capacities[7] demonstrates that the creameries were flexible with respect to the number of centrifuges installed (Bøggild 1896, pp. 469-72). The

[6] See e.g., Van der Vleuthen 1994. Axelsen Drejer (1925-33), p. 41, reports numbers of cream separators from the journal 'Ugeskrift for Landmænd', according to which in 1881 there were 90 separators in Denmark. By 1887, the number had risen to about 2200.

[7] Here measured by number of cows.

earliest example, from 1887, illustrates that 'room was left for an additional centrifuge.' The newest ones, from 1889 and 1890 had 2 and 4 centrifuges installed respectively.

There was, of course, an upper limit to the possibility of adding more centrifuges to the original steam engine. This did not necessarily have to be hit very early in the life of a modern creamery, however. Micro evidence from the diary of an influential farmer, involved in the first cooperative creamery on Zealand in 1884, tells us that this creamery was successful in attracting suppliers from the neighbouring villages, and that it had to add new machines on several occasions. It was not, however, until 1907 before it had to be 'rebuilt and modernized' (Jensen 1985, p. 86). All in all, it might seem reasonable to expect, if not constant returns, then less diminishing returns to the new technology compared to the old.

Efficiency differences

Turning to differences in efficiency, it is first important to note the fact that in some ways the institutional development of the cooperatives was inseparable from the technological development of the separator. In fact, the centrifuge at first presented a challenge to Danish agriculture, which the new organizational form helped to solve. The first steam-driven cream separators were made for the daily milk of 300 to 400 cows, thus exceeding by far the average Danish herd size of 6 to 14 cows. Only a small fraction of Danish farmers, mostly traditional estates, could aspire to run these cream separators on their own. However, even many of these estates had herd sizes far below 300.[8] The new technology thus presented difficulties for the organization of the second step of production, since increasing the average herd size to optimum sizes for all farms would have required reallocation of land and farms to a degree

[8] For example, Orupgaard, the most important of the farms run by Edward Tesdopf, the president of the Association of Estates, had a herd of c. 220 milk cows in the early 1870s (Fenger 1873). The average herd size of the 27 estates covered in the dairy survey of the journal of Tesdorpf's association, the *Tidskrift for Landøkonomi*, for 1882 was 75.5, with a maximum of 176 and a minimum of 7 (Sonne 1883).

exceeding that possible (since it would have involved many small tenants becoming dependent farm workers, see Persson 2010, p. 86).

By bringing together large numbers of small producers, the cooperative movement was able to take advantage of the many benefits the centrifuge offered, perhaps most importantly that cream could be instantly separated from the milk without requiring time for separation. This was even the case for milk which had been transported over long distances, which would have been completely homogenized by the process of transportation, and thus would have required much longer time for separation under the old system, with higher risks of the milk spoiling. The Danish cooperative dairies, relying as they did on the transportation of milk from outlying small producers to a central creamery, depended exclusively on the centrifuge technology. Also, Hviid (2006) describes how the ability to produce large quantities of a homogeneous product helped small producers to realize a better price for their product. Moreover, Henriksen (1999, p. 61) quotes historical evidence about the new technology that suggests that it was able to produce about 25 to 30 percent more butter out of the same amount of milk, when compared to the simplest version of the *bøtter* technology as used by small herd-owners. The change from the *best* traditional practice, the ice dairy, to the steam driven separator would still improve efficiency by more than 10 per cent.[9]

An alternative organizational form which enjoyed some brief success in the 1870s and 1880s was the *fællesmejeri* (private creamery). These have often been overlooked in the literature, although see Bjørn (1977). They bought milk from surrounding farms and thus differed from cooperative creameries which were collectively owned by their suppliers. Importantly for us, however, both used essentially the same technology (Henriksen 1999, p. 63), but Henriksen (1997) and Henriksen and Hviid (2005) have argued that cooperative creameries were the superior institutional form for several reasons. First, they were attractive to farmers because

[9] See Bøggild 1896, pp. 365-66, referring to experiments carried out 1879-83, as well as modern authors on the subject (Jensen 1988, p. 324).

they offered them a larger slice of the cake, since farmers as owners not only received payments for their milk as suppliers, but also dividends as residual claimants. This should have reduced deadweight losses and adverse redistribution effects due to the market power of the owner of the cream-separator. Second, they seem to have been the best option to avoid the problem posed by the large initial investment involved in acquiring the cream separator and the associated capital (particularly the creamery building and steam power generators) which involved the risk of ex-post extortion by milk suppliers ('lock-in' and 'hold up'). They achieved this by forcing their members to sign collective agreements for the regular provision of all their milk (except that for own consumption in the household) to their creamery for a fixed minimum, thus ensuring that the initial investment could be recovered. Third, the cooperative institutional form was also helpful for dealing with asymmetric information on the quality (cream content) of the milk provided and could furthermore ensure year-round supply of milk by forcing their members to provide winter-feeding of milk cows (see Henriksen 1997, Henriksen and Hviid 2005, Henriksen and O'Rourke 2005).

To obtain a good result the milk had to be fresh, that is newly milked, given the technology for transport and refrigeration in the late nineteenth century. In our readings of the minutes of 210 cooperatives (see Henriksen et al 2010) we find that this was an issue particularly in the (few) creameries that were closed on Sundays for religious reasons. The members were supposed to find use for the Sunday milk in their own household and were, consequently, rebuked for delivering a conspicuously large amount of milk on Mondays. The milk also had to be clean that is free from microbes that could make the buttermaking process fail. Before the introduction of better measurement methods, for example, the lactoscope, the creameries had to rely on being able to see or smell dirt. The manager of the creamery was authorized to reject such supplies and the board of the cooperatives was in most cases to inspect the stables of a member suspected of neglecting cleanliness. Both old and dirty milk would lead to more waste in the production process. Equally important was the avoidance of deliberate fraud that lowered the fat percent of the milk, making it less suitable for butter production per kilo of milk. In Henriksen and Hviid (2005) we showed how new technology for everyday testing of the fat percent was, albeit somewhat slowly, adopted by the cooperatives. The resistance to paying the milk according to the fat content came from suppliers that suspected they were going to loose in the process because the milk from their cows was naturally meagre. Henriksen et al (2010) demonstrate how the cooperatives, before complete testing was implemented, monitored and enforced the statutes on milk adulteration, mostly resulting in hard material punishment to the perpetrators. The claim is that private contractual arrangements on hygiene and adulteration could not have accomplished the same result.

Private dairies seem therefore to have faced a problem of less regular milk supply and potentially lower quality of the supplied milk due to hold-up problems. Additional problems for the quantity of supplied milk (although not for the quality) might come from their weaker position as regards the enforcement of winter-feeding among their suppliers. A lower fat content might lead to lower quality of the butter, higher milk-to-butter ratios and temporary or permanent underutilization of the capital embodied in the cream-separators and the creamery (see Henriksen 1999, p. 68; Bjørn 1977, p. 78, Pedersen 1885, p. 44).

For the third institutional form, vertically integrated private estate-dairies, for which we happen to have more data than for private creameries, the predictions are less clear. Henriksen (1999, p. 71) refers to the islands of Lolland and Falster, where relatively few cooperatives were active, and explains this by the presence of large estates that did not have to rely on external suppliers to run a cream separator. However, Henriksen and Hviid (2005, p. 367, 390) mention in general a problem of surveying the effort of employees responsible for milking, where the last drops of milk have the highest fat content, and therefore would provide the highest butter-to-milk ratio. This problem should be increasing with herd size, and hence might be less problematic for the average cooperative-member herd size cited above than for estates having a herd size large enough to supply a cream separator on their own. Contemporary accounts also expressed much concern that larger herds, such as those associated with the estates, were less efficient than the smaller herds associated with the cooperatives, since owners of small herds were better able to focus giving feed to the most productive animals, thus taking advantage of each animal's productive potential (see for example Bøggild 1895, pp. 120-2).

In general, therefore, we can establish two kinds of hypotheses for our empirical work: first, the steam-driven cream-separator was technically able to extract a higher share of the cream from milk of any fat content in a shorter period of time than the traditional system of containers and cooling, which should translate into lower milk-to-butter ratios for the new system compared to the traditional one. We might also expect the old technology to be subject to more sharply diminishing returns to scale. Moreover, the centrifuge technology was improving over time, thus we would expect a trend in milk/butter ratios. Second, for several reasons we would expect – given the same technology – that cooperative creameries were able to use this technology more efficiently than private creameries. Since these reasons are mostly related to the hold-up power of suppliers, private creameries might have been also less efficient than estate dairies, which were integrated owner-suppliers. However, the latter might face principle-agent problems in milking and additionally might be running cream-separators below their best capacity utilization because not all of them actually had sufficiently large herd sizes. We should therefore also test whether there is an efficiency gain from being a cooperative creamery that was independent of the size of production: as is clear below, cooperatives were generally more productive than other creameries, but they were also generally larger.

A final point that is worth bearing in mind is that it seems from contemporary evidence (see Bøggild 1896, p. 469-72) that larger creameries were often newer than smaller creameries and thus might be expected to have a more advanced capital stock. We are unable to control for capital in our analysis, since we only have inputs of milk. Except for the initial fixed costs associated with building a creamery and buying the power generator, capital was certainly a relatively minor part of the variable costs of production, usually less than 10 percent of turnover (Bøggild 1899, p. 159). Nevertheless, if creameries were established at different times, then a higher individual productive efficiency might also be due to a newer capital stock.

4. The data

Our data are collected from a number of sources. We have used archival sources[10], as well as data published in the Danish journals *Tidsskrift for Landøkonomi* and *Mælkeritidende*; and in the survey of Danish creameries compiled by Ellbrecht (1915-1918). Our sample comprises 27 time series for creameries using old technologies (primarily ice dairies). All of these are estates or private creameries. In addition we have time series for 334 centrifuge creameries (a mixture of private, estate and cooperative creameries). We focus on the period from 1865 until 1900, but we have included in some cases at most one observation from after this date in order to have time series of at least three observations for each dairy. Our panel is unbalanced, and most time series contain some gaps, i.e. they do not have observations for every year for the period they cover. Table 1 gives descriptive statistics of average input-to-output ratios for the different organizational forms using the two different technologies. Note that there were no cooperatives using the old technology.

Table 1: Summary Statistics on Milk per Butter ratios

	All	**Estates**	**Private**	**Cooperative**
Old Technology	30.7	30.7	27.4	N/A
Period	1865-1900	1865-1900	1871-74	N/A
N	186	182	4	0
Number of dairies	27	26	1	0

[10] The archival sources are for the estates of Broholm (1865-69) and Søholm (1865-70) and for the private creameries Visby mejeri (1870-1875) and the draining company for the lake Sjørring sø (1894-1902), which drained this lake in Northwest Jutland and established a rather large private dairy. The records for Broholm and Søholm can be found in the provincial archives for Fyn (Fionia, Funen) in Odense, the records for Visby mejeri in the Institut for Sønderjysk Lokalhistorie in Aabenraa and those for the Sjørring sø draining company in the Danish Business Archive (Erhvervsarkivet) in Århus.

New Technology	26.8	28.0	27.1	26.7
Period	1882-1904	1882-1900	1882-1904	1884-1904
N	1389	176	19	1194
Number of dairies	329	33	4	292

Clearly, the old technology gave on average worse ratios than then new technology, and cooperatives were on average more efficient than private dairies, which were on average more efficient than the estates. We have, however, very few observations from private creameries.

5. Method

Assessing productive inefficiency requires the estimation of a production function. For this we need data on inputs and outputs. We argue that the relevant input variable for our analysis is the amount of milk used, and the output is of course the amount of butter produced. This gives us a simple production function of the form

$$\ln(butter_{it}) = \beta_{0t} + \beta_{1t}\ln(milk_{it}) \quad (1)$$

where *butter* is output of butter in *pund* (500 grams) and *milk* is the input of milk in *pund*. Our data is a panel, so inputs vary across both creameries (*i*) and time (*t*).

We are aware that this is a somewhat untraditional production function, since the usual factors of production (capital, labour, etc.) are not present. Nevertheless, it is a production function, in the sense that it gives the production of an output based on an input. Moreover, the literature on productive efficiency usually terms these production functions, so this choice of words is also to avoid confusion. Also, this should be seen in the light of the fact that the production of butter is in reality a two-stage process, the first being the production of milk (which requires labour and capital, in the form of land, cows, a dairy, etc.), and the second being the production of butter from the milk.

We concentrate on the second stage, where the role of capital and labour in the production process is of rather secondary importance,[11] if we consider this to be largely a story about extracting cream from (whole) milk. By this, we effectively assess the technological efficiency of the creameries in our sample, not cost efficiency, which would imply also using data on prices.[12]

Our motivation for focusing on the second stage is that data for the first stage (numbers of cows, labourers etc.) is lacking in almost all cases, since the vast majority of the milk suppliers were small farms for which no records have been preserved, if kept at all. This also implies that the two stages were conducted for all producers except the estate dairies in two different firms. Moreover, the main technological innovation concerns the second stage, i.e. the movement from ice creameries to those using centrifuges. We can capture the form of the production function under the alternative technologies using this simple one-input specification although, as discussed above, the inefficiency term might be capturing inefficiencies in the first stage rather than in the second stage.

---

[11] There is an additional implication to looking at just one input: By estimating a one-factor production function we cannot capture allocative efficiency of production factors. However, Henriksen and Hviid (2005) argue based on historical evidence that in butter-making the use of other inputs (especially transport services and energy) are proportional to the amount of milk processed for the relevant part of the cost/production function, which would make allocative efficiency a minor issue. In the first stage, labour input might be of importance, since through winter feeding, which was labour intensive not just during the winter, but also because it required beet root cultivation before, the amount of milk produced per cow (a capital good) could be increased, but not its quality (Henriksen and O'Rourke 2005). Hence the amount and regularity of milk processed in the second stage could be affected, but not the quality of the latter.

[12] Input prices for raw milk are not available in many cases (by definition not for the integrated estate dairies), and additionally might only be weakly informative, since effective pricing of milk supplies based on the fat content of the milk, which is the most characteristic for the production process, was not technically feasible at the beginning of our period and introduced only slowly and incompletely during our period (see Henriksen and Hviid 2005).

To estimate the production function, we use the stochastic frontier model with a time-varying technical efficiency term formulated by Battese and Coelli (1995) and described by Kumbhakar and Lovell (2000, p. 271).[13] These models have the general form

$$y_{it} = \boldsymbol{\beta}'\boldsymbol{x_{it}} + v_{it} - u_{it} \tag{2}$$

where $u_{it} = g(\boldsymbol{z_{it}})|U_i|$ where U_i is half normal

and $g(z_{it}) = \exp(\boldsymbol{\eta}'\boldsymbol{z_{it}})$

Equation (2) is the general formula for a stochastic frontier model in a panel setting, where the production of *y* is given by a vector of inputs, ***x***. The important contribution of these models is the separation of the error term into a standard stochastic error, v_{it}, and an inefficiency term, u_{it}. The Battese and Coelli (1995) formulation of the model allows us to explain this inefficiency term with a vector of variables $\boldsymbol{z_{it}}$.

For our purposes, y_{it} obviously corresponds to the (log) output of butter, and x_{it} to the (log) input of milk. We also introduce a trend, *t*, to capture for example technological progress over time. Since we have two technologies, we estimate two production functions, one for the old technology (primarily ice creameries) and one for the new (using centrifuges). For the centrifuge creameries we wish to explain the inefficiency term with reference to their institutional status: estates, private creameries or cooperative creameries (since no cooperatives used the old technology). These are coded through the use of the dummies *ESTATE* (= 1 if an estate) and *PRIVATE* (= 1 if private). Due to data scarcity for private creameries, we however initially introduce only one dummy, *ESTPRIV* (= 1 if estate or private). In addition, we control for 'size' in the efficiency term, which we measure by the (log) input of milk.

[13] In economic history, this method has also recently been applied by Burhop and Lübbers (2009) who look at the product efficiency of 28 German coal mines between 1881 and 1913.

6. Results

Table 2 gives the results of our estimations. Models 1 and 3 are from a standard stochastic frontier analysis for the creameries using the old and new technologies respectively. Models 4 and 5 attempt to explain the inefficiency term by institutional type, and models 2 and 6 introduce the 'size' explanation of inefficiency.

Table 2a: Estimation results, Old Technology

	(1) Old Technology	(2) Old Technology
Constant	-2.632***	-2.773***
$\log(milk_{it})$	0.947***	0.959***
t-value for test of constant returns to scale	-2.33	-1.65
trend	-0.002	-0.002
'size'	N/A	0.472
λ	1.635***	0.005
σ	0.089***	0.000
η	-0.023	N/A
Period covered	1865-1900	1865-1900
No. of cross-sections	27	27
No. of observations	186	186
Log likelihood	253.278	255.726

Table 2b: Estimation results, New Technology

	(3) New Technology	(4) New Technology	(5) New Technology	(6) New Technology
Constant	-3.298***	-3.251***	-3.250***	-3.215***
$\log(milk_{it})$	0.999***	0.996***	0.996***	0.993***
t-value for test of constant returns to scale	-0.34	-3.03	-3.07	-3.85
trend	0.004***	0.004***	0.004***	0.004***
$ESTPRIV_{it}$	N/A	0.954***	N/A	0.717***
$ESTATE_{it}$	N/A	N/A	0.991***	N/A
$PRIVATE_{it}$	N/A	N/A	0.433	N/A
'size'	N/A	N/A	N/A	-0.159**
λ	1.505***	1.088***	1.086***	11.358***
σ	0.043***	0.031***	0.031***	0.330***
η	-0.005	N/A	N/A	N/A
Period covered	1882-1904	1882-1904	1882-1904	1882-1904
No. of cross-sections	329	329	329	329
No. of observations	1389	1389	1389	1389
Log likelihood	2730.760	2765.371	2766.154	2762.48

Notes: **/*** = significant difference from 0 at 5%/1% level; $\lambda = \sigma_u/\sigma_v$; $\sigma = \sqrt{\sigma_u^2 + \sigma_v^2}$; stochastic frontier, $e = v - u$; time varying $u_{it} = exp[-\eta(t-T)]|U_i|$ (for models 1 and 3) or $u_{it} = exp(\eta z_{it})|U_i|$ (models 2, 4, 5 and 6).

The results seem intuitive and in line with our *a priori* expectations as discussed in section 2. For the old technology (models 1 and 2), there is no significant trend, which implies that productivity was not increasing over time using this technology, and there were diminishing returns to scale. For the new technology (models 3, 4, 5 and 6), however, we see productivity growth of 0.4% per year and we now have (approximately) constant returns to scale. This growth in productivity might be due to technological progress, the breeding of cows which could produce a higher fat content in their milk, or might be due to the sort of institutional innovations such as performance related pay discussed by Hviid (2006).

The average inefficiency of creameries under the old system was 6.6%. For the new system we estimate four models. Model 3 uses the same methodology as model 1, but for models 4 and 5 we also attempt to explain the relative efficiency of the various systems. Since we have relatively few observations for private creameries, we group them with the estate dairies in the first estimation attempt, giving the results for model 3. The mean inefficiency for the whole sample is 3.1%, so significantly lower than for the old technology above. However, and as expected, model 4 reveals that estates and private dairies were significantly less productive than cooperatives: the coefficient should be interpreted as implying that they had 95.4% higher inefficiency. This implies that the average efficiency of estates/private creameries was (1-0.031)*0.954 = 0.924%, giving an average inefficiency of 7.6% - rather similar to their inefficiency under the old system of 6.6%.

Although we have very few observations of private dairies, we attempt to differentiate between them by coding them differently in model 5. As might be expected, since we have so few observations, the coefficient for private creameries is insignificant. However, it nevertheless implies that they were in fact less inefficient than estate dairies.

Finally, in models 2 and 6 we control for ‘size’ in the efficiency term. There is an insignificant positive effect for the old technology, implying that larger creameries were less efficient than smaller. A tentative interpretation might be that this reflects the gains from better monitoring and greater milking effort, since most of this sample consists of estates, so a larger amount of milk processed corresponds to larger herd sizes, which is not the case when we look at cooperatives, who source their milk from a large number of small herds. For the new technology we thus find a significant negative coefficient, so larger creameries were more efficient[14]. Interestingly the *ESTPRIV* coefficient falls, but remains significant, implying that, as expected, the efficiency gains from cooperatives are less when we control for the size of the creameries.

To assess the economic implications of our results, in table 3 we report the results of putting the sample mean of milk inputs into the production functions obtained from the stochastic frontier models as reported in table 2 (and our preferred models 1 and 4), in terms of milk per butter ratios for the average enterprise. We calculate these for 1900 and use three kinds of assumptions about the average enterprise, given in Table 3 together with the results.[15]

---

[14] This corresponds to the findings of studies of modern dairies, although these typically look at the production of milk rather than the final products, see Álvarez and Arías (2004), Bailey et al (1989), Fan et al (1996), Hallam and Machado (1995), Heshmati and Kumbhakar (1994), Kumbhakar et al (1989), Kumbhakar et al (1991), and Tauer (2001).

[15] Since the estimates are conducted in logs, the simple antilog of these estimates is likely biased. We therefore apply the Goldberger (1968) correction by adding 0.5 times the squared standard error for every log-coefficient before taking the antilog. Since the estimates are very precise, the correction is very small.

Table 3: Comparisons of the efficiency of different types of creameries at different scales of production

		Old technology, private creamery	New technology, private creamery	New technology, cooperative creamery
(1)	Milk	4172026	4172026	4172026
	Butter	122705	153485	160960
	Ratio	34.0	27.2	25.9
	% of new coop	76	95	100
(2)	Milk	1094899	1094899	1094899
	Butter	34566	40504	42476
	Ratio	31.7	27.0	25.8
	% of new coop	81	95	100
(3)	Milk	292990	292990	292990
	Butter	9918	10898	11429
	Ratio	29.5	26.9	25.6
	% of new coop	87	95	100

Notes: The trend is set to 1900; (1) Using average milk input for whole sample; (2) Using average milk input for private creameries; (3) Using average milk input under old system; '% of new coop' is the % butter extracted from the given amount of milk as a proportion of cooperatives with the new technology.

We observe that, depending on the scale of production for the old technology, the new technology used between 9 and 20 percent less milk for the production of the same amount of butter for the same institutional form with – as reported above – almost identical average inefficiency. Additionally, since for the creameries in our sample the old technology showed decreasing returns to scale, creameries using the old technology would have been much less productive at the sort of scales the cooperatives operated at in 1900, which is in line with the fact that cooperatives did not use the old technology.

For the new technology however, the amount of milk used does not have such an impact, since it has constant returns to scale. If we compare the two governance forms, we find a 5-percentdifferential in the milk-to-butter ratios. This would suggest that of the total gain of technological progress and institutional innovation of 13 to 24 percent, between 63 and 79 percent would be due to the technological innovation of the cream separator and the rest due to the greater efficiency of the cooperatives in using it. However, note that we might well be underestimating the efficiency gains of the cooperatives and the centrifuge, since we are comparing them to the best practice of old-style buttermaking, as represented by the estates who sent accounts to the *Tidsskrift for Landøkonomi*.

Looking at some implications of our results for all of Denmark we should first note that it would have been impossible to match the levels of production seen in the late nineteenth century if the centrifuge had not been introduced - to run efficiently there would have had to have been very many small creameries. Clearly, the technological innovation was vital for the success of the Danish dairy industry. This should not, however, distract from the economic significance of the institutional innovation of the cooperatives. In 1900-04 Denmark produced approximately 83.8 million kilograms of butter (Johansen 1985, p. 150) of which ca. 90 percent was exported. Given the volume of Danish foreign exports of butter over this period, this corresponds to rather large volumes of missing trade, if the cooperative movement had failed to take off as it failed to, for example, in Ireland (O'Rourke 2007). Moreover, since exports of butter accounted for approximately 9 percent of Danish GDP, the 5 percent drop in production suggested by our estimates might have implied almost 0.5 percent lower GDP.

7. The importance of the cooperatives reconfirmed

It might be tempting to conclude from our analysis that the impact of the technological innovation dwarfed that of the cooperative movement. This would be wrong however. As noted above, the introduction of the centrifuge through most of Denmark was only possible because of the cooperative ownership form. The calculations above on the impact of the cooperatives is rather large considering that it is purely attributable to the institutional form and completely independent of the technology.

It is possible that cooperatives might have offered even more advantages in terms of cost efficiency. There is some evidence of economies of scale through having larger or more centrifuges, although our evidence is from sources that are rather late in our period and which only compare cooperatives of different sizes. *Danmarks Mejeri-Drifts-Statistik* (starting in 1899) is commented on both by Bøggild (1900, p.27-28) on the 1900 figures and Brinkmann (1908, pp. 78-80) on the 1899-1904 figures. They calculated the working expenses measured in øre per 1000 (Danish) pounds of milk and found that these were generally 50 percent lower in the largest compared to the smallest class of creameries. Brinkmann, furthermore, calculates the total cost including the costs of milk transport to the creamery and finds that these do not completely offset the cost advantage, although they diminish it to about one third.

This opens up the question of whether or not the cooperatives were superior because they grew through attracting more suppliers and because they gave their suppliers the best incentive to expand their herds. We know from our readings of the minutes of their meetings that the cooperatives were indeed concerned about this issue: so concerned that they often awaited the building of the creamery until they had ensured that the owners of at least 300-400 cows would join them. In addition to these efforts, the annual amount of milk delivered from a given herd was boosted by winter stall feeding, much encouraged by the cooperatives, see Henriksen and O'Rourke (2005). So it appears that the cooperatives, by establishing large creameries, also enjoyed significant cost advantages compared to rival institutional forms.

8. Conclusions

This has been the first attempt to quantify some of the well known hypotheses for explaining the success of the Danish dairy system at the end of the nineteenth century, using a new database of dairy statistics. We find that the old technology exhibited diminishing returns to scale whilst the new technology exhibited constant returns to scale. The inefficiency of the estates and the private creameries at 7% was approximately the same under the new and the old technologies and twice that of the cooperative dairies, thus demonstrating that the institutional innovation had an impact separate from that of the technological innovation. For the story of the take off and growth of the Danish economy, both technology and institutions clearly mattered.

References

Acemoglu, D., S. Johnson and J.A. Robinson (2005). Institutions as a Fundamental Cause of Long-Run Growth. *Handbook of Economic Growth*, Chapter 6, pp. 385-472

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

Álvarez, A. and C. Arías (2004). Technical efficiency and farm size: a conditional analysis. *Agricultural Economics* 30, 241-250

Attack, Jeremy (1987): 'Economies of Scale and Efficiency Gains in the Rise of the Factory in America, 1820-1900', in: Peter Kilby (ed.), *Quantity and Quiddity: Essays in Honor of Stanley L. Lebergott*, Wesleyan University Press (1987), 286-335.

Axelsen Drejer, A. (1925-33). Mejeribruget. In K. Hansen (ed.). *Det danske landbrugs historie*. 4. bind. Copenhagen: G.E.C. Gads Forlag.

Ayers, Robert U. (1989): *Technological transformations and long waves*, Vienna: International Institute for Applied Systems Analysis (RR 89-1).

Bailey, D., B. Biswas, S.C. Kumbhakar and B.K. Schulthies (1989). An Analysis of Technical, Allocative, and Scale Inefficiency: The Case of Ecuadorian Dairy Farms. *Western Journal of Agricultural Economics* 14(1), 30-37

Battese, G.E. and T.J. Coelli (1995). A Model for Technical Inefficiency Effects in a Stochastic Frontier Function for Panel Data. *Empirical Economics* 20, 325-332.

Bjørn, C. (1977). Fællesmejerierne – En fase i Dansk Mejeribrugs Udvikling. *Bol og by* 2 (1), pp. 65-80.

Bjørn, C. (1982). *Dansk mejeribrug 1882-1914*. Aarhus: De Danske Mejeriers Fællesorganisation.

Brinkmann, Th. (1908). *Die dänische Landwirtschaft*. Jena: Gustav Fischer

Burhop, C. and Th. Lübbers (2009). Cartels, Managerial Incentives, and Productive Efficiency in German Coal Mining, 1881-1913. *Journal of Economic History* 69 (2), 500-527.

Bøggild, B. (1895). Mælkeribruget i Danmark 1894. *Tidsskrift for Landøkonomi* 5:14, 98-134.

Bøggild, B. (1896). *Mælkeribruget i Danmark*. Copenhagen: Det Nordiske Forlag.

Bøggild, B. (1899). Mælkeribruget i Danmark 1898. *Tidsskrift for Landøkonomi* 5:18, 133-163.

Bøggild, B. (1900) *Andelsmælkerierne og deres Betydning for det danske Landbrugs Udvikling*. Odense: Mælkeritidendes Forlag

Clark, Gregory (1994): Factory Discipline, *Journal of Economic History* 54, 128-163.

Danmarks Mejeri-Drifts-Statistik (1899-1904) edited in Odense by Udvalget for Mejeri-Statistik

Ellbrecht, G. (1915-18). *Danske Mejerier. Illustreret haandbog for mejeribruget i Danmark.* Copenhagen: Selskabet til Udgivelse af Nationale Haandbøger.

Fan, Y., Q. Li and A. Weersink (1996). Semiparametric Estimation of Stochastic Production Frontier Models. *Journal of Business & Economic Statistics* 14:4, 460-468

Fenger, R. (1873). Kan Kjødproduktionen betale sig under de nuværende Forhold i Danmark? *Tidsskrift for Landøkonomi*, 4:7, pp. 381-408.

Goldberger, A. S. (1968). The interpretation and estimation of Cobb-Douglas Functions. *Econometrica*, 35, 464-472.

Hallam, D. and F. Machado (1995). Efficiency analysis with panel data: A study of Portuguese dairy farms. *European Review of Agricultural Economics* 23, 79-93

Henriksen, I. (1993). ‘The transformation of Danish agriculture’ in K.G. Persson (ed.) *The Economic Development of Denmark and Norway since 1870*. Aldershot: Edward Elgar.

Henriksen, I. (1999). Avoiding lock-in: Cooperative creameries in Denmark, 1882-1903. *European Review of Economic History*, 3 (1), 57-78.

Henriksen, I. and M. Hviid (2005). Diffusion of new technology and complementary best practice: A case study. *European Review of Economic History*, 9 (3), 365-397.

Henriksen, I. and K. H. O'Rourke (2005). Incentives, technology, and the shift to year-round dairying in late nineteenth-century Denmark. *Economic History Review* LVIII (3), 520-545.

Heshmati, A. and S.C. Kumbhakar (1994). Farm Heterogeneity and Technical Efficiency: Some Results from Swedish Dairy Farms. *The Journal of Productivity Analysis* 5, 45-61

Hviid, M. (2006). Incentive Pay in the Danish Cooperative Dairies. *Advances in the Economic Analysis of Participatory and Labor-Managed Firms* 9, 149-176.

Jensen, S.P. (1985). Landbrugets systemskifte 1870-1914 belyst gennem dagbøgerne og regnskaber fra en enkelt gård. *Bol og By* 2 pp. 56-101.

Jensen, S.P. (1988). ‘Planteavlen 1860-1914’ and ‘Husdyrbruget 1860-1914’. In: Bjørn, C. (ed.). *Det dansk landbrugs historie III,* 1810-1914. Odense: Landbohistorisk Selskab.

Johansen, H.C. (1985). Danish historical statistics 1814-1980*.* Copenhagen: Gyldendal

Kumbhakar, S.C. and C.A.K. Lovell (2000). Stochastic Frontier Analysis. Cambridge: Cambridge University Press.

Kumbhakar, S.C., B. Biswas and D. Bailey (1989). A Study of Economic Efficiency of Utah Dairy Farmers: A System Approach. *The Review of Economics and Statistics* 71:4, 595-604

Kumbhakar, S.C., S. Ghosh and J.T. McGuckin (1991). A Generalized Production Frontier Approach for Estimating Determinants of Inefficiency in U.S. Dairy Farms. *Journal of Business & Economic Statistics* 9:13, 279-286

Landes, David S. (1986): What Do Bosses Really Do?, *Journal of Economic History* 46, 585-623.

Mælkeritidende, tidsskrift for dansk mejeribrug (edited Odense by Dansk Mejeristforening). various dates.

Mann, Julia de L. (1958): 'The Textile Industry: Machinery for Cotton, Flax, Wool, 1760-1850', in Charles J. Singer et. al. (eds.), *A History of Technology IV: The Industrial Revolution, c. 1750 to c. 1850*, Oxford: Oxford University Press, 277-307.

Marglin, Stephen A. (1974): What Do Bosses Do? The Origins and Functions of Hierarchy in Capitalist Production, *Review of Radical Political Economics* 6, 33-60.

O'Rourke, K.H. (2007). Culture, Conflict and Cooperation: Irish Dairying before the Great War. *Economic Journal* 117, 1357-1379.

Pedersen, J. (1999). *Teknologisk udvikling i maskinindustrien, Burmeister & Wain 1875-1939*. Copenhagen: Polyteknisk forlag.

Pedersen, M. C. (1885; 1981 reedn by C. Bjørn). *Beretning om Andelsmælkerivirksomheden i Vestjylland 1884-85*. Esbjerg: Sydjysk Universitetsforlag.

Persson, K.G. (2010). *An Economic History of Europe: Knowledge, Institutions and Growth, 600 to the Present*. Cambridge: Cambridge University Press

Sokoloff , Kenneth L. (1984): Was the transition from the artisanal shop to the nonmechanized factory associated with gains in efficiency? Evidence from the U.S. Manufacturing censuses of 1820 and 1850, *Explorations in Economic History* 21, 351-382.

Sonne, Chr. (1883). Mejeribruget i Danmark 1882. *Tidskrift for Landøkonomi* V (2), 33-60.

Tauer, L.W. (2001). Efficiency and Competitiveness of the Small New York Dairy Farm. *Journal of Dairy Science* 84, 2573-2576

Tidsskrift for Landøkonomi (edited in Copenhagen by Det kgl. danske Landhusholdingsselskab), various issues.

Van der Vleuthen, E. (1994). Smør og Damp. In: H. Buhl and H. Nielsen (eds.). *Made in Denmark. Nye studier i dansk teknologihistorie*. Aarhus: Klim.

Williamson, Oliver E. (1980): The Organization of Work. A Comparative Institutional Assessment, *Journal of Economic Behavior and Organization* 1, 5-38.