UNIVERSITY OF OXFORD

Discussion Papers in
Economic and Social History

Number 27, Dec. 1998

THE DIFFUSION OF THE HERRINGBONE PARLOUR: A CASE STUDY IN THE HISTORY OF AGRICULTURAL TECHNOLOGY

OLIVER GRANT

St. John's College, University of Oxford

Discussion Papers in
Economic and Social History

are edited by:

papers may be obtained by writing to
Avner Offer, Nuffield College, Oxford, OX1 1NF
email:avner.offer@nuffield.ox.ac.uk

Abstract

The herringbone parlour, a mechanical milking technology, was invented in 1908, but took over 70 years to be adopted by the majority of British farmers. Among the reasons were the need to improve original designs, the need for complementary institutional changes such as management systems, new labour contracts and suitable herd sizes. These determinants are analysed by means comparison of regions in Britain, which also brings out roles for farmer age, capital constraints, resistance to change, and path dependence. A critical factor was the ability of regions which were late adopters to avoid investment in intermediate systems and to leap-frog the leaders. The paper concludes with a theoretical model of the innovation process.

Abbreviation: MMB – Milk Marketing Board

THE DIFFUSION OF THE HERRINGBONE PARLOUR: A CASE STUDY IN THE HISTORY OF AGRICULTURAL TECHNOLOGY.

I. Introduction.

The "herringbone" is a simple design of milking parlour[1]: a place to which cows are brought to be milked. It is a configuration of cow places, operator pit, stall-work, exit and entry gates, which maximises cow through-put, and minimises operator discomfort and the time spent milking each cow. It enables a large number of cows to be milked by one person. It made it possible to realise the full economic potential of mechanical milking (originally developed around 1900).

Despite the benefits offered by the system the diffusion process took a long time. The system was first invented in Australia around 1908-9. But it was not until the early 1980's that the design was adopted by the majority of British herds. This study looks at the reasons for this seventy-year gap between invention and adoption.

The main findings are that the process of diffusion involved far more than the construction of parlours to a single unaltered design. The design itself had to be adapted to local conditions. But more importantly a system had to be evolved which made effective use of the design. This involved a series of other changes: in management systems, in labour relations, in the organisation of related farm tasks, and in the understanding of diseases and other veterinary problems. These added up to a major exercise in "learning-by-doing".

It was only after the learning-by-doing process had been completed that it became possible to organise a dairy farming enterprise on a scale which derived the full economic benefit from the new design.

The role played by learning-by-doing in the diffusion of technology has important implications. In the first place the outcome can be hard to predict. It is only when the learning-by-doing process is complete that a technology can be fully evaluated. It may be necessary to explore the possibilities offered by a number of designs before the best one can be selected.

Secondly, much of the information may be hard to transmit. The experience acquired in the operation of new designs will consist to a large extent of "tacit" knowledge, not easily "codified", and the transmission of this may require personal contact, and quite possibly the existence of facilitating institutions (formal or informal) or "networks".

Thirdly, the effect of learning-by-doing is to create "sunk costs" associated with any technology which has been in operation for some time. Those who have invested in some mature technological system may be reluctant to change to a superior system for the reason that they will thereby lose the value of the knowledge accumulated operating the older system. Eventually, competition from new entrants and others may oblige existing producers to switch but this could take some time.

II. A brief history to 1945.

The basic concept of the modern milking machine, a vacuum-operated intermittent suction unit, was developed in the late nineteenth century. With the patenting of the double-chambered teat cup in 1903, the design problems which had limited the effectiveness of earlier mechanisms were largely solved, and the form of the basic unit has remained essentially the same since that date[2]. However, the full economic potential of this engineering breakthrough could only be realised when it was embodied in a system which made the most effective use of the operator's time, minimising the time spent on activities such as cow-handling, milk transfer and just walking between cow places.

In a 1912 publication of the government of New South Wales, *Dairying in Australia*, a government dairy advisor, M.A.O'Callaghan described a system then known as "Echelon Milking Stalls" which had been invented, patented and installed by an Australian farmer, W.L.Boyce in 1908/9. He concluded: "it is highly adapted to the milking of cattle by machinery.... it is undoubtedly a money-saving affair[3]".

---

[1] diagrams showing the different designs are provided in an appendix.
[2] Collins (1992) p.6.
[3] O'Callaghan (1912) p.13.

Fifty years later only 2% of British dairy cows were milked using this system, then called the herringbone parlour. But over the next 20 years O'Callaghan's opinion came to be shared by the majority of British dairy farmers. By the early 1980's 70% of cows were milked in herringbone parlours[4].

The obvious question is: how did this take so long? The design was described and illustrated in a published work in 1912, yet it took 70 years for the majority of herds to use it.

The first part of the answer is that, in the period up to 1945, British farmers were slow to adopt mechanical milking of cows in general. There were a number of difficulties with mechanical milking. These were foremost problems of hygiene and cleanliness. Tests carried out by the New York State experimental station in 1906 found 692,542 bacteria per c.c. in milk produced by machine milking against 16,643 per c.c. in milk produced by hand milking.[5] This was obviously unacceptable. Much effort went into the development of cleaning systems. Brine soaking was tried. Steam cleaning was more effective but caused rapid deterioration of the rubber parts. The only solution before the development of stronger, steam-resistant, rubbers was complete dismantling and hand cleaning of the equipment. Even with steam cleaning this was necessary on a periodic basis.[6]

Despite these disadvantages Australian and New Zealand farmers moved over to mechanical milking. By 1919-20 51.2% of the New Zealand herd was milked mechanically, and this rose to 74% in 1931[7]. The uptake in Britain was much slower. It is estimated that in 1934-5 only 11-12% of cows in England and Wales were machine milked, and this increased to just 15% in 1939[8].

There were a number of reasons for this difference. Labour shortages were a factor in the early interest shown by Australian farmers. To quote O'Callaghan in 1912: "every Australian farmer who has had to manage with hand labour for milking is generally ready to grumble. It appears that not only is it difficult to get good milkers in Australia at present, but it is also difficult to keep them, and this has led to the share system in dairying, a system whereby the farmer provides the land and the cattle, and the dairyman..... provides all the labour for milking, separating etc. and growing the necessary fodder for the cattle. The latter obtains a certain percentage of the gross earnings, which varies from one half to one third." Machine-milking offered Australian farmers the opportunity to reduce their dependence on hired labour.

In Britain labour was, apparently, not so short. Productivity in the English dairy industry had been stagnant or falling for some time. It is estimated that in 1860 milk output per labour hour was 4.29 galleons, in 1910 this had fallen to 3.83 galleons[9]. It is not part of this study to consider reasons for this poor performance, which may well have reflected an accurate assessment of the potential profits to be made from investments in dairying, but the important point is that the situation of the British dairy industry in the early twentieth century was, when compared to the more advanced countries such as Australia, New Zealand and the United States, one of low productivity, low wages, low investment and, partly in consequence, slow uptake of innovations.

In the interwar period the slow progress of mechanical milking gave rise to concern, resulting in a number of publications, official and unofficial[10]. These concentrated on two aspects of the problem: the difficulty of maintaining high hygienic standards and the need for efficient labour organisation if the potential of mechanical milking were to be fully realised. In the context of the 1920's and 1930's some caution on the part of farmers with regard to innovations which threatened hygiene standards was understandable. Fresh milk had a rather poor reputation as a possible source of infection, and farmers and farmers organisations were concerned to improve standards and to promote milk as a safe and healthy product. In fact the main threat to human health came from bovine tuberculosis, which was not affected by milking procedures, but the general level of concern was high, and mechanical milking was regarded with suspicion as a result.

---

[4] MMB figures: MMB (1970);MMB (1984).
[5] quoted in O'Callaghan (1912) p.400.
[6] the solution to this problem was eventually found in the 1950's through the use of caustic soda.
[7] Philpott (1937).
[8] Bridges (1939) p. 64.
[9] estimates from Taylor (1976).
[10] amongst others: the 1919 Enquiry into the Use of Milking Machines, Ministry of Agriculture (1919), Wiltshire County Council (1937), Petitt (1939) and Hoyland (1939).

Farmers were also concerned about the effects on the health of their cows. The main worry was mastitis[11]. Again, milking procedures were not the cause of this problem. When better mastitis control procedures were developed in the 1950's and 1960's these involved greater emphasis on clean bedding, better fly control, teat disinfection after milking and the use of prophylactic antibiotics for the dry period. But in the 1930's it was widely believed that mastitis was caused by a failure to extract every last drop of milk from the udder during milking. Consequently it was a common practice in herds milked mechanically to use "hand-stripping", meaning that the final stage of the milking was carried out by hand. Later special procedures for "machine-stripping[12]" were developed. However, once the mastitis problem was better understood (from about 1965 onwards) both procedures were abandoned, with a consequent gain in efficiency. This in turn made the adoption of improved milking systems much easier.

Labour problems were another theme of the literature of the interwar period. There was resistance to the introduction of mechanical milking. Farmers who invested in the new technology were often unable to persuade their workers to operate it. They were, on occasions, obliged to replace their entire workforce with younger workers, or with workers from a non-agricultural background[13]. But Hoyland, whose 1939 study of the problem gives a relatively balanced contemporary view, made the point that farmers were offering their workers little reason to co-operate in the introduction of the new technology. He quoted two anonymous workers:

> "I know how this machine should be worked, and I could work it like that, but why should I? Before it was put in four of us did the milking at 35/- per week each. Two of those men have been sacked, saving the master £3: 10/-, and my mate and I still get the same money. If he had given us 5/- a week extra we'd have worked it as well as the next."

and another:

> "I'm a good hand milker, and was getting 42/- a week before this thing came in. Now I've got the **** stripping to do at 6/- a week less money, and what I think is **** the machine milking[14]."

Hoyland's conclusion is that it was a "lack of understanding of the workman's mental outlook" which was holding up the spread of machine milking: "the erroneous impression that any fool will do to operate a milking plant is too prevalent". This in turn was responsible for many of the prejudices against mechanical milking: that it led to low yields, udder troubles and short lactations.

If there was a reason for the niggardly attitude of farmers, it may have lain in the limited increase in profits which they were achieving from mechanical milking. A study by G.H.N.Petitt published in 1939 used data from 63 herds collected in 1934-7[15]. This showed a saving of labour costs of £1:11/- per cow per annum from mechanical milking, but the deduction of running costs, depreciation and interest reduced this to 19/- per year. On a thirty cow herd, with two herdsmen, the £28:10/- increase in annual profits would have been largely swallowed up by the offer of a 5/- weekly wage rise, costing £26 per year. This may explain why farmers were reluctant to pay more for mechanical milking.

The problem was that, although mechanical milking did reduce milking time significantly, milking time was only a relatively small part of the total time spent tending the cows. Hoyland estimated that milking a 60 cow herd by hand would require 18 man hours daily. This could be reduced to 10 hours using mechanical milking into buckets. But only 25% of the total labour time was devoted to milking, so the reduction in total labour hours was just 11%[16]. Keeping cows in cowsheds was labour-intensive, involving much handwork for feeding and dunging-out.

---

[11] an inflammation of the udder caused by a variety of bacteria, commonly found in straw bedding or carried by flies.

[12] one procedure involved the placement of weights on the clusters during the final stage of milking, at the same time the dairyman would massage the udder to improve letdown. Such things are unknown in the modern dairy industry and of interest only to historians.

[13] for the memoirs of a farmer who had this experience, see Street (1932). Farmers' memoirs inevitably give a rather one-sided view of the problem.

[14] Hoyland (1939) p.19; asterisks as in original.

[15] Petitt (1939); a number of other studies are mentioned in Collins (1992), mostly these give similar results, Bridges (1939) showed a 20% labour saving from mechanisation for large herds.

[16] Hoyland (1939) and Collins (1992).

Hoyland's figures are almost identical to those produced by Petit. A saving of 8 hours for a 60 cow herd, with labour costing 35/- for a 50 hour week, implies a saving of £1: 14/- per cow per annum. The farm worker previously quoted saw his master's wage bill falling by 70/- per week, implying savings of between £4:10/- and £6 per cow per year (depending on herd size). The discrepancy shows that the savings anticipated, both by farmers and by their workers, were not being realised in practice.

To what extent this was due to the uncooperative attitude of labour, implying that the industry was stuck in a low pay - low productivity game theoretic equilibrium, with neither party able or willing to make the move which could have led to a new high pay - high productivity equilibrium, is difficult to say. The alternative view is that the introduction of mechanical milking in British agriculture, with its costly system of winter housing, simply created bottlenecks, or "reverse salients", in other areas[17].

To break out of this position would require simultaneous advances in milking technology, in housing systems and in labour relations. This could come about either as an act of entrepreneurial initiative, or as a result of cost pressures, especially from wages, which would then force farmers to undertake the inevitably costly process of search, and of trial and error, which would be needed to find solutions to these problems.

One radical approach was developed by a Wiltshire dairy farmer, Arthur Hosier, in the 1920's. This did away with the cowshed altogether. Instead the cows were kept out all year and milked in "bails", portable milking parlours incorporating a diesel engine, vacuum plant, milk cooling facility and (typically) four stalls connected to a pipeline. The system was particularly suitable to the free-draining chalk downlands of southern England. It had considerable advantages. Getting away from the cowshed improved cow health, and reduced the risk of tuberculosis. It was more hygienic: the bail could be moved each day to a fresh patch of ground, which was better than trying to produce clean milk in a dirty cowshed. Much less time was required for feeding and bedding the cows. Milking times were much faster than in the cowshed. Forty cows per hour were possible with one milker, reducing total daily milking time for a sixty cow herd to just 3 hours[18].

There were also disadvantages to the system. It was only suitable to the lighter, free-draining soils. Even on these, keeping cows out in the winter was difficult. In a bad winter cow condition and milk yields would suffer. This was a particular problem because the town dairies offered higher prices to secure supplies in the winter months. Although the number of cows milked through bails went on increasing into the 1960's, at the peak it was only 6.6% of the total herd, and the system declined rapidly in the 1970's, faced with competition from newer parlour designs and more modern housing systems.

However, the bail did offer a very cheap way of starting up a dairy herd, and quite a number of farmers who went on to develop large herds using different systems started their farming careers milking through a bail. Perhaps this encouragement to entry through lowered barriers was the most important feature of the system.

Hosier set up his own firm to manufacture milking plants and concentrated on this business. The bail system was extremely effectively used by a Hampshire farmer, Rex Patterson, who started milking with a bail in 1928 (milking the cows himself), and built up, over the next thirty five years, a farming empire which came to include 18 farms, totalling 9,000 acres, and 3,000 dairy cows[19].

Patterson is of interest for a number of reasons. He became a well-known (if controversial) figure in British agriculture. His entrepreneurial drive and evident success, particularly in the 1930's and 1940's, contrasted strongly with the generally depressed state of British farming, and made him a source of inspiration to younger innovative farmers in the 1950's and 1960's. He showed that large scale farming, using modern technology, was both possible and profitable under British conditions.

Patterson also found a solution to the labour problems which had troubled other farmers. He did not set up large herds, typically his herds had 40-60 cows (this increased to around 80 in the 1960's). This

---

[17] with perfect labour divisibility this should not be a problem, but in practice, on a farm, labour is not fully flexible. Certain tasks have to be performed at certain times in the day. Labour released from one job cannot necessarily be redeployed on another.

[18] Hosier described his farming system in an article published in Orwin (1931) pp.1-36.

[19] Patterson (1965); Patterson's farms were in Hampshire, Wiltshire, Dorset, Somerset and South Wales; these being the regions which offered the most suitable conditions for the out-wintering of dairy cattle.

meant that the herd could be looked after by a single stockman, who was given considerable responsibility. In 1965 Patterson set out his principles for labour management:

- create the best possible working conditions;
- isolate the stockman and his unit, "so that he has the maximum opportunity to show his ability" and to "see how his results compare with others working under similar conditions";
- "encourage an employee to accept as much responsibility as possible" and "give the opportunity to increase earnings by bonus payments";
- "give them the opportunity to act as if they were self-employed, and the freedom to use their own initiative within the framework of the general policy[20]".

. Patterson was an innovator in the development of management systems and the organisation of labour as well as in the use of technology. He offered his workers greater responsibility and motivated then by bonus payments, at a time when other farmers were trying to solve problems through stricter management control. In effect he introduced a different type of labour contract.

In the 1930's Hosier and Patterson were pioneers whose approach to technology contrasted with the general attitude which was one of reluctance to change. However, the second world war brought about a change. Wartime labour shortages meant that there was no alternative to mechanisation. The number of dairy farms using mechanical milking increased from 23,860 in 1942 to 40,359 in 1946, despite the difficulty of obtaining the equipment. After the war the increase continued, to reach 69,176 in 1950[21].

Most of these installations involved the use of bucket plants in cowsheds. Although there were some improvements in the design of these machines, the increase would appear to owe more to labour shortages and wage rises than to technical developments. It can be argued that, in addition, high wartime prices, and indications that government support would continue in the post-war period, gave farmers the confidence to invest.

Contemporaries thought the threshold for mechanical milking had been brought down. A 1951 study calculated that a 15-20 cow herd would benefit from mechanisation, before the war the threshold had been around 25-30[22]. Higher wages affected this calculation. In the tighter labour market conditions of the post-war period it was more difficult to persuade younger family members, an important source of labour for smaller farmers, to stay on the farm.

The sharp decline in hand milking which began during the war continued until, by 1968/9, only 1% of cows were still milked by hand. However, the bucket-plant systems which initially replaced hand milking were cumbersome and slow. Early models had incorporated small electric motors to produce the vacuum, which made the equipment heavy and awkward. In the 1940's portable milking machines were produced, which were mounted on trolleys and could be pushed around the cowshed[23]. But the milk still had to be carried to the dairy by hand, using buckets or churns. These considerations limited the number of cows which could be milked by one person in a cowshed.

III. Diffusion in the 1950's and 1960's.

In the 1950's there was increased use of milking "parlours": specialised buildings in which the cows were milked. Separate buildings had to be provided for winter housing for herds on land which was not suitable for out-wintering.

The decline in the cowshed and the rise of alternative systems can be studied using the results of the Milk Marketing Board permanent sample of producers[24]. Figure 1 shows that, over the period 1963-

---

[20]ibid., Patterson invented a simple milk graph, in which a calculation of potential milk production was compared to actual production for each herd. It is still in use today (modified for increased yields).

[21] Collins (1992).

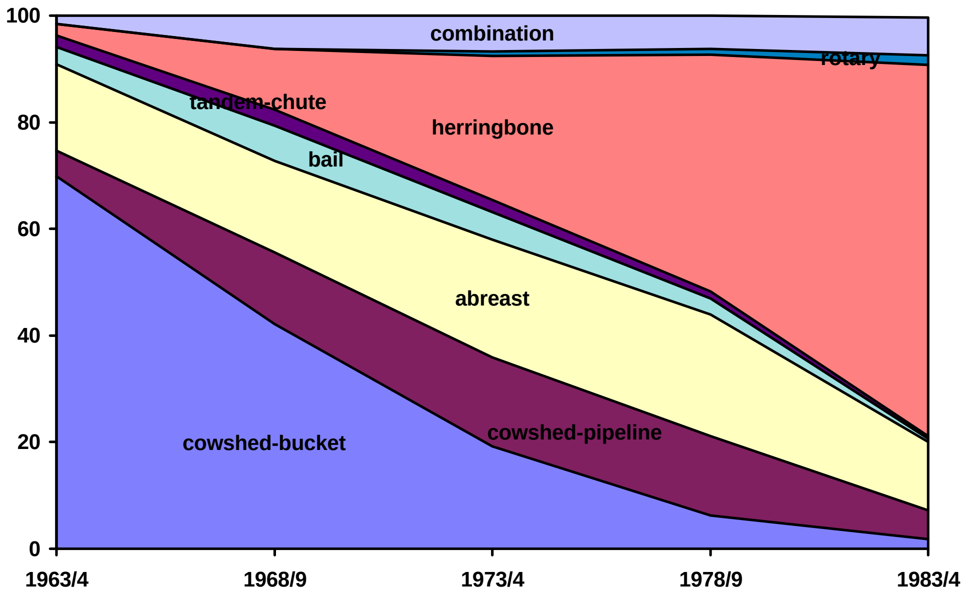
[22] ibid.; there was much discussion of thresholds at the time, and divergent views were expressed.

[23] according to the report on the first post-war dairy show, carried in the *Farm Equipment and Machinery Review (vol. 73, 1947-48, p.671)*, there was great interest in such machines, and one manufacturer (Alfa-Laval) reported selling 2,300 in twelve months.

[24] this was a sample survey of around 1,500 producers which was carried out in 1963/4, 1967/8, 1973/4, 1977/8 and 1983/4. The aim was the survey the same group of producers each time. The results were used in MMB publications and also in internal studies. The same questions were not asked on each occasion. The 1963/4 and 1969/9 surveys covered larger numbers of farms (6,000 in 1968/9).

1983, the UK dairy industry moved from one dominant technology, the milking of cows in cowsheds using bucket plants, to another, the use of herringbone parlours. However, in the intervening period a number of other systems were also tried.

Figures 1. Percentage of dairy cows in England and Wales (from MMB survey) milked in different systems.



The alternative systems represented a series of different technological paths. The first one was to seek to improve the cowshed by using a pipeline to transfer the milk to the dairy. Then there were a series of different parlour designs[25]. The herringbone was quite clearly the best, as was shown by the 1983/4 MMB producer survey, which recorded labour hours per cow.

Table 1. Annual labour requirements per cow, 1983-84 (in hours)[26].

Type of parlour	Milking time	Tending time	Total
Cowshed, with bucket system.	46.6	51.0	97.6
Cowshed, with pipeline.	32.8	28.4	61.1
Bail	29.4	25.0	54.4
Tandem/Chute	22.8	26.6	49.4
Abreast	25.1	20.5	45.7
Herringbone	17.0	15.1	32.1

This table shows that milking times were lower in parlours, and especially in the herringbone. It also shows that farmers investing in herringbones had also improved the efficiency of their other operations, so that tending time had fallen as well.

Why were the other designs tried at all? The answer seems to be that the advantages of the herringbone were not so apparent in the early 1960's as they were by the early 1980's. In a 1970 study the MMB commented:

"within the parlour system, the biggest improvement was made with the herringbone parlours whose potential has been more widely recognised in the last few years. The average labour performance

[25] some of which are illustrated in an appendix.
[26] MMB (1984); the 1983/4 survey seems to have been the only one to record the division of labour between milking and tending.

achieved with herringbone parlours in 1963-4 was only moderately higher than those of other systems. By 1968/9 the performance achieved with herringbones had drawn well ahead of the others, both in terms of cows milked per worker and per labour hour. It should, of course, be borne in mind that the herringbone in 1968/9 was not strictly the same system as in 1963-4. There have been improvements in design - sunken pits, improved automatic feeding devices, low level recording jars and pipelines, improved udder washing facilities, *etc*. Moreover these systems are very frequently combined with a farm vat which increases the proportion of time that a cowman can spend handling cows rather than churns[27]."

Moreover, there were still improvements to be made. Table 2 gives some figures from a study in 1970 of work routines in abreast and herringbone parlours.

Table 2. Work routines in abreast and herringbone parlours, in seconds per cow[28].

	Abreast	Herringbone
Wash cow	25	20
Take fore-milk (to check for mastitis)	9	5
Move to next cow	2	1
Machine strip	24	15
Remove cluster and transfer	4	3
Apply cluster	7	7
Move to next cow	2	1
Batch changeover	-	5
Cow transfer	9	-
Restraining chain	4	-
Move to next cow	3	1
Average work routine	89	58
Allowance for contingencies (15%)	14	9
Total	103	67

This table shows the advantages of the herringbone design fairly clearly. However, it also shows some of the factors which were slowing down milking in the 1960's. In both parlours considerable time is spent washing cows. Obviously this will be related to how dirty the cows are when they come in. In New Zealand, where the cows live outside, few should need washing. In a typical British straw yard system, a high proportion would have to be washed. But in the 1970's, the introduction of cubicle housing (when correctly managed) greatly improved cow cleanliness, which contributed to faster milking. Another item is "machine-stripping". This was common practice at the time. But with better understanding of mastitis it was abandoned, and instead much greater emphasis was placed on teat disinfection after milking (which took less time than machine-stripping). A third improvement came with the introduction of small visible filters in the milk lines. These eliminated the need to take foremilk (to check for mastitis clots).

The result was that the time spent on each cow could be reduced to 8 seconds when applying the clusters (from 33 seconds), and to 4 seconds when removing (from 26 seconds). With automatic cluster removers the time spent removing was eliminated. With time spent on each cow reduced by 80% there was obviously room to increase the number of points and hence overall cow throughput[29].

In short, what is described here is a classic case of learning-by-doing, of small improvements in parlour routine, and in other aspects of dairy husbandry, which cumulatively enabled the number of points controlled by one milker to rise from 4 to 16 or (with automatic cluster removers) 20[30]. But in the 1950's

---

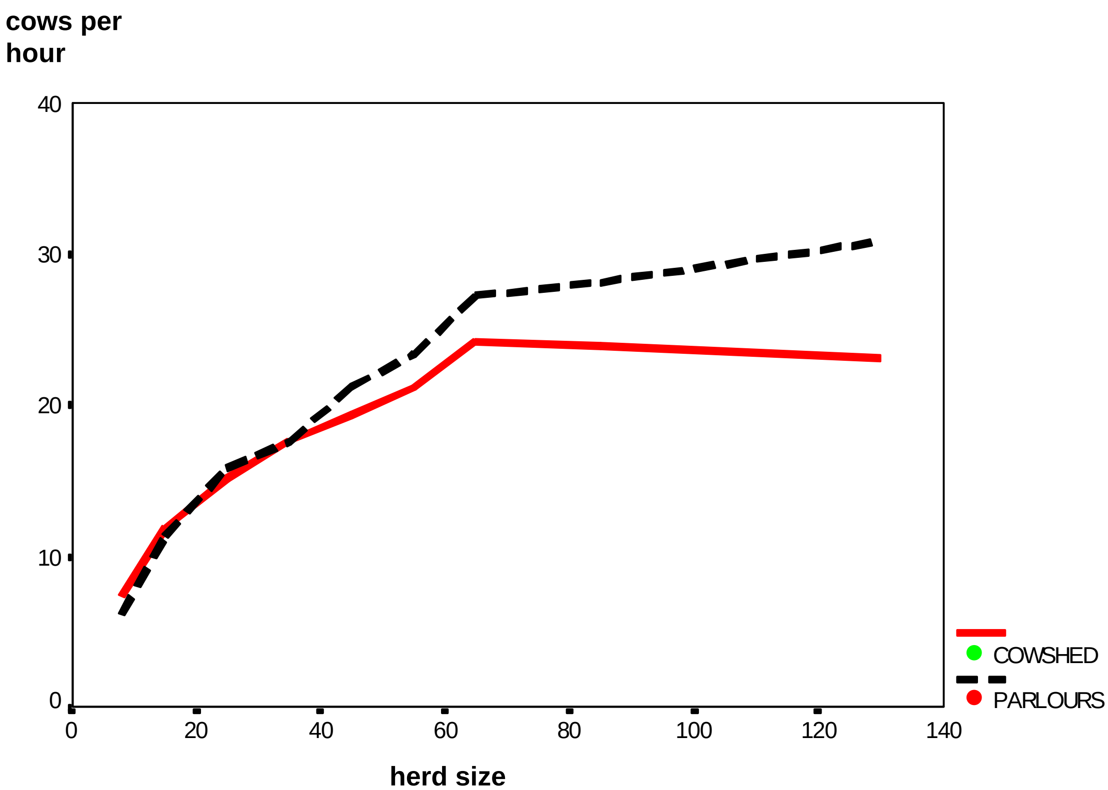
[27] MMB (1970); this implies that some of the earliest herringbones were constructed with inadequately sunken pits, which would explain their poor performance.
[28] Barnard et. al. (1970) p. 110.
[29] these figures are the ones implied from table 3.4, allowing for time to move between cows. They are in agreement with figures recorded from the author's own 20x20 herringbone (with ACR's) in 1991. It took on average 1 minute 8 seconds to apply clusters to a row of 10 cows: 7 seconds per cow.
[30] "....most long-run increases in technical efficiency.....have been the result of the cumulation of a myriad of small improvements. These incremental modifications are usually based on experience gained in actual

and early 1960's it was difficult to foresee the improvements which turned out to be possible with the herringbone parlour. And this explains the temporary popularity of the alternative designs.

IV. Thresholds and the regional pattern of diffusion.

Figure 2 shows the relationship between herd size and labour productivity[31]. The figures refer to all parlour types, not just the herringbone (bails are excluded). As can been seen, there was no advantage to parlour milking with herds of less than 40 cows in this period. At around 60 cows there was a difference of about 10%. Thereafter, as herd size increases, productivity in the cowshed stagnated at around 23-24 cows per hour, while productivity in parlours increased to 31 cows per hour.

Figure 2. Cows milked per labour hour, by herd size and system, for 1968/9.



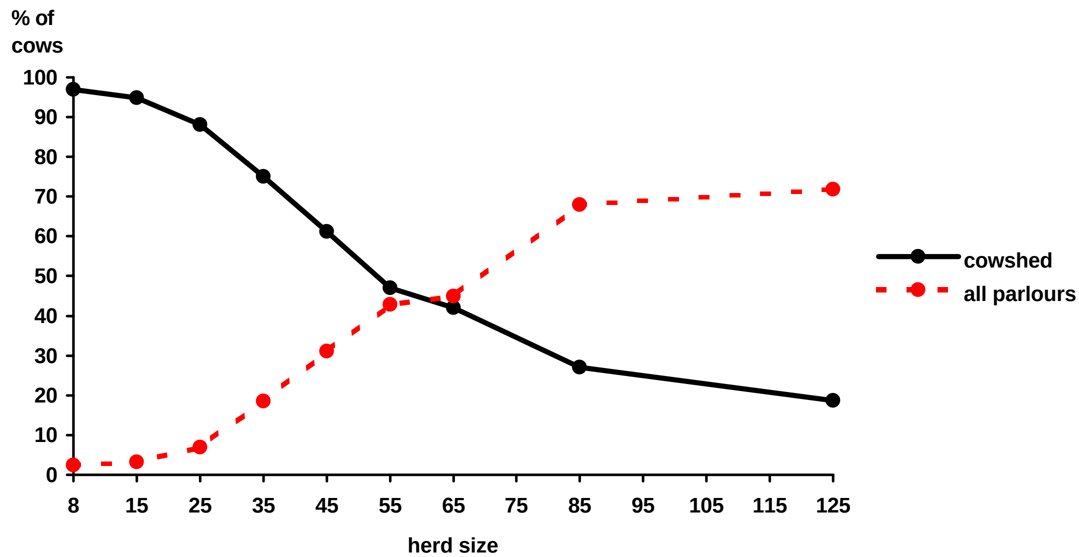
These results suggest that there might have been a threshold at around a herd size of 60 cows. Below this the difference was not great enough to justify scrapping existing equipment which was not already obsolete.

Looking at the relationship between herd size and the usage of parlours against cowsheds, as in figure 3, shows a crossover point which is, once again, at around 60 cows. The use of parlours overtakes the use of the cowshed at exactly the point where the productivity figures show productivity in the cowshed reaching a plateau. This appears to provide strong support for the existence of a threshold at this point.

production operations and in the repeated interactions between the users and the manufacturers and vendors of complex products" David (1993) p.217.

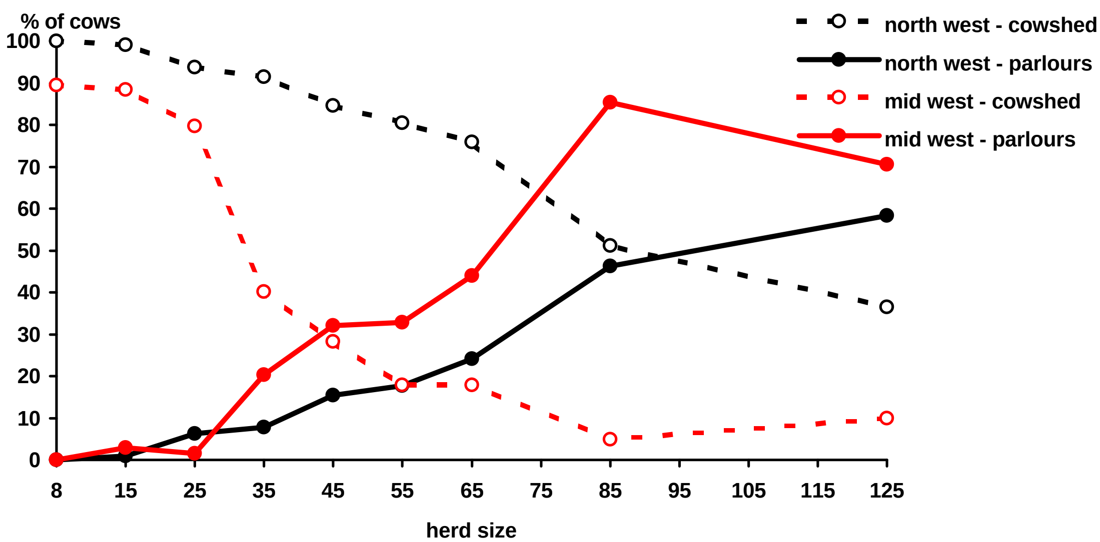
[31] published in MMB (1970) and MMB (1984).

Figure 3. Percentage of cows in each herd size category milked in cowsheds compared with the percentage milked in parlours, 1968/9, England and Wales.



However, when the relationship between herd size and the use of the different systems is examined at the regional level some striking discrepancies are found which considerably complicate the picture. There are eleven MMB regions, so graphical representation of results for all regions would be too complex. Econometric results will be presented later, but to give a flavour of the problem, figure 4.3 compares the two largest regions (by number of cows), North Western and Mid Western.

Figure 4. Percentage of cows in each herd size category milked in cowsheds compared with the percentage milked in parlours, 1968/9, north western and mid western regions.

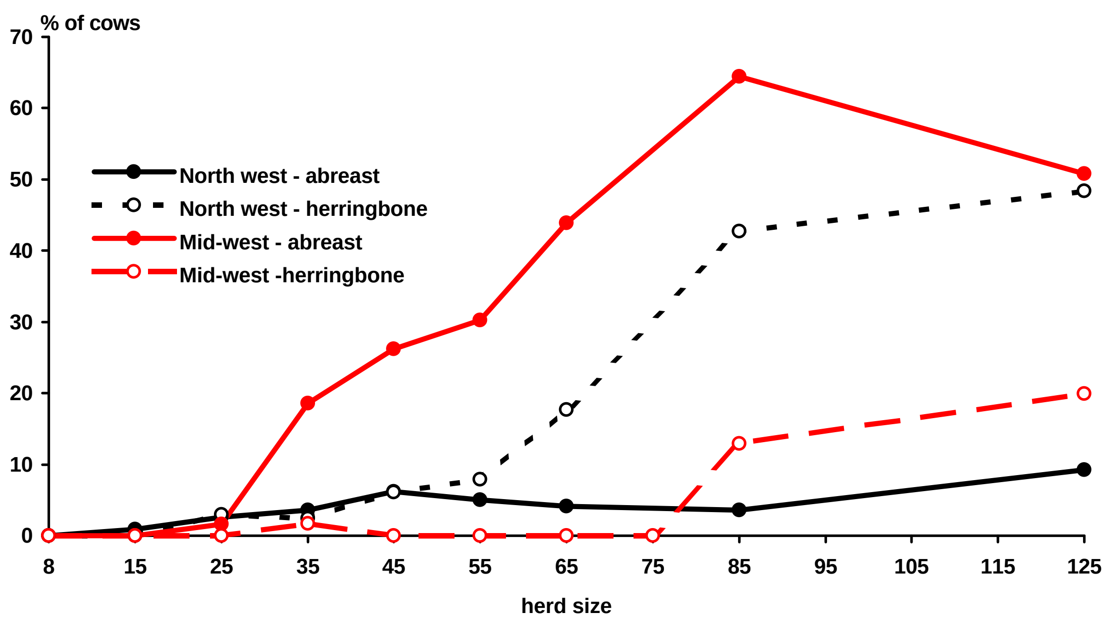


The picture in the two regions is a very different one. In the mid western region the crossover point is at around 45 cows (and if cows milked in bails were included with the other parlour designs, it would be lower still). In the north western region there is a crossover at around 90 cows (in the northern region the crossover was higher still, even when herd size rose above 100 cows, more cows were still milked in cowsheds than in parlours).

So, it appears that the threshold herd size above which farmers switched from the cowshed was 45 cows in one region, but 90 cows in another. And this was despite the existence of a national milk co-operative which set a uniform price for all regions.

Moreover, when the choice of successor system is compared there are also regional differences which appear to be unrelated to herd size. Figure 5 compares use of the abreast and the herringbone in the two largest regions.

Figure 5. Percentage of cows milked through abreast parlours compared with the percentage milked through herringbone parlours, north western and mid western regions, 1968/9.



Is there some connection between these results? Was the mid western region held back by an "early start", leading it to invest heavily in abreast parlours, which it was then reluctant to scrap? By contrast, did the fact that farmers in the north west held onto their cowsheds make it easier for them to leapfrog directly into the herringbone design?

V. Statistical analysis.

a). data and methodology.

The 1968/9 MMB survey provides information on milking systems used by a sample of 6,000 producers, grouped by region and herd size. There are eleven regions (England and Wales only) and nine size classes: a total of 99 groupings.

The analysis looked at two decisions: the first being the decision to give up the cowshed and the second being the choice of the herringbone as successor system. These are essentially binary decision variables. Consequently, the preferred method of analysis is Maximum Likelihood Estimation of a logit function. Two dependent variables are created: QCOWSHED being the number of sampled farms which still used the cowshed; QHERRBONE being the number of farms who no longer used the cowshed who had adopted the herringbone. Thus, the total count in the first stage of the analysis is the total number of sampled farms; in the second it is the number of farms who no longer used the cowshed[32].

---

[32] a further adjustment to the original data was the exclusion of farms using more than one system (which were recorded as "combination").

The form in which the results are presented makes it relatively easy to look at regional effects and the effect of herd size on diffusion. Having described the regional differences, the question then arises whether these are the result of some spatial process, the slow diffusion of information for example, or whether they reflect other explanatory factors which also differ by region. Six possible explanatory variables were considered:

Table 3. The additional explanatory variables:

	Description	Range	Expected effect on diffusion
FARMERAGE	"farmer age" - % of dairy farmers aged over 50	41.5-62.9%	-
INDIVFARMERS	"individual farmers"- % of producers who were neither partnerships nor companies	65.3-86.5%	-
TENANCY	% of producers who were tenants	27.9-45.3%	-
NONAIUSE	% of producers who did not use artificial insemination (standardised)[33]	see note	-
FRIESIAN	% of herds using Friesian cows	44.0-75.9%	+
ACUND100	% of the total acreage of dairy farms which was in farms of less than 100 acres	8.6-44.3%	-

These variables represent a number of factors which might be expected to affect diffusion. The age of the farmer will influence the time scale over which the pay-off from an innovation will be calculated. TENANCY and INDIVFARMERS will be important if there are capital constraints: tenant farmers can offer less collateral for borrowing; individual farmers may have less access to outside sources of capital. ACUND100 provides a measure of the extent to which herd size was constrained by farm size: small herds on large farms might be more prepared to innovate in the knowledge that there was no obstacle to increasing herd size to take advantage of a successful innovation. FRIESIAN and NONAIUSE proxy for "resistance to change" by measuring the up-take of other innovations which were also being introduced at the time.

Apart from NONAIUSE these variables are only available as regional averages. NONAIUSE is available for different herd sizes (from a different source - the agricultural census of 1965).

b).the decline of the cowshed.

The first step was to estimate a basic model with just HERDSIZE as an explanatory variable. This was then compared with an analysis allowing for regional effects (a) , and one which introduced the other explanatory variables (b). The results are given in table 4.

The addition of the regional effects produces a much better fit, as would be expected, with the percentage of correct predictions rising to nearly 84%. The pattern revealed is similar to that shown by previous analysis using regional dummies: the decline in the cowshed was most advanced in the southern and eastern regions: Midwest, South, Southeast and East.

All of the various explanatory variables have the "correct" signs. Apart from FRIESIAN they are all significant or nearly so. Judging from the t-ratios, it appears that NONAIUSE and ACUND100 have the strongest influence on diffusion.

[33] this was standardised because there was a strong negative relationship between herd size and artificial insemination, i.e. small farmers would be much more likely to use it. This is because a bull is a clear "indivisibility"(it would probably be a mistake to try), so smaller herds gain more from the use of AI. Standardisation removed this effect. Use of the unstandardised form produced a spurious positive coefficient when modelling diffusion.

Table 4. Logit analysis with QCOWSHED as the dependant variable.

model:	**basic model**		**a**		**b**	
	coefficient	t-ratios	coefficient	t-ratios	coefficient	t-ratios
HERDSIZE	.0344	32.5	.0339	29.4	.0339	29.9
NORTH			+1.76	10.6		
NORTHWEST			+1.88	12.7		
EAST			+.02	0.1		
EASTMIDLANDS			+.55	3.0		
WESTMIDLANDS			+.51	3.2		
NORTHWALES			+2.12	8.5		
SOUTHWALES			+.87	5.1		
SOUTH			-.30	1.6		
MIDWEST			-.47	3.0		
FARWEST			+.46	3.0		
ACUND100					+.051	8.0
FRIESIAN					-.001	0.2
FARMERAGE					+.039	2.9
INDIVFARMERS					+.012	1.7
NONAIUSE					+.861	10.2
TENANCY					+.023	2.9
Measures of fit[34]:						
Log likelihood ratio	1236.6 (97 df)		505.3 (87 df)***		745.4 (91 df)***	
% correct predictions	68.8		83.8		79.8	
squared correlation between pred. & count	.859		.979		.967	

One way of examining the results is to look at the percentage of correct predictions by region. This is done in table 5, for the basic model and for the model with the other explanatory variables added. Two statistics are given. The first shows the overall percentage of correct predictions. The second shows how the actual number of cowshed using farms compares with the predicted number, expressing the difference as a percentage of the total number of farms in the sample.

[34] predicted counts were compared with actual counts, both by adding up the number of correct predictions and by calculating a correlation coefficient. Asterisks in the log likelihood ratio row indicate whether the subsequent models have produced results significantly different from the basic model, as measured by a chi-squared test on the log likelihood ratio; *** shows a result significantly different at the 1% level, ** at the 5% level etc.

Table 5. Analysis of predictions by region.

model:	**basic model (HERDSIZE only)**		**b (HERDSIZE+ other expl var)**	
	overall % correct	pred. of cowshed[a]	overall % correct	pred. of cowshed[a]
1.NORTH	68.0	+16.0	72.1	+11.6
2.NORTHWEST	64.0	+18.0	90.5	+3.1
3.EAST	71.2	-12.0	80.5	-4.8
4.EASTMIDLANDS	82.6	-3.9	81.6	0.0
5.WESTMIDLANDS	79.7	-4.8	83.8	+1.9
6.NORTHWALES	65.8	+19.7	83.6	0.0
7.SOUTHWALES	71.8	+1.8	85.3	-7.3
8.SOUTH	66.4	-16.5	90.9	0.0
9.MIDWEST	57.0	-19.6	67.7	-11.0
10.FARWEST	79.2	+10.4	81.3	0.0
11.SOUTHEAST	64.6	-12.2	77.0	+2.2

[a] - positive value shows that actual level of cowshed use exceeded level predicted by model by a number expressed as a percentage of all sampled farms.

There is a close correspondence between the over or under prediction of cowshed use from the basic model and the regional effects shown by analysis a in table 1. Bearing in mind that approximately 2 % of herds moved away from the cowshed each year in the early 1960’s (according to the overall sample), the difference between the values shown for the MIDWEST and the NORTHWEST imply that, for herds of equivalent size, the midwestern region was nineteen years ahead of the north-west in the diffusion of alternative milking systems.

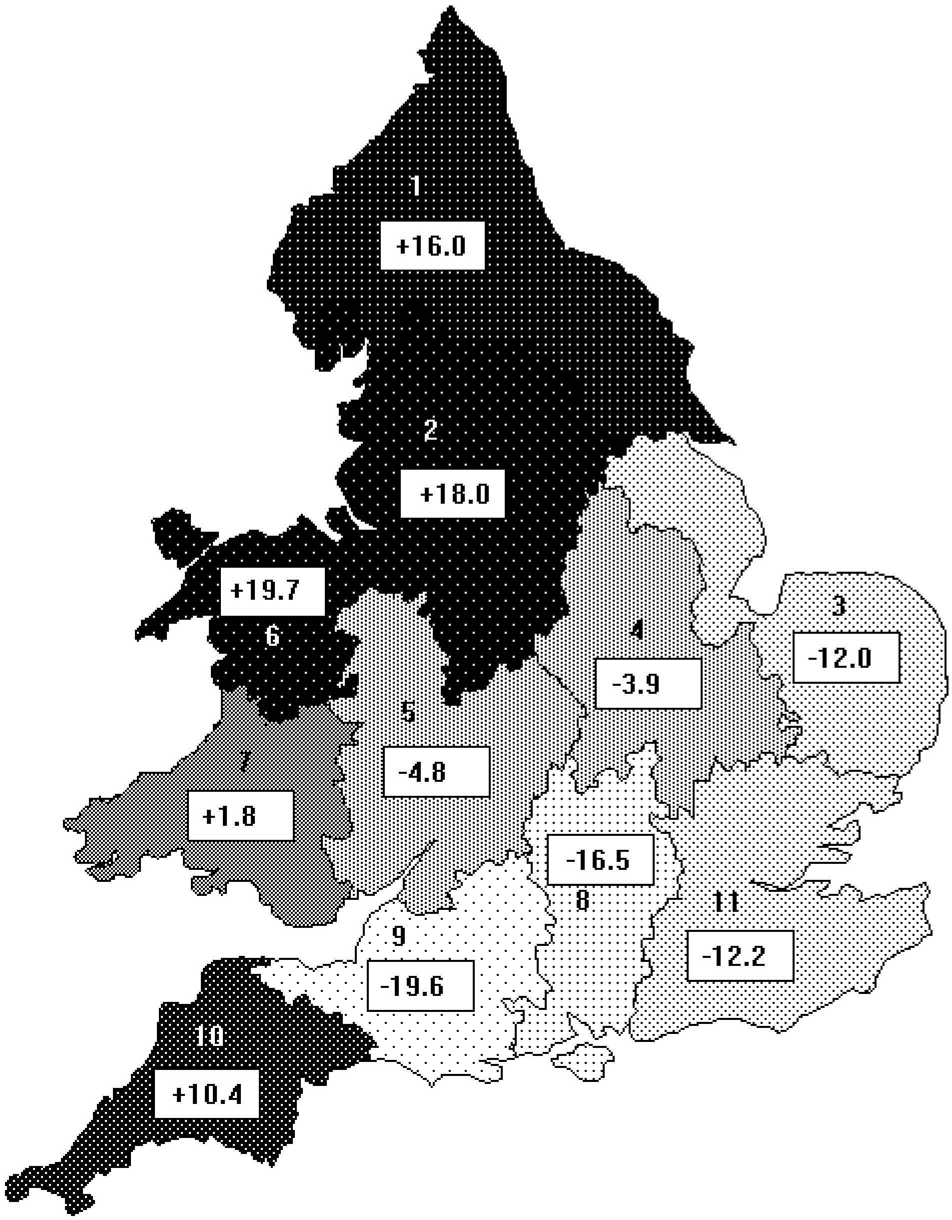
The second part of the table looks at the results when the other explanatory variables are added. There is an evident improvement in the accuracy of the predictions for all regions. Regional differences as measured by the over or under prediction of cowshed use are much less marked. The implication is that much of the regional variation in the decline of the cowshed can be explained by measurable regional differences in such factors as the size of farms and reluctance to use artificial insemination (proxying for resistance to change). However, this should not obscure the fact that important regional differences do still exist. The values shown for MIDWEST and NORTHWEST imply that for similar farms the diffusion of alternative designs was approximately seven years ahead in the midwestern region.

Another way of looking at the results is to consider the variance of cowshed use by region. The original figures for the percentage of herds using the cowshed had a variance of 384.7; the prediction errors shown in column two of table 2 have a variance of 206.6; those in the fourth column have a variance of 34.8. So the implication is that 46% of the original variation in cowshed use by region can be explained by differences in herd size; and a further 45% by the other explanatory variables, leaving just 9% unexplained[35].

To illustrate the results two maps are presented. The first (figure 6) gives the results for the comparison of actual cowshed use to the level predicted by the basic model (the second column of table 5).

[35] this refers to the variance in the total number of farms using the cowshed, the variance of the results by size class is less well explained. As table 2 shows, even when there is no tendency to over or under estimate cowshed use, there can still be 20% incorrect predictions because of unexplained variations by size class.

Figure 6. Comparison of the actual number of herds using the cowshed to the number predicted by the basic model (HERDSIZE as sole explanatory variable)[36].



The pattern has a strong regional aspect. The pioneer region was Mid-West. This was the region where the decline of the cowshed was most advanced. It was also the region where Hosier started his operations in the 1920's and where Patterson had a number of farms on the chalk downlands of Wiltshire and Dorset. However, the decline of the cowshed is not explained entirely by the use of bail systems on land suitable for out-wintering. Only 9.4% of herds were out-wintered in this region (the national average was 5.1%)[37]. Although bail use was certainly high, use of abreast parlours (which was not associated with out-wintering) was also twice the national average. The implication is that, in this pioneer region, the success of Patterson and others operating bails on the uplands stimulated lowland farmers to try related systems such as the abreast, which were suitable for in-housed herds.

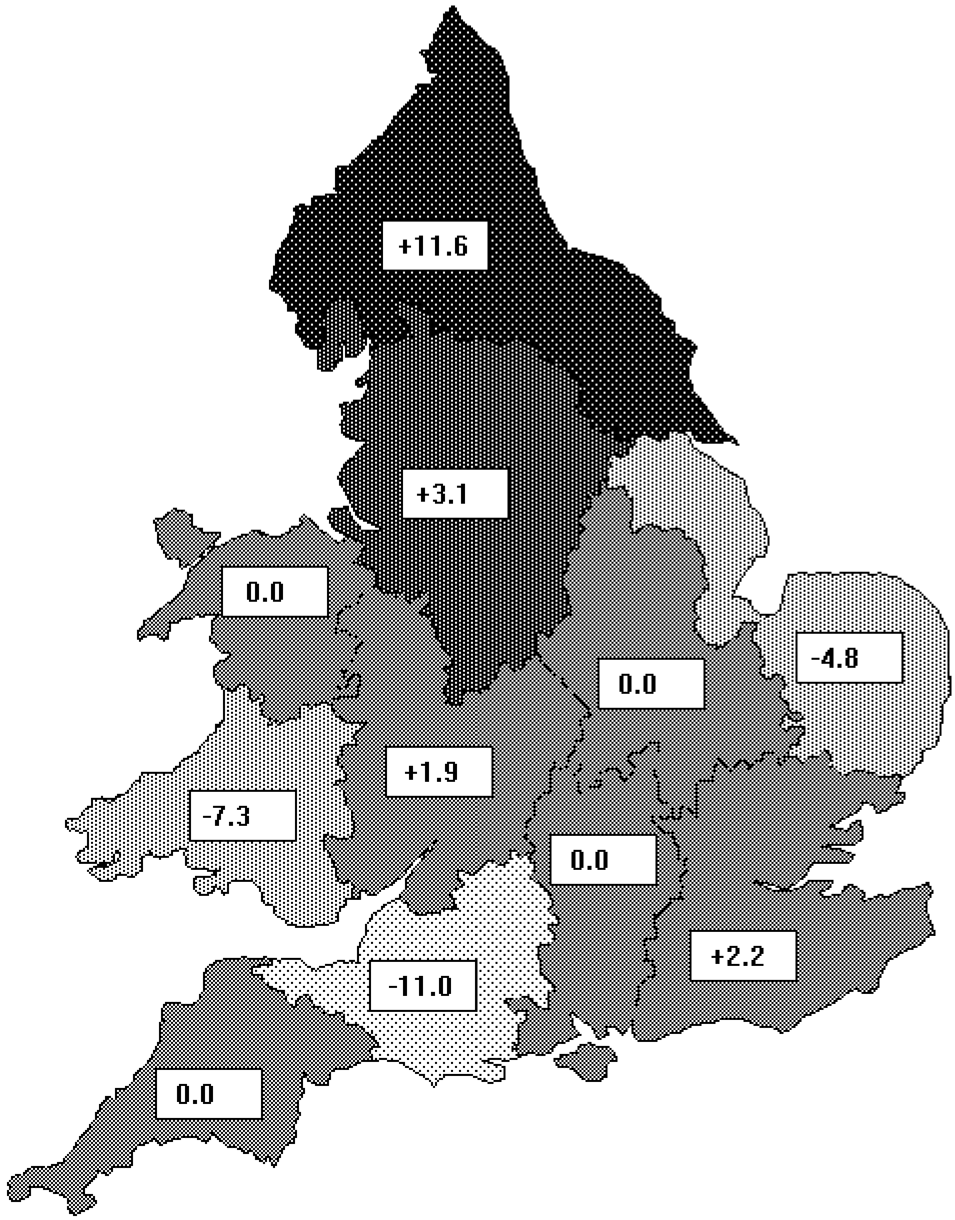
---

[36] see note a to table 5; regions are identified by numbers which refer to those used in table.

[37] MMB (1970) p.95.

From the Mid-West the pattern of diffusion is strongest to the east, and weakest to the west. However, this is not the pattern shown by figure 7, which compares actual cowshed use to the levels predicted when the other explanatory variables are added.

Figure 7. Comparison of the actual number of herds using the cowshed to the number predicted by model b (other explanatory variables added).



Again, the Mid-West is shown to be the pioneer region, followed by South Wales (a region where Patterson was operating in the 1930's) and East (where he did not operate). The result for the eastern region may be explained by the fact that this was an area where dairy farming was in decline as arable specialisation increased (so obsolete equipment was more likely to be scrapped).

The results suggest that, for example, the more rapid decline of the cowshed in South compared to Far-West shown in figure 6 can be explained by the additional explanatory variables, principally (in this case) the greater use of artificial insemination in South and the smaller number of herds on farms with low acreages.

The result is that a regional pattern remains but one which is less extreme than that shown by the basic model. The Mid-West was about five years ahead of adjacent regions like South and Far-West. It still took eleven years for the alternative milking technology to transfer from the pioneer region (MIDWEST) to the laggard region (NORTH), the latter being also the furthest removed geographically. These are more plausible results than the nineteen year gaps estimated earlier.

c). the adoption of the herringbone.

The second stage of the analysis looks at the choice of successor system. The sample is now restricted to those farmers who were no longer using the cowshed. A similar procedure was used: a basic model which only included HERDSIZE as an explanatory variable was compared to one including regional effects and another introducing other explanatory variables.

Table 6. Logit analysis with QHERRBONE as dependant variable.

model:	**basic model**		**a**		**b**	
	coefficient	t-ratios	coefficient	t-ratios	coefficient	t-ratios
HERDSIZE	+.0050	(5.5)	+.0086	(8.1)	+.0065	(6.4)
NORTH			+1.39	(6.2)		
NORTHWEST			+1.90	(9.9)		
EAST			+0.55	(2.5)		
EASTMIDLANDS			+0.97	(4.3)		
WEST MIDLANDS			+0.30	(1.5)		
NORTHWALES			+0.91	(2.4)		
SOUTHWALES			+0.60	(2.3)		
SOUTH			+0.01	(0.4)		
MIDWEST			-1.11	(5.5)		
FARWEST			+0.84	(4.1)		
ACUND100					+.053	(5.6)
FRIESIAN					-.003	(0.4)
FARMERAGE					+.050	(2.7)
INDIVFARMERS					-.003	(0.4)
NONAIUSE					+.500	(4.2)
TENANCY					+.017	(2.0)
Likelihood ratio	668.3 (97 df)		293.5 (87 df)***		521.1 (91 df)***	
% correct predictions	63.6		79.3		69.5	
squared correlation between pred. & count	.833		.956		.897	

Comparing the results of this analysis with those of the analysis with QCOWSHED as dependant variable shows that in general the variation in herringbone usage is less well explained (looking at the t-ratios, the percentage of correct predictions and the correlations between predicted and actual counts). The regional effects show a pattern which is almost the opposite of the one shown by cowshed use: that is, the use of the herringbone was most advanced where the decline of the cowshed was most retarded.

The results obtained when the other explanatory variables were entered were unsatisfactory. Although the likelihood ratio shows a significant difference from the basic model, the coefficients were in every case apart from INDIVFARMERS (which was insignificant) “incorrectly” signed, even when the t-ratios indicated a significant result.

As a further test the additional explanatory variables were entered separately. The results are shown as table 7. The signs on four of the variables are still incorrect. That on TENANCY is correct, and the coefficient is just significant at the 5% level, but the addition of this variable does not produce a significant improvement in the model as measured by a chi-squared test on the change in the likelihood ratio. The only satisfactory result is the one obtained when FRIESIAN is added. Here the coefficient is correctly signed, the t-ratio indicates a high level of significance and the likelihood ratio shows an improvement in the model fit.

Table 7. Entering each additional explanatory variable separately.

model:	**a**	**b**	**c**	**d**	**e**	**f**
HERDSIZE	+.0075	+.0058	+.0050	+.0063	+.0045	+.0054
	(7.6)	(6.2)	(5.4)	(6.6)	(4.9)	(5.8)
ACUND100	+.046					
	(10.2)					
FRIESIAN		+.026				
		(6.3)				
FARMERAGE			+.008			
			(0.8)			
INDIVFARMERS				+.049		
				(7.4)		
NONAIUSE					+.814	
					(7.7)	
TENANCY						-.016
						(2.0)
Likelihood ratio (96 df)	562.7***	627.2***	667.6	609.7***	608.9***	664.4
% correct predictions	67.3	65.7	63.8	65.8	66.0	63.8
squared correlation between pred. & count	.872	.850	.835	.841	.858	.838

Taken together the results so far suggest that an early move away from the cowshed may be disadvantageous to the adoption of the herringbone as a successor system. This could explain some of the perverse results on the explanatory variables. A variable which was positively correlated with the move away from the cowshed would then be negatively related to the use of the herringbone. One way of testing this is to use the results of the 1963/4 survey. Obviously, farms which were using the herringbone in 1963/4 would be highly likely to be still using it in 1968/9, but the percentage distribution of non-herringbone using farms (by alternative system) can be entered as additional explanatory variables. The results are shown in table 8.

Table 8. Introducing 1963/4 milking system variables[38].

model:	a		b		c	
	coefficient	t-ratios	coefficient	t-ratios	coefficient	t-ratios
HERDSIZE	+.0130	11.6	+.0061	6.5	+.0120	10.7
COWSHED63/4	+.0280	13.8				
BAIL63/4			-.0612	11.2		
ABREAST63/4					-.0263	11.3
Likelihood ratio (96 df)	453.9***		522.9***		529.6***	
% correct predictions	74.4		70.4		71.4	
squared correlation between pred. & count	.926		.900		.896	

The results are quite clear. High use of the cowshed in 1963/4 had a positive effect on the diffusion of the herringbone in 1968/9. By contrast, an early move away from the cowshed into other systems such as the abreast or bail retarded the subsequent adoption of the herringbone.

One explanation is that this reflects the importance of sunk costs. Those who had recently invested in new systems were reluctant to give them up. To examine the importance of what might be termed "physical sunk costs", models b and c compare the effects of previous investments in abreast parlours with the use of bail systems. The point of interest here is that abreast parlours were constructed *in situ* and so could not be moved, while bails were either mobile or prefabricated (and so could be unbolted and moved relatively easily). Hence, the absolute value of the negative coefficient on ABREAST63/4 could be expected to be larger than that on BAIL63/4. In fact, as table 8 shows, the opposite is the case. Which could reflect the importance of other geographical factors which favoured bail systems in certain regions, or it could show that the sunk costs which mattered were not physical but arose as a consequence of "learning-by-doing".

This is however a side issue. The preferred model is now the one shown as **a** in table 8 (with HERDSIZE and COWSHED63/4 as the explanatory variables). The other explanatory variables were now added again, first as a group and then separately. The results are summarised briefly in table 9.

Table 9. Effect of re-introducing explanatory variables (HERDSIZE and COWSHED63/4 also included).

	"correct"	variables entered together		variables entered separately	
	sign	coefficient	t-ratios	coefficient	t-ratios
ACUND100	-	+.029	2.9	+.010	1.8
FRIESIAN	+	-.011	1.3	+.002	0.4
FARMERAGE	-	+.042	2.3	+.008	0.8
INDIVFARMERS	-	-.010	1.0	+.005	0.7
NONAIUSE	-	+.205	1.7	+.264	2.3
TENANCY	-	+.016	1.9	+.011	1.3

These are completely unsatisfactory results. Again, the coefficients generally have the wrong signs. The exceptions (FRIESIAN and INDIVFARMERS) are not significant. So the preferred model remains unaltered. Table 7 shows an analysis of predictions by region for this and the basic model

[38] the variables are entered separately as there is an obvious problem of collinearity if they are entered together (since COWSHED63/4 + BAIL63/4 + ABREAST63/4 = 100); the variables give the numbers of cows milked through the different systems by size class expressed as a percentage of the number of cows in the size class not milked through "other parlours" - a category used in the 1963/4 survey to include the herringbone and related designs (the chute and tandem).

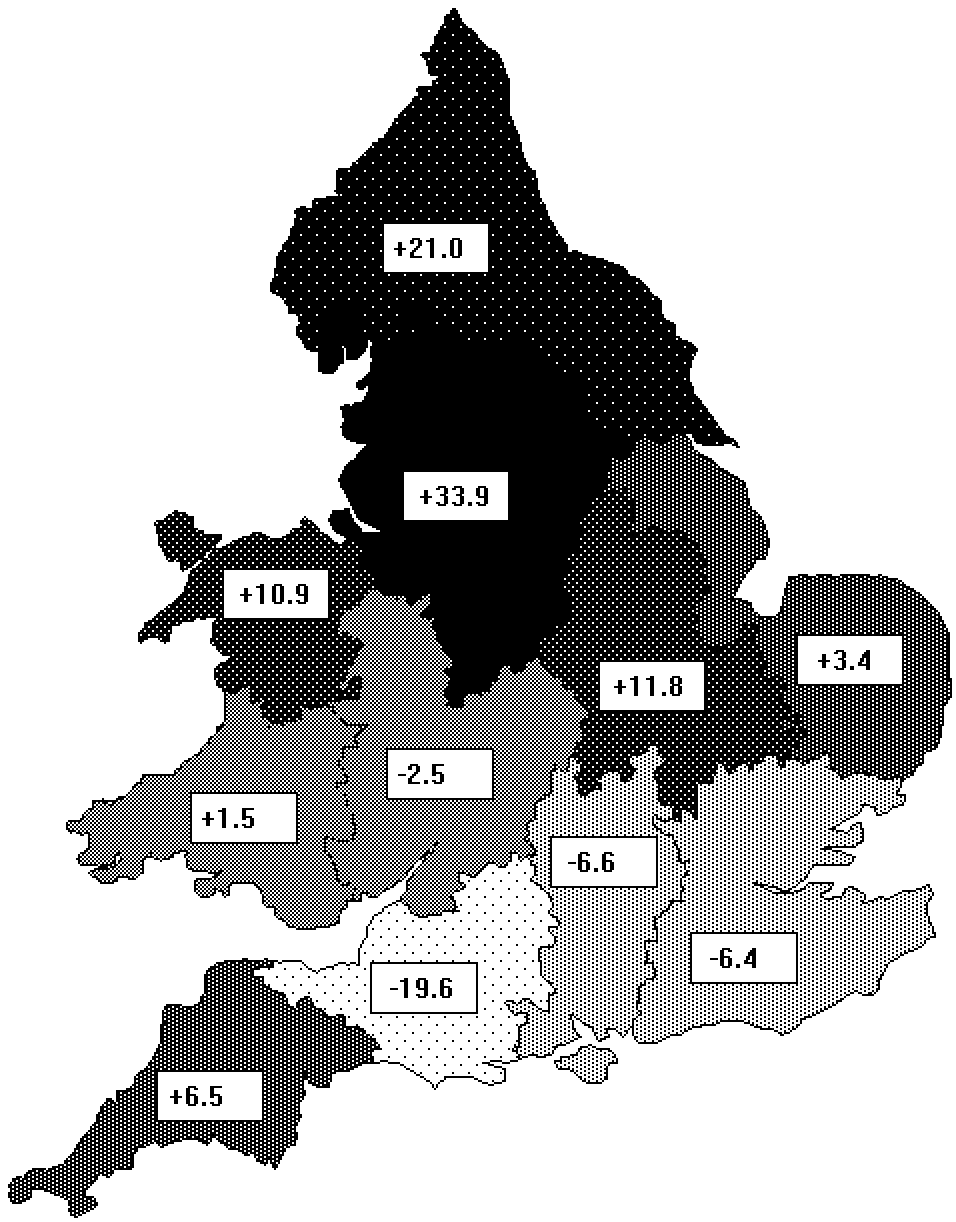
Table 10. Analysis of predictions by region.

model:	basic (HERDSIZE only)		preferred (HERDSIZE+COWSHD63/4)	
	overall % correct	pred. of herrbne[b]	overall % correct	pred. of herrbne[b]
NORTH	57.0	+21.0	86.3	+3.0
NORTHWEST	32.0	+33.9	67.6	+13.0
EAST	73.1	+3.4	75.4	+4.7
EASTMIDLANDS	57.6	+11.8	61.7	+8.8
WEST MIDLANDS	61.2	-2.5	54.0	-5.8
NORTHWALES	69.7	+10.9	76.4	-3.4
SOUTHWALES	76.2	+1.5	92.1	-3.9
SOUTH	86.9	-6.6	79.2	+2.3
MIDWEST	60.7	-19.6	83.4	-6.9
FARWEST	74.6	+6.5	77.9	0.0
SOUTHEAST	74.8	-6.4	80.1	0.0

[b] - positive value shows that actual level of herringbone use exceeds level predicted by model.

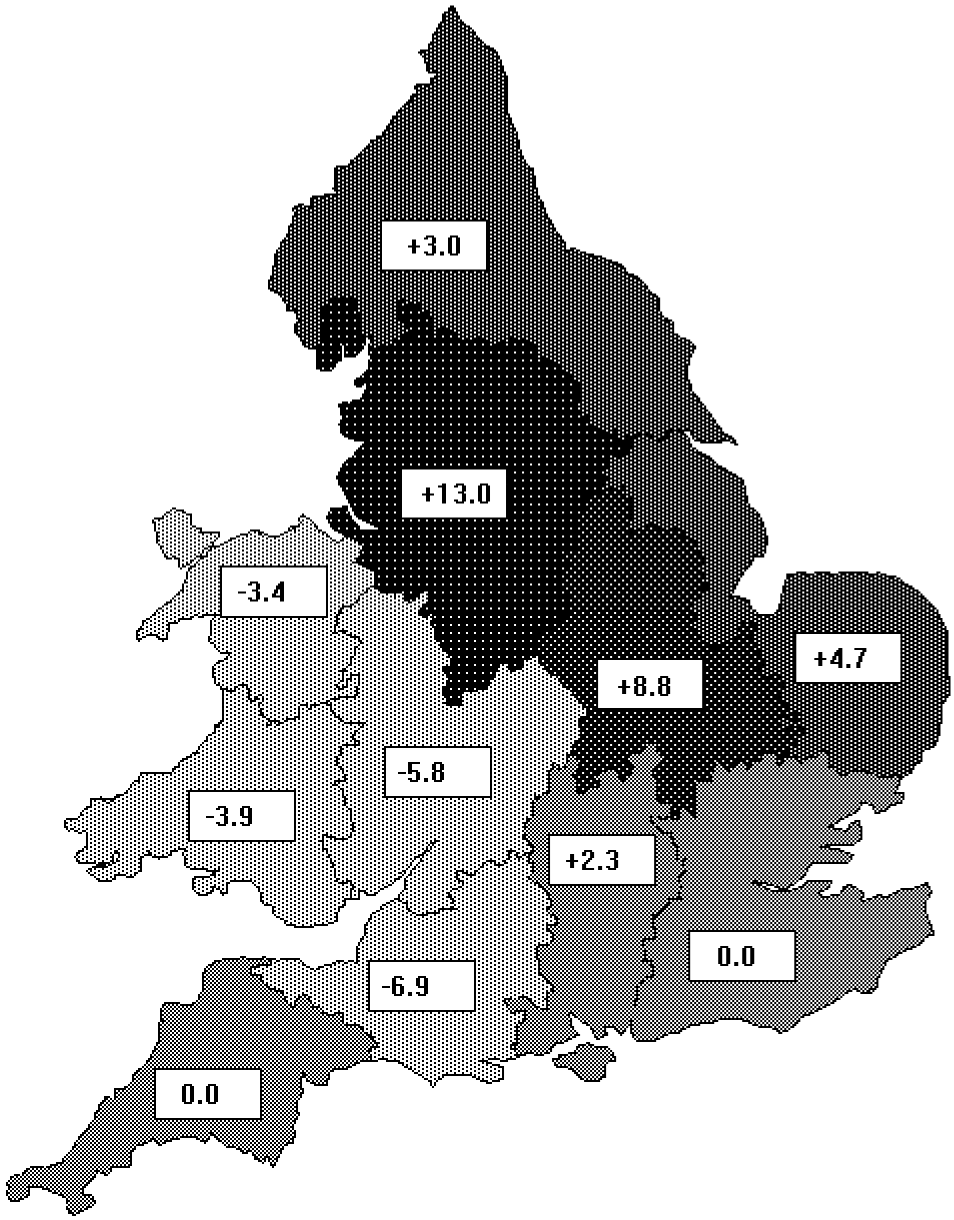
As before, the comparison of predicted counts of herringbone use from the basic model repeats the pattern given by the calculation of regional effects. Once again the results are presented on two maps. Figure 8 provides the comparison for the basic model.

Figure 8. Comparison of the actual number of herds using the herringbone to the number predicted by the basic model (HERDSIZE as sole explanatory variable).



This shows that herringbone use was most advanced in the north. But when the preferred model is used, with COWSHED63/4 added, the pattern (shown in figure 9) becomes less extreme.

Figure 9. Comparison of the actual number of herds using the herringbone to the number predicted by the preferred model (HERDSIZE + COWSHED63/4 as explanatory variables).



Again, the yardstick provided by the average number of non-cowshed using herds which switched to the herringbone between 1963/4 and 1968/9 can be used. This was again 2% per annum, which suggests that NORTHWEST was, according to the basic model, 26 years ahead of MIDWEST in use of the herringbone. Use of the preferred model, which allows for the fact that many farms in the midwestern region had already invested in alternative designs, reduces this gap to ten years, which is still substantial.

d) conclusions.

The decline of the cowshed can be relatively well explained by the model presented here. Factors such as farmer age (which reduces the period over which an innovation can provide a payback), capital constraints (as shown by the influence of tenant land-holding and the presence or absence of partnerships), the availability of additional land within the farm enterprise and resistance to change (as proxied by the use of artificial insemination had the expected effects on the diffusion of alternative milking systems. The pioneer region, Mid-West, was still ahead after allowance had been made for these factors, but the gap had been greatly reduced.

The adoption of the herringbone can also be explained, but in this case the critical factor was the ability of regions which were late in giving up the cowshed to avoid heavy investment in intermediate systems and leap-frog straight into the herringbone. An early start was clearly a disadvantage.

VI. Conclusions and implications: the consequences of learning-by-doing.

a). Conclusions.

The question was posed: why did a design invented in 1908 take over 70 years to be adopted by the majority of British dairy farmers? The answer can be summarised as follows:

In the first place, there was a long delay in the diffusion of mechanical milking in the United Kingdom. Part of this was due to the need to improve the original designs, but the slow diffusion in Britain compared to other countries indicates the presence of specific problems, of which labour relations was probably one. This makes the point that the adoption of innovations will often require complementary organisational or institutional changes: new management systems, new labour contracts (implicit or explicit).

Once the switch-over to mechanical milking was under way, as it was from 1939 onwards, then the choice of system became the immediate problem facing farmers. This required the development and evaluation of appropriate systems, and the transmission of this information. This process of search, experimentation and transmission took time. It was inevitably influenced by past experience and thus subject to path dependence. “Mistakes” were made: meaning that systems were installed which did not perform as well as expected. The reason for this was that the performance of a system was subject to alteration through learning-by-doing process and this could not be predicted in advance. Such mistakes were not made by irrational or ignorant farmers, but by some of the more advanced and entrepreneurially-minded. If they had known how well the herringbone would perform they would have used it, but they did not know.

An important point is that the potential of the system was only fully realised with larger herd sizes. And this raised another set of managerial and technical problems. Solving these problems required other advances, other complementary innovations, and the result was the creation of a complex set of information, part of which could be codified and relatively easily transmitted, but part could not, and thus was “tacit” knowledge, requiring personal contact through networks. The networks then became the repositories for this stock of information, which was gained through learning-by-doing. The result was that different regions could become committed to particular designs, through the accumulation of experience. This in turn could be an obstacle to the diffusion of alternative designs.

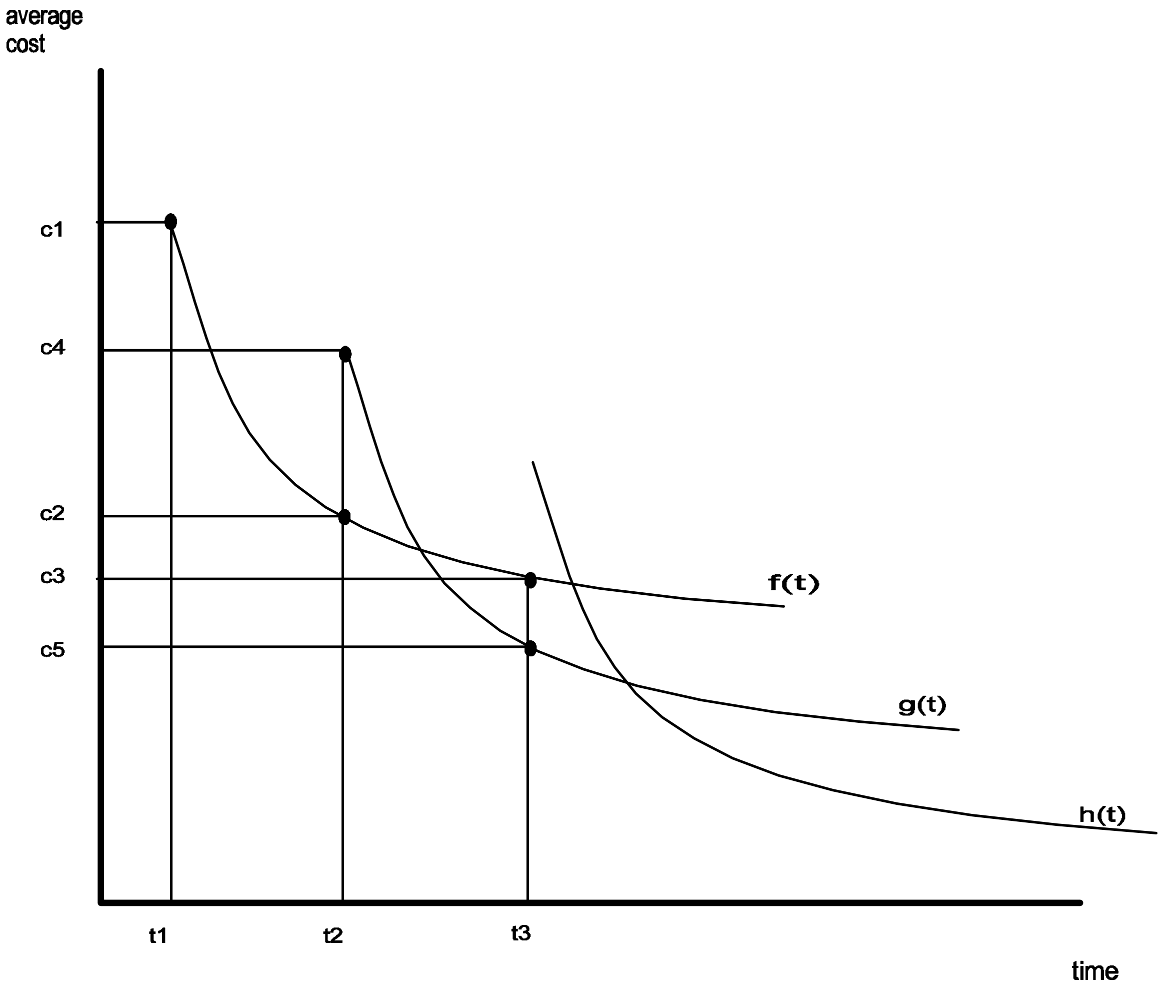
But in the end this was not an insurmountable obstacle. Path dependence was not absolute. The superiority of the herringbone was demonstrable and measurable, and this information could be codified and transmitted more easily. By the early 1970’s most farmers were aware that it was the superior system. It was then just a matter of acquiring the necessary knowledge to operate the system, and making the necessary investments. Diffusion was relatively rapid from 1970 onwards.

Viewed as a whole, what is described is a long process of learning-by-doing, a series of complementary innovations which improved the performance of the system. The diffusion problem thus has to include the transmission of this complementary information.

b). Implications: the possibility of “leap-frogging”.

With learning-by-doing, the introduction of new products or technologies can give rise to “leap-frogging”. Figure 10 shows a succession of technologies - f(t), g(t) and h(t) - which exhibit learning-by-doing, causing average costs to fall over time.

Figure 10 A succession of technologies with learning-by-doing.



An economic unit A (a firm, region or country) using f(t) will experience cost falls from c1 to c2 and c3. By this time (period t3) average costs would be lower if g(t) were used. But A will take into account the fact that initially average cost using g(t) is higher, by c4-c2 in period t2. Although this may not cause A to decide against using g(t) it will make A reluctant to shift. A will take into account the learning already done with f(t). In effect the learning costs act as sunk costs, and if A is a monopoly producer it will take the rents earned from sunk costs into account when deciding whether to switch or not. If A is a region in which there are competitive firms benefiting from learning exernalities, then A will still act in this way.

But for a second unit B (again, a firm, region or country) who enters in period t2 the choice is much clearer. Here, if f(t) is selected, then not only are ultimate costs higher, but because the whole learning process has to be traversed, initial costs at c1 are higher than initial costs with g(t) at c4. So g(t) is chosen.

What happens then depends on the nature of the product. If a single homogeneous good is being produced (like milk) then the entry of B will eventually drive down prices, A will write off the sunk costs associated with f(t) and switch to g(t) (this assumes a certain foresight on the part of A, if A is completely myopic it could wait until prices fall to c5 and then be wiped out).

In the case examined in this study this is what happened. Once the southern farmers realised that the herringbone was the superior option they wrote off their investments in the abreast and other systems and switched.

But, if f(t) and g(t) produce different goods then the result is more complex. It may now pay A to remain with f(t) and trade with B. A will have a lower rate of growth than B, but should benefit from improving terms of trade as B's costs fall. In effect A has allowed itself to be leap-frogged by B.

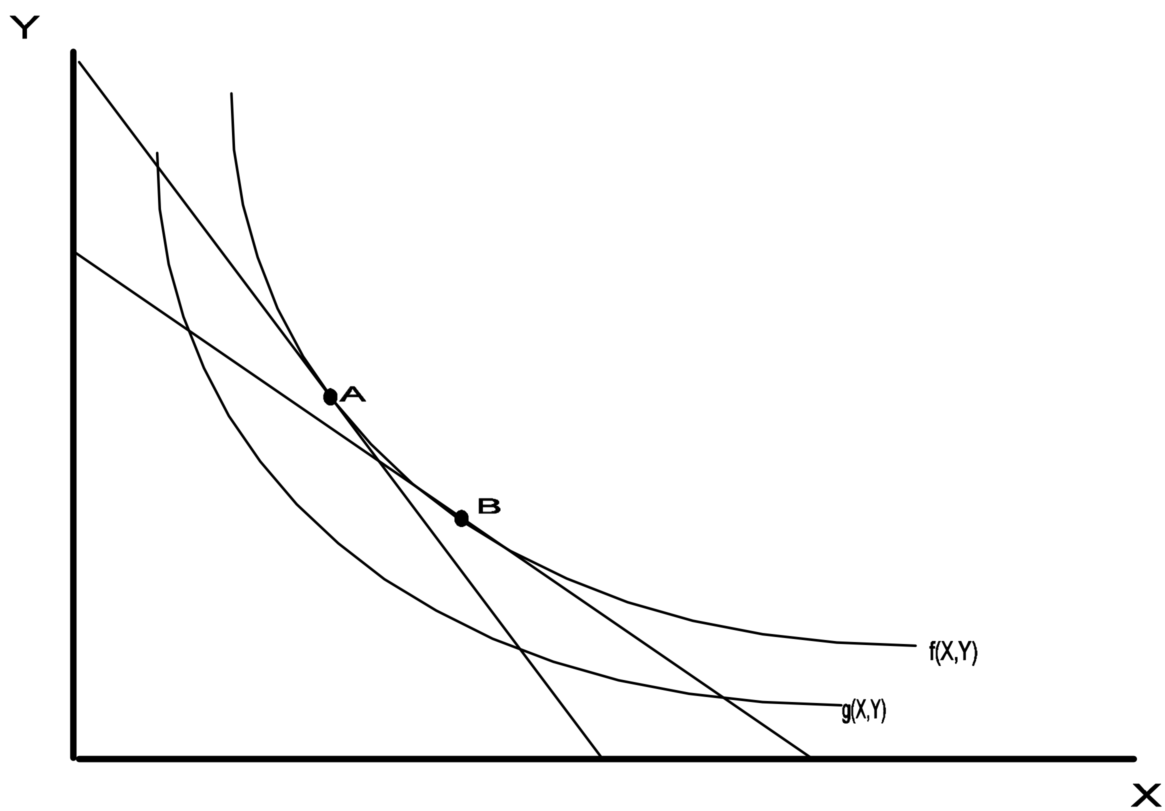
Differing income elasticities for the two products will cause the benefits to be unevenly distributed. Either A or B may come out ahead. The appearance of a third technology h(t) could lead to adoption by A (having exhausted learning possibilities with f(t)), who thus leap-frogs back over B, or it could be adopted by a third entrant C leaving A stuck on f(t).

"Early start" is not inevitably a disadvantage, but it is not inconceivable that it might be.

c). Implications: innovation and factor prices.

Learning-by-doing also introduces the possibility that shifts in factor prices can lead to induced innovation. In conventional static analysis, as in Salter's *Productivity and Technical Change*, changes in factor prices simply cause movements round an unaltered production isoquant, as in figure 11. Here different combinations of X and Y are used according to the slope of the budget line. As this changes the quantities of X and Y are altered, moving from A to B, but there is no reason for this to produce a shift to a different level of technology (g(X,Y) rather than f(X,Y)).

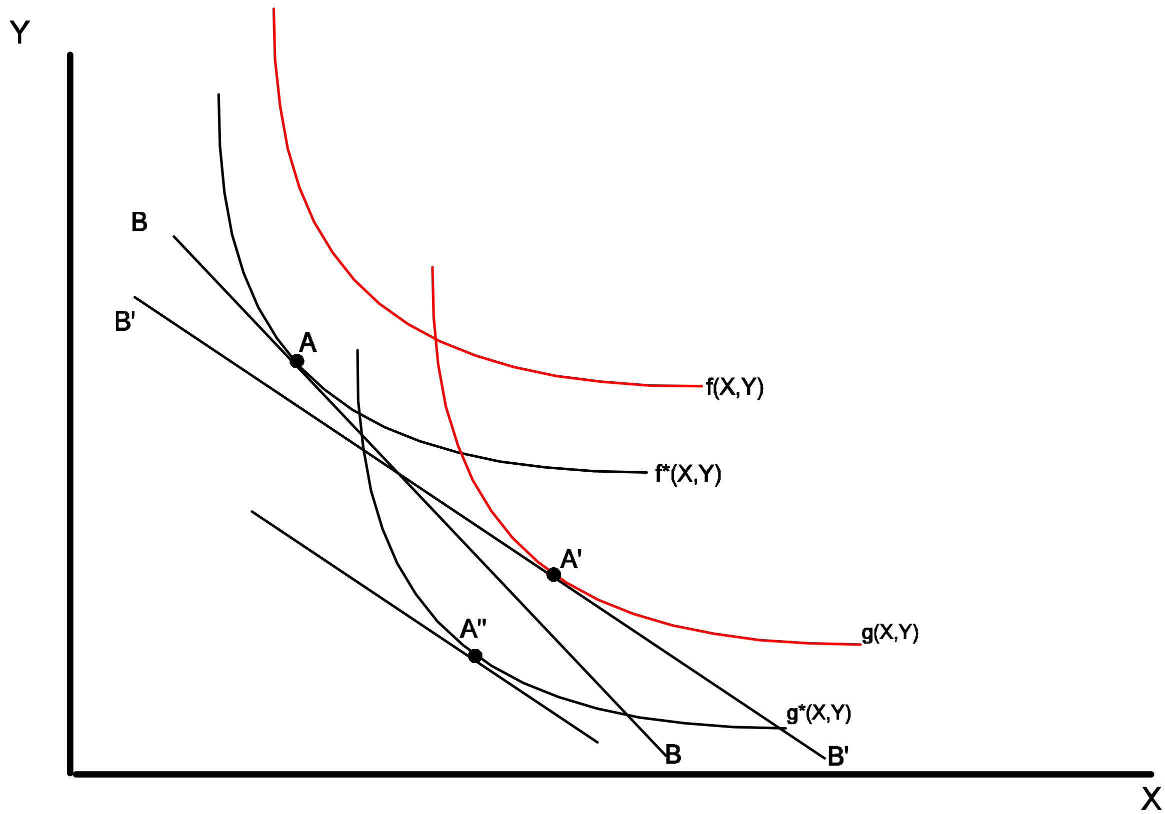
Figure 11. A conventional analysis of factor price changes: with two factors, X and Y, used to produce a given quantity; f(X,Y) and g(X,Y) are isoquant curves representing different levels of technology.



The introduction of learning-by-doing changes this. Here, as in figure 12, there are two technologies, both of which improve with learning. They are separate technological systems, which are "lumpy", so it is not possible to combine a little of one with the other, it has to either all or nothing.

The learning effect is shown by the movement from f(X,Y) to f*(X,Y) and from g(X,Y) to g*(X,Y), which represent improvements in efficiency so that a given quantity can be produced with reduced inputs. The initial point is A, representing the optimal combination of X and Y, given the budget line BB, for a "mature" technology, f*(X,Y): that is, one which has exhausted the possibilities of learning-by-doing. The alternative technology is potentially superior, in that, in its mature state g*(X,Y), part of its production possibility curve lies in front of the budget line (or closer to the origin). However, this does not apply to the immature function g(X,Y). So, given the budget line BB there is no reason to make the innovative move from f*(X,Y) to g(X,Y).

Figure 12. The effect of factor price changes with learning-by-doing; f(X,Y) and g(X,Y) are initial production isoquants before learning has taken place; f*(X,Y) and g*(X,Y) are isoquants after learning.



The diagram shows the effect of a change in the relative prices of X and Y which shifts the budget line to $B'B'$. Now, the point A' is superior to A. But the choice of innovative move to A' triggers the learning process which brings about a move to A''. Thus the change in the factor price ratio has brought about a move to a superior technology, a technology which was superior both at the new factor price ratio and the old.

What if the firm is aware that there is the potential learning effect of the innovative move to g(X,Y)? Then this benefit will be taken into account when considering the move. But, if part of the learning benefit is external to the firm, in that it helps other firms to move from g(X,Y) to g*(X,Y), then the full social benefit of the innovative move will not be taken into account.

But, there is also the problem of how the firm discovers that there is a learning benefit associated with the new technology. Consider the possibility that there is an “information provider”, who experiments with technology and sells the information thus derived. This firm may discover the existence of the learning benefit, and sell the information to a producing firm. The producer then decides that the innovative move to g(X,Y) is profitable in the light of this information even if factor prices remain at BB. But once one firm has made the innovative move other firms will be able to deduce that the benefit exists, and also move, without paying the information provider. This is the problem of excludability: if it is not possible to prevent others using the information without paying, then investment in the provision of information will be sub-optimal.

Suppose that it is possible, through patents and other devices, to make all those who move pay the information provider. Then the problem becomes the non-rival nature of information. It can be used repeatedly without reducing its value. The social cost of making available the information that there is a learning benefit associated with the innovative move is zero. The social benefit is maximised by making the information freely available so that all firms who would benefit from the innovative move make the move. But if the information provider is allowed to charge for the information, then some of those who should have moved will not do so. The result is again sub-optimal.

Relating these considerations to the subject of this study, it is suggested that the hand-milking technology of the 1930's is represented by the f*(X,Y) curve: it was a fully mature technology with no learning possibilities. The possibility of an innovative move to mechanical milking was relatively unattractive at the BB price ratio, given that the system which was immediately on offer, milking in a cowshed with a bucket plant, was not particularly efficient. So diffusion was slow. In the war years there was a labour shortage which shifted the relative price of labour and capital (to B′B′), and as a result there was a move to the cowshed/bucket plant system, which can be represented as the g(X,Y) curve. This then triggered the learning process, which eventually improved the performance of mechanical milking sufficiently to move to g*(X,Y). This represents the herringbone system.

Obviously, movements in factor prices are fortuitous, and can be beneficial, in the sense of leading to innovative moves with learning possibilities, or not. Labour shortages can have this favourable effect under certain circumstances, but it cannot be relied upon. A more general result is that economically valuable information will be under-provided. So there is a case for public sector provision.

d) implications for entrepreneurship.

Returning to figure 12, the entrepreneurial function can also be re-interpreted in the context of learning-by-doing. The simple maximisation exercise - choosing between f*(X,Y) and g(X,Y) using the BB budget line - yields a sub-optimal result. The entrepreneur has to try to estimate the learning possibilities of the innovative move in the context of an inadequate supply of information from either profit-maximising information providers or the public sector. Moreover, the more of the learning benefits that can be captured, the greater the profit from the move. This calls for a move of "scale and scope": not just a tentative assay of the new technology, but a drive to exploit all its potential and, if possible, dominate the new market.

The value of a probabilistic approach is likely to be limited. A Bayesian search process, where the likelihood of success is estimated from previous experiments, is of use where a large number of repeated actions can be used to build up experience. But most innovations are large and not repeated. And the fact that the learning process takes time to complete makes it difficult for any individual entrepreneur to acquire the necessary experience. But institutions, such as innovative corporations with a strong track record, may be able to do so.

For the individual entrepreneur, innovation is a step in the dark. All aspects of the problem cannot be known in advance. And diffusion is similar in that many aspects of the operation, under new circumstances, of techniques or equipment already in operation elsewhere cannot be foreseen. The learning possibilities may be smaller or greater.

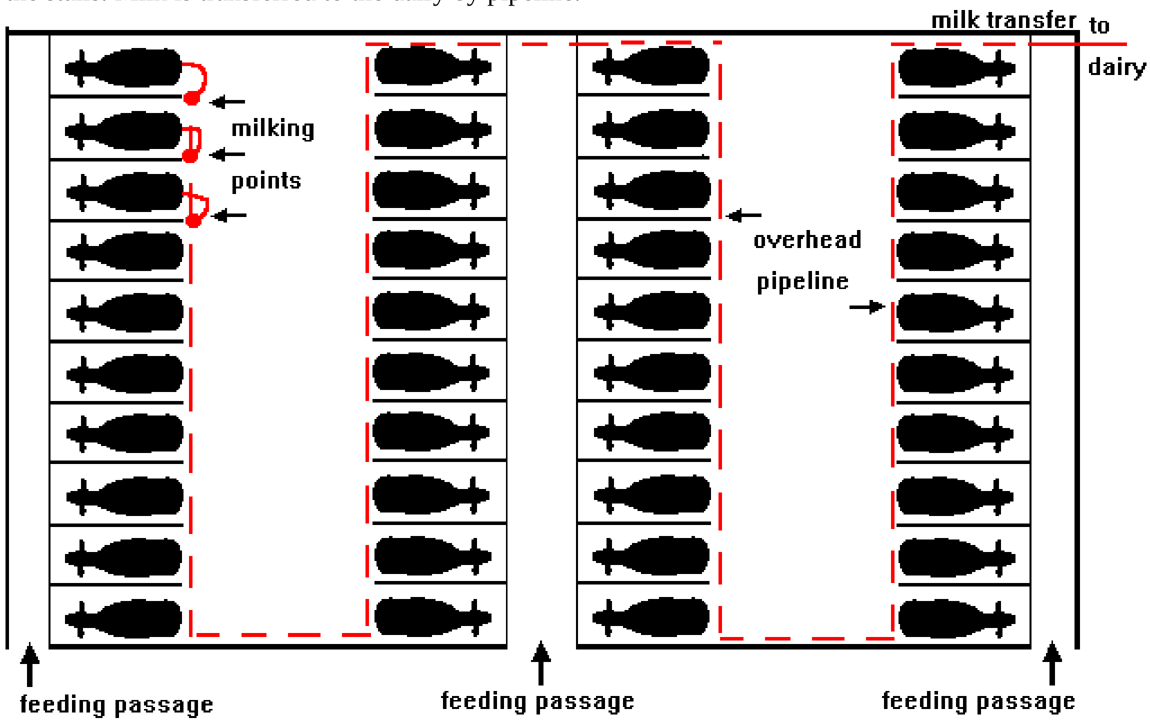
So, entrepreneurship is not just about the pursuit of profits using a given information set. It is about creating and expanding that set. It is about searching for and acquiring information, selecting and evaluating it and, by applying it, creating new information.

References.

Barnard, C.J., Halley, R.J. and Scott, A.H. (1970), *Milk Production.*
Bridges, A. (1939), " The economics of machine-milking", *Journal of the Ministry of Agriculture,* 46.
Collins, E.J.T. (1992), "The uptake of the milking machine in England and Wales" in Herrman, K. and Winkel, H, eds., *Vom "flessigen zum produktiven" Bauern.*
David, P.A. (1993), "Knowledge, Property, and the System Dynamics of Technological Change" in Summers, L. and Shaw, S. eds. *Proceedings of the World Bank Annual Conference on Development Economics 1992.*
Hoyland, A. (1939), *Machine Milking - A Bane or a Boon?*
MMB (1970), *Dairy Farming in Transition.*
MMB (1984), *Dairy farm structure in England and Wales 1983-4.*
Ministry of Agriculture (1919), *Enquiry into the Use of Milking Machines.*
O'Callaghan, M.A. (1912), *Dairying in Australasia.*
Orwin, C.S. (1931), *Progress in English Farming Systems, volV.*
Patterson, R. (1965), *Milk from Grass: The Massey Ferguson paper no.2.*
Petitt, G.H.N. (1939), *Labour in the Cowshed*, Royal Agricultural Society of England.
Philpott, H.G. (1937), *A History of the New Zealand Dairy Industry 1840-1935.*
Salter, W.E., (1966), *Productivity and Technical Change.*
Street, A.G. (1932), *Farmer's Glory.*
Taylor, D. (1976), "The English Dairy Industry, 1860-1930", *Economic History Review*, 29.
Wiltshire County Council, Agricultural Education Sub-Committee, (1937), *Advisory Report on Milk Production.*

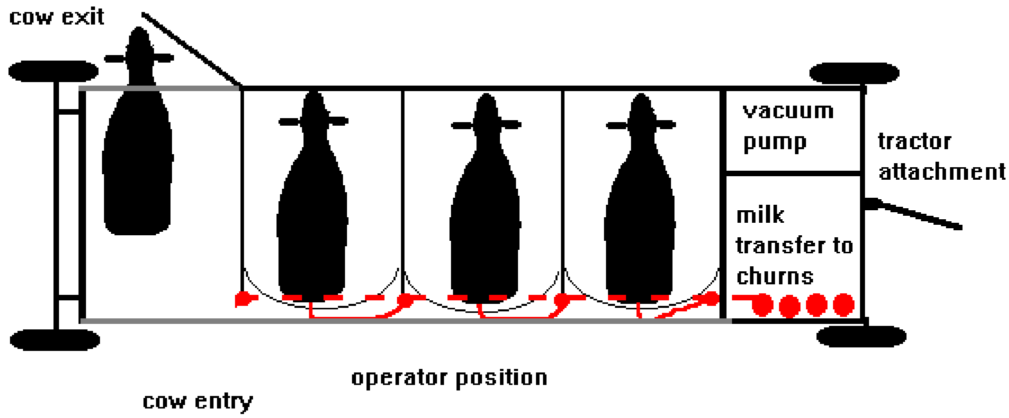
Appendix: the different designs.
1. Cowshed System with pipeline.

In this system the cows spend the winter in stalls, and the milking equipment is moved between the stalls. Milk is transferred to the dairy by pipeline.



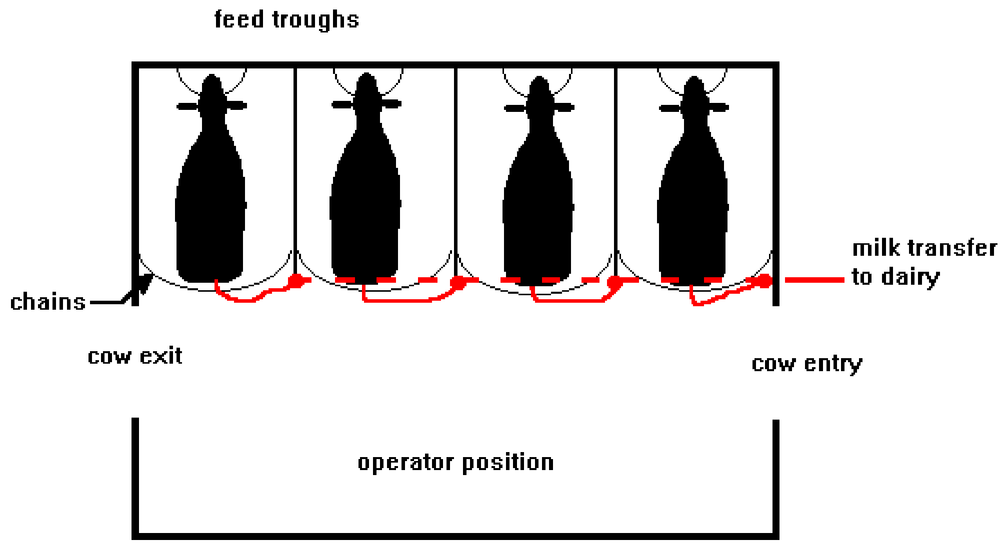
2. Mobile Bail.

The system developed by Hosier in the 1920's was a mobile "bail", which could be moved each day. The cows were milked in individual stalls as before, but the equipment was fixed.



3. Abreast parlour.

A fixed parlour design, to which the cows were brought in individually for milking. It did not offer split-level milking, so the operator was on the same level as the cows, which was uncomfortable.



4. Herringbone parlour.

The herringbone, and the tandem and chute designs (which were similar but inferior) offered split-level milking, in which the operator stood in a pit some 2½ feet below the cow level. This was a considerable advantage. The cows entered in batches of 4 or more (8 in the illustrated design) saving time on this part of the job. The compactness of the design meant that a large number of points could be monitored by one operator.