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SPECIAL ISSUE—BETWEEN THE FARM AND THE CLINIC: AGRICULTURE AND REPRODUCTIVE TECHNOLOGY IN THE TWENTIETH CENTURY

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Cutting across nature? The history of artificial insemination in pigs in the United Kingdom

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Abstract

Artificial insemination (AI) has a considerable cultural significance in addition to its economic and technical impact. This study is the first to examine the history of its application to pigs, and uses evidence provided directly by both the scientists involved in its development, and some of the farmers who were among the first to use it, in addition to archival and published sources, to show how the scientific studies of the 1950s evolved into a widely available commercial product by the 1980s. It describes the initial scientific work and quantifies the extent to which the technique was used at various points in time, showing that by 1990 nearly one half of UK pig herds were using AI for more than 25% of all services. It traces changes in the techniques employed and argues that these were the result of a multi-dimensional process of contemporaneous change. The various dimensions are identified firstly as authorities, meaning the people and organisations controlling the perception, administration, control, and so on, of the technique; secondly the discourses employed by the authorities; and thirdly the media by which the discourses were disseminated. Finally, it is suggested that this approach might be used more widely to examine the construction of other technologies.

Keywords: Artificial insemination; Pigs; Technical change

1. Introduction

In the process of domesticating farm animals, their feeding patterns had been changed, their body shapes had been transformed, and their behaviour had been altered. By the beginning of the twentieth century they were the products of thousands of years of human

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intervention and control. It was possible to ask 'Are animals technology?' (Schrepfer & Scranton, 2004, p. 261). Perhaps the only thing that they still did as they had done in the wild was to mate. This was not without its inconveniences for farmers. It meant that they had to bear the cost of feeding sires that did nothing productive but pass on their genes (and with them, in some cases, diseases), and of housing and controlling bulls and boars that were powerful enough to injure or even kill people. Nevertheless it was necessary: cows will not produce milk until they have given birth to a calf, and fat cattle, pigs and sheep have to begin as calves, piglets and lambs, so cows, sows and ewes needed to be mated with bulls, boars and rams. So it had always been. Animals might be artificially housed, and fed on feedstuffs imported from the other side of the world, and have their mates chosen for them. But to produce more domesticated animals they had to be left to do what their undomesticated forebears had done, and in much the same way. For farm animals, mating was the last bastion of nature against agri-culture.[1] Artificial insemination (AI) breached this bastion, and therefore has a cultural as well as an economic and technical significance that makes its investigation worthwhile.

Most of the work on the history of AI in Britain has been concerned with its use in dairy cows. It began to be available in 1942, and by 1950 20% of the cattle in the country were being inseminated. By 1960 over two million cows per year were involved, which was 80% of the maximum level that AI would reach (Brassley, 2000, p. 71; Edwards, 1952, p. 477). The technique was also adopted to some degree for other farm animals, such as beef cattle and poultry, but hardly at all for sheep. In the case of pigs, AI eventually became an important part of herd management, especially in breeding herds, but it took some time to do so. It is with pig AI that this paper is specifically concerned, for the delays in development and adoption of the technique led to the accumulation of much information on the processes involved, and therefore make it an excellent case study of technical change. The purpose of this paper is therefore not only to examine the development of pig AI, but also to suggest another methodology for the study of technical change in general.

The basic outlines of the process of artificial insemination of pigs have remained unchanged over time, although the details have varied considerably. In essence, it requires the collection of semen from a boar, followed by the separation of the semen into several doses that are then used to inseminate sows that may be on farms at considerable distances from the boar. Professor Christopher Polge, who carried out the initial work on the technique in the United Kingdom, recalled that

> I trained some boars to mount a 'dummy' sow and learned how to collect the semen. I first used an artificial vagina designed on lines similar to those suggested by Arthur Walton some years previously, but later switched to using the 'gloved hand' method, which was a lot easier.[2]

Initially, the sows were then inseminated using a long plastic tube with an inflatable cuff at the end.[3] This was superseded by the Melrose spiral catheter, which Dick Melrose, then of the Reading AI centre, 'had made from a mould of a boar's penis', and which, in Polge's opinion, 'was an important advance in AI technique and in promoting its development'

[1] Sarah Franklin makes a very similar point in the context of human reproduction in Franklin (1997), pp. 17–24.

[2] Polge (2005). Dr Arthur Walton was one of the pioneers of AI in cattle in the UK.

[3] This is illustrated in Aamdal (1968), p. 253.

(Polge, 2005). Polge's initial work was done in the 1950s, and there were further developments in the 1960s. They offered a cheaper alternative to keeping a boar for smaller producers, and promised genetic improvement to all pig farmers, but in order to do so they required technical expertise, and initially produced low conception rates. National authorities worked on both of these problems and succeeded in solving them by the 1970s, leading to an expansion of use to the present level by the end of the 1980s. The problem with this basic account is that it poses as many questions as it answers, if not more. Why, for example, did scientists working on cattle AI turn their attention to pigs? Why were farmers looking for a cheaper way of impregnating sows, and why did they believe that genetic improvement mattered? Was it simply profit maximisation or was there more to it? If it was profit maximisation why did various agencies of the state go to such lengths to promote it?

This paper examines these questions. It begins by quantifying the uptake of AI in pigs, then considers the factors that affected it, and concludes by using this case study to suggest a new framework for the examination of technical change in general.

2. The development of artificial insemination in pigs

Artificial insemination in pigs in the UK seems to have begun in about 1954. In October of that year, following Polge's initial work, his colleague L. E. Rowson of Cambridge Cattle Breeding Centre wrote to the Ministry of Agriculture saying that the centre was thinking of developing a pig AI service, and the following month Dr Polge published an article in *Pig Farming* describing research on semen storage and AI techniques.[4] On 22 November 1954 the Board of Management at Dartington Hall Cattle Breeding Centre decided to begin a pig AI service on an experimental scale, and by 1957 the AI centres at Cambridge, Lyndhurst, Ilminster and Langford were also offering pig AI. Bromsgrove in Worcestershire joined the list in the following year.[5] Nevertheless, take up was slow as Tables 1 and 2 reveal.

The figures in Table 2 probably look more exact than they are, because there were in the UK in 1990 around 700,000 sows and in-pig gilts, each requiring to be served roughly twice each year, which means that a total of 423,000 inseminations (395,000 + 28,000) would represent roughly 30% of total servings. However, the same publication from which the figures in Table 3 are taken also states that there were 407,000 inseminations in the UK, but that these represented only 11% of total servings.[6] The Meat and Livestock Commission (MLC) subsequently changed the way in which it reported AI use, presumably because more semen was being sold by breeding companies who were less willing to release their sales figures. Instead it reported the use of AI in the 171 farms in its industry survey, as in Table 3.

Perhaps the best way of describing what these data suggest is that by the 1990s AI was firmly established in regular use in the UK pig industry, but it was by no means the

[4] The National Archives, MAF 124/90, f. 6, letter from L. E. Rowson to F. Harold Smith, 9 October 1954 (NB all subsequent references to MAF files refer to Ministry of Agriculture Files in the National Archives, Kew); Polge (1954).

[5] MAF 124/90, f. 11b, E. A. Farey to W. P. Dodgson; f. 65, list of AI centres with pigs; f. 83/4, D. R. Melrose, Survey of AI in pigs, 16 September 1958.

[6] Meat and Livestock Commission (1991), p. 58; Gordon (1997), p. 33.

Table 1
Number of first inseminations of sows in the UK (from MAF 124/91, f. 1a; PIDA, *PIDA Record*, *20*, Winter 1965–1966)

1955	951
1956	1957
1957	2299
1958	2763
1959	3582
1960	4328
1961	5646
1964–1965	6455

Table 2
Estimates of UK insemination activity (these figures are estimated from graphs in Meat and Livestock Commission, 1991, p. 56)

	Number of bottles of semen sold	Inseminations by inseminators
1981	80,000	30,000
1982	85,000	31,000
1983	90,000	34,000
1984	100,000	33,000
1985	110,000	38,000
1986	145,000	44,000
1987	175,000	40,000
1988	205,000	31,000
1989	240,000	27,000
1990	395,000	28,000

Table 3
AI use in the breeding herd (%) 1997 (from Meat and Livestock Commission, 1991, p. 58)

1–5% of services	18
5–25% of services	35
25–50% of services	28
More than 50% of services	19

dominant means of serving sows, as only 19% of herds used it in more than half of their services. International comparisons are interesting here: in 1990 80% of pigs in East Germany were bred by AI, compared with only 23% in West Germany, while the figures for Norway, which was prominent in the early history of pig AI, were 71%, with the Netherlands 51% and Denmark 25%. France was at about the same level as the UK in this list, with 10%, whereas the USA was only 7%.[7] It would probably require a further study, of equal length to this one, to elucidate the reasons for these differences. The overall picture for the United Kingdom is, however, reasonably clear. When pig AI was first introduced in the 1950s its use expanded, although it only represented a very small percentage (less than 1) of total services by the middle of the 1960s. Most of these inseminations would have been by professional inseminators employed by the AI centres. In the next fifteen

[7] Meat and Livestock Commission (1991), p. 58.

years AI use expanded ten-fold, and then in the 1980s it increased further so that by 1990 it was of about the same order of magnitude as it is at the present time, and most of these inseminations would have been carried out by the farmer and his staff (DIY inseminations) using semen sent by post from AI centres operated by the MLC or the major breeding companies.

3. Factors affecting the development of pig AI

As the preceding paragraphs demonstrate, pig AI developed more slowly than AI in the dairy herd, but over a forty-year period it gradually became established as an accepted part of commercial pig farming. The remainder of this paper attempts to explain what happened in the UK pig industry and how it relates to theories of technical change.

3.1. Pig AI techniques as perceived by their users

It is important to remember that the pig industry was evolving rapidly at the same time that AI techniques were developing. UK pigmeat production increased by over 50% between the mid-1950s and the mid-1980s, largely because the number of pigs reared per sow per year also increased by about 50%, while the amount of food used per pig decreased by about a quarter. Many farmers, not to mention smallholders and backyard pigkeepers, had a few pigs in the mid-1950s. As late as 1964 there were over 75,000 breeding pig herds in England and Wales, 72% of which had less than ten sows, giving a national average breeding herd size of 9.5 sows. The next twenty years were a period of rapid specialisation, in which most of the small herds disappeared, while the bigger herds increased in both number and size. By 1986 there were only about 12,500 breeding herds, and the average herd had just over fifty-seven sows, often kept in purpose-built housing and looked after by trained and experienced staff, marketed through specialist organisations, and forming a significant part of the farm business. Only one in ten of the very small herds (that is, those with less than ten sows) remained (Marks & Britton, 1989, pp. 216–218). This prevalence of small herds at the time when AI was first being introduced, and the increasing specialisation and professionalisation of pig farmers when the adoption of AI was increasing, were almost certainly significant factors in explaining the introduction and expansion of the technique.

Until the mid-1950s all sows and gilts were served by boars. Apparently simple as it may have been, this was in fact not without its problems. Boars could be difficult to control—there is an example of one that put its tusk through a tractor tyre when annoyed—and their progeny were untested. Geoff Hearnden, of Bridford in Devon, began to work on farms in about 1950, and remembers traditional breeders:

> I can remember one breeder saying he used to sit by the fire at night and think to himself which boar would knit with which sow to produce the perfect pig. So there was no, absolutely no, science in it at all.[8]

There was another problem for small farmers, which was that keeping a boar for only a few sows was an expensive business. Not only did they have to be fed and securely housed,

[8] Interview with G. Hearnden of Bridford, Devon, 18 February 2005, transcript p. 5.

they also had to be licensed.[9] Consequently many small pig producers did not keep their own boar, but took their sows to a boar owned by a bigger producer, a time-consuming process, or hired the services of a travelling boar. Geoff Hearnden again:

> The Ministry [of Agriculture] were licensing boars and they were also running a premium boar service. The inspection was just a visual appraisal, and people with travelling boars largely bought these premium boars and travelled them around the country in a trailer, and they went from farm to farm with the same boar and incredibly they served several sows on the same day, and it goes against absolutely everything we've learned since about biosecurity, but it seemed to work . . . it was run by individuals. It was a little service industry![10]

Mr Hearnden began to specialise in pigs after the winter of 1963, and expanded quickly until he had about a hundred sows, which at that time was a big pig unit. He soon began to use AI:

> I'd be guessing a bit, but I think it was quite early on, so probably 1964 and I think it was an experimental system run by Dartington AI and it may well have been free on the farm. I'm not sure. It was certainly delivered and the insemination was done by a person . . . they didn't use the catheters later developed which resembled boars' penises. They had a little plastic bottle with a little plastic tube on it, and I think basically it didn't work! (Q: what sort of conception rates were you getting?) I've got no idea but I don't think they got the techniques right. They were experimenting, because we didn't have a proper catheter. My guess is that they didn't work very well.[11]

The little plastic tube was probably the Norwegian equipment that used an inflatable cuff to stopper the cervix during insemination.[12] Figures for pig AI collected at the Ministry of Agriculture Fisheries and Food (MAFF) cattle breeding centre at Shinfield confirmed that conception rates were initially low, from as little as 18.1% in 1955 rising to 62% in 1961 (natural conception rates would be expected to be close to 90%).[13] Some pig breeders too remained unimpressed. Mr F. W. Trewhella, a Cornish breeder of Large White pigs was quoted as saying

[9] The Agriculture (Miscellaneous Provisions) Act, 1944 stated that 'the Improvement of Livestock (Licensing of Bulls) Act 1931 shall . . . apply to pigs as it applies to cattle' (Great Britain, 1944, Section 6). The original 1931 act was part of an attempt to bring about livestock improvement by controlling the use of poor quality sires (often referred to at the time as 'scrub' bulls). The process required a visual inspection by a Ministry inspector, followed by an official mark on the animal, often an ear tattoo. This was not without its problems: when the legislation was extended to pigs the Large Black Pig Society wondered how their boars could be identified. (See MAF 52/243). More seriously, there was a controversy over the value of the process for both cattle and pigs. W. S. Mansfield, Director of Cambridge University farms, and a colleague of Rowson and Polge, produced some serious criticisms of its effects in a *Farmer and Stockbreeder* article (23 June 1953), and as late as 1967 a ministry official was still defending it: 'You will have to eliminate the scrub farmer rather than the scrub bull before you can safely do away with licensing' (internal memo from C. H. M. Wilcox to Emrys Jones, 9 October 1967, in MAF 121/216).

[10] Interview with G. Hearnden, p. 10.

[11] Ibid., p. 2.

[12] This equipment is illustrated in Perry (1968), p. 253.

[13] MAF 124/91, f. 1a, memo from D. L. Stewart to E. S. Virgo, 25 January 1963.

> I cannot see any future in it for the people such as ourselves who breed for quality and the future . . . Nine or ten generations of AI cannot be as virile as stock by natural mating. It is cutting across nature.[14]

It is perhaps tempting to see a moral dimension in the language used in this statement. It is impossible to know now whether or not this was intended by the speaker. What perhaps mattered more at this point in the development of AI was that the moral issues raised in the early years of cattle AI no longer appeared to be so important, and Mr Trewhella's remarks may equally have been the result of his background as a pedigree breeder.

Geoff Hearnden returned to AI in the mid-1970s. By this time, he felt, the problems had been sorted out. The semen came by post, or was sent by rail to be picked up at Exeter station, and he had been on a training course run by the Meat and Livestock Commission (MLC) to learn how to carry out the inseminations himself: '. . . there were plenty of people anxious to do on-farm training . . . and you learnt on the job. Also the technology got better. The diluents they used got better, the life of the semen got better and we got to know more about timing'. Conception rates were as high as 80%, 'never quite as good as boars, but nevertheless very satisfactory', and the benefit, he felt, was that he had access to much better genetic material than he could have afforded to buy himself. By the mid-1960s, according to Professsor Polge, it had become clear

> that the 'nitty gritty' of making pig AI work better on farms could best be done by the specialist AI centres themselves. In my opinion the work of Hugh Reed at the MLC Pig Breeding Centre at Selby did most to increase conception rates and really make it work effectively. For example it was he who introduced the sending of semen to farmers by postal service so that they could do the AI themselves. This was a great advance. We collaborated a bit with Hugh on the development of 'long-life' semen extenders. Our work on ovulation also shed light on when this took place in relation to the onset of oestrus. We were therefore able to recommend the optimum time for insemination relative to oestrus in order to achieve the best fertilization results . . . The MLC also had a performance testing station, so they were able to select the best boars for the AI service'. (Polge, 2005)

Mr Hearnden could see the results of this performance testing in improved carcase quality returns from the bacon factory: 'some things were very easy to shift, like the thickness of backfat and length of carcase and these things improved dramatically'. At the same time it did not involve expensive changes to his whole farming system.[15] Professor Peter Brooks, an academic pig expert at the University of Plymouth, concurs with these views, and adds that big herd owners preferred this 'do it yourself' (DIY) system of AI because it reduced disease risks.

> The main concern was the transmission of anything that could be carried on clothes, boots etc. between one farm and another. At the time it was assumed that semen would come from healthy boars and that it would not in itself pose a problem . . . there was concern about transmission of the major bacterial diseases. The problem with these would only arise if the preceding unit was incubating a disease and it

[14] Anon. Test tube pigs arrive: doubts in West Cornwall, *The Cornishman*, 22 October 1955 (press cutting in MAF 124/90, f. 41).

[15] Interview with G. Hearnden, p. 3.

> had not appeared clinically. At least as great a concern was transmission of the various E. coli strains that are pig specific and can dramatically impair performance without constituting a disease outbreak as such. Having an AI inseminator going from herd to herd was seen as compromising biosecurity (although the term was not in common parlance then). Remember AI development was coming in at the time that units were increasing in size and producers were developing the idea of 'closed' herds (i.e. importing minimum animals to maintain health and also restricting visitors to the minimum). It did not make sense to be doing that and having some guy trooping around 20–30 pig units in a day spreading bugs as he went. Hence the development of the postal service, which overcame the problem.[16]

In 1991 the Meat and Livestock Commission listed the advantages of DIY AI as 'justification for the purchase of higher-calibre boars, ready availability of semen, costs of semen transport and risk of delays eliminated, marginally cheaper than public AI services'. On the other hand, they admitted, the practice had

> a number of shortcomings: staff responsible for AI must be of a higher calibre, higher degree of training needed, higher labour input required, higher capital costs involved, more attention to detail needed, risks of inbreeding if not careful, wider fluctuation in fertility levels and genetic progress more likely.[17]

Not all of these points are immediately self explanatory. In particular, it is certainly not clear why capital costs should be increased. For most commercial breeders, however, it was clearly the prospect of genetic improvement that was the major incentive to engage in AI. John Barwood, who has managed a large pig herd near Exeter since 1977, reports that in the 1970s he used AI to ensure genetic improvement in the grandparent generation of the herd, whereas in recent years it has been more for genetic stability. Biosecurity is also an advantage. He now uses AI for roughly 25% of matings, but intends to increase up to 50%. He too learned the technique on MLC courses, and by working with an inseminator from the West Buckland (Devon) AI centre. He now buys semen from the breeding companies, and speaks nostalgically of the days when there were celebrity boars standing at AI centres and conversations with other breeders would begin with 'Have you used such and such a boar?' In those days the breeders were people and you knew them by name. Now, he says, you just talk to the breeding company's salesman. There is now more science in it, it's more efficient, but it's not such fun. The boars don't have names any longer, just numbers.[18] At the upper end of the genetic spectrum, British Livestock Genetics, which co-ordinates semen export sales from UK livestock, includes frozen pig semen in its product range, although admittedly conception rates from frozen semen are still poor.[19]

Over the forty years from the middle of the 1950s, therefore, parts of the product, service or technique had changed, while others remained the same. The main changes were in the equipment and the expertise of the inseminators, and the concomitant success of the insemination process. What remained the same was the main reason for using AI: access to better genetic material, and, for bigger herds, a saving in the number of boars needed. A micro-economic explanation of innovation and adoption would see this as a way of

[16] Brooks (2006).
[17] Meat and Livestock Commission (1991), p. 57.
[18] Interview with J. Barwood, 2 March 2005.
[19] Interview with R. Wills, British Livestock Genetics, 1 March 2005.

increasing output without incurring much if any extra cost, and at the same time reducing costs of acquiring, feeding and housing boars. There is one factor, however, which may be seen as either technical or financial or an indivisible combination of both, that was crucial: low conception rates had a major effect on pig herd profitability, so widespread AI was unimaginable until conception rates were roughly comparable with those of natural service. But this still leaves several questions unanswered. How did the whole process begin? Was it just an inevitable offshoot of dairy AI, or was something else needed? How were the technical changes brought about? Why did the meat and Livestock Commission help to provide the semen and training? If AI was such a good idea, why did it take so long to catch on even after the mid-1970s when the major technical problems had been overcome? In order to attempt to answer these questions it is necessary to examine further dimensions of the history of AI.

3.2. Authorities and pig AI

Authority, in this context, means people and organisations with some ability to affect the way in which an innovation is perceived, administered, controlled, provided or sold. The first authorities were the scientists who acquired, from their own work or from other scientists, through the normal means of scientific communication, some knowledge of the principles and techniques of AI. Initially scientific work in the UK concentrated on AI in cattle, and was mainly carried out at Cambridge University. Then in 1954 Glover and Mann published a paper on the composition of boar semen in the *Journal of Agricultural Science*, and in October of the same year L. E. Rowson, who also worked at Cambridge, wrote to the Ministry of Agriculture, Fisheries and Food (MAFF) announcing that experimental work on preserving boar semen had been going on there with a view to developing pig AI.[20] At this point in time, in Professor Polge's recollection, pig AI work was entirely a matter of scientific curiosity:

> It was . . . the next step I took after I had been working on freezing bull semen during previous years. I moved from the National Institute for Medical Research in London, where we had started the semen freezing work, to the Animal Research Station in Cambridge in 1954. I had been coming to Cambridge quite a lot before then to apply semen freezing in cattle breeding, so I knew the Research Station quite well. John Hammond was then head of the ARC [Agricultural Research Council] Unit of Animal Reproduction at the Animal Research Station, but was due to retire fairly soon. He had some pigs that he had been using for in-breeding experiments. No one seemed to have any particular designs on these animals so I took them over in order to have a go at freezing boar semen. Pigs were one of the species I had not tried previously . . . I obtained quite good pregnancy rates in sows using fresh semen or semen kept in various diluents. But I got no pregnancies with the frozen semen. (Polge, 2005)

However, Rowson's letter to the Ministry soon introduced a new set of authorities into the development process. Six weeks later, as noted above, Dartington Hall Cattle Breeding Centre became involved, and on 10 December 1954 the matter was discussed at a meeting of the private AI centres group. MAFF then asked the Agricultural Improvement Council

[20] Glover & Mann (1954); MAF 124/90, f. 6, L. E. Rowson to F. Harold Smith, 9 October 1954. The first paper specifically on AI in pigs was Polge (1956). I am most grateful to Professor Polge for this information.

for comments, and on 16 December began to explore the possibility of expanding the terms of reference and membership of its Central Advisory Committee on AI (CACAI) to take in pig AI. On 26 January 1955 the British Veterinary Association wrote to the Ministry to ask what was happening about pig AI.[21] Within a little over four months, therefore, an extensive network of advisory bodies were reacting to the initiative of the scientists. In fact, it probably went further, because the membership of the Central Advisory Committee on AI contained representatives of the Royal Agricultural Society, the National Farmers' Union (NFU). The Milk Marketing Board (MMB), various breed societies, and the MAFF chief veterinary officer and chief livestock husbandry officer.[22] These groups were also in contact with the Ministry's Bull and Boar Licensing Advisory Committee.[23]

The next major development came in the autumn of 1957, when the assets of the now defunct Pigs Marketing, Bacon Marketing, and Bacon Development Boards were transferred to the Pig Industry Development Authority (PIDA), which had been established under the provisions of the 1957 Agriculture Act. The governing body included representatives of commercial and pedigree pig producers, farm workers, and pig processors and retailers.[24] PIDA remained as an independent body for about ten years before it was subsumed into the Meat and Livestock Commission (MLC).[25]

Each of these authority groups was, of course, composed of people, and, in its early days especially, pig AI was a small world. The scientists involved came from the group of workers at Cambridge who had originally started work on cattle AI, led by Dr (later Sir) John Hammond, with Dr Arthur Walton and Dr Joseph Edwards, who subsequently went to head the Production Division of the MMB. (Seddon, 1989, p. 42) This group had been instrumental in setting up the first cattle AI centre at Cambridge in 1942, and had appointed L. E. Rowson as the Veterinary Officer in Charge. Rowson subsequently spent part of his time at Hammond's Animal Research Station (later the Unit of Animal Reproduction) at Cambridge University, where he was later joined by Polge (Polge, 2000). He was also a friend of the Cambridge University farms director, W. S. Mansfield, who in 1953 wrote an article attacking bull and boar licensing.[26] Interestingly, Hammond and Edwards were both members of the Ministry's Bull and Boar Licensing Advisory Committee, together with W. Bellerby of the National Pig Breeders Association. Its secretary, always a MAFF civil servant, was initially G. R. Woodward and subsequently F. J. S. Culley.[27] Woodward and Culley were also secretaries of the Ministry's Central Advisory

[21] MAF 124/90, f. 11, letter from E. A. Farey to W. P. Dodgson, 24 November 1954; f. 12, report by G. R. Woodward on the meeting of the private AI centres group, 10 December 1954; f. 14, letter from G. R. Woodward to the Agricultural Improvement Council, 16 December 1954; f. 21, letter from the BVA to the AIC.

[22] MAF 124/18, MAFF press release 10 June 1952.

[23] MAF 121/152, re operations and membership of the committee.

[24] MAF 124/90, ff. 77, 78, MAFF press releases on 25 September 1957 and 2 October 1957.

[25] The Meat and Livestock Commission was established under the provisions of the 1967 Agriculture Act and incorporated the Pig Industry Development Authority and the Beef Recording Association. It remains in existence as a non-departmental public body funded through a levy on slaughtered or exported livestock, supplemented by EU and UK government grants and the revenue from its own commercial activities, and directed by Commissioners appointed by the Department for Environment, Food and Rural Affairs, the Scottish Executive and the Welsh Assembly. See www.mlc.org.uk.

[26] *Farmer and Stockbreeder*, 23 June 1953. The article was noted in MAF 121/216 Bull and Boar Licensing: criticisms. I am grateful to the late John Halley for information on Rowson and Mansfield.

[27] MAF 121/152, list of committee members, n.d. but probably 1954. See also MAF 124, f. 40.

Committee on AI, the membership of which overlapped with the bull and boar licensing committee, in that it included Hammond, Edwards and Bellerby. Rowson was also a member by 1959, and so was A. S. Cray, who represented the pedigree pig breeders and was also on the governing council of PIDA. There were also representatives of the AI centres, by 1970 the associated AI centres had a liason group of their own that met with MAFF officials.[28] At upper levels, therefore, it is possible to discern a series of interlocking groups who knew each other through their memberships of MAFF committees, if through no other connection.[29] The same sort of links are also apparent at officer level. D. R. Melrose from the Ministry's AI centre at Reading was loaned to PIDA to work on pig AI in 1959. He subsequently became a permanent and senior member of the PIDA, and then the MLC staff, and it was he who invented the spiral catheter.[30] There were also international connections. While Melrose was still working at Reading he mentions contacts with Dr John Aamdal in Norway and Dr Niwa in Japan, and in 1961, together with I. C. Beattie, the scientific secretary of the PIDA, he attended the international conference of animal reproduction at the Hague.[31] Dr Hugh Reed of the MLC also worked with colleagues in the Netherlands.[32]

The final group of authorities was the breeding companies. The first of these to be involved in AI appears to be T. Wall and Sons Ltd (not a breeding, but a pigmeat production company), who in 1966 applied for a licence to distribute semen to producers who were contracted to them.[33] By the 1970s others such as the Cotswold Pig Development Company and the Pig Improvement Company (PIC) had emerged, although they were not initially enthusiastic about AI.[34] Professor Polge recalls attempting to persuade Dr Maurice Bichard, the PIC geneticist, to adopt AI: 'he always said that all their research effort was geared to their breeding programme and he didn't see a place for these new techniques in their work' (Polge, 2005). Eventually their main competitor introduced AI after recruiting a research worker from the Scottish counterpart of the Cambridge University Unit of Animal Reproduction, the Animal Breeding Research Organisation (ABRO, as it then was) in Edinburgh. As Polge explains,

[28] MAF 52/319, minutes of the CACAI, 20 October 1959; MAF 124/90, f. 77/8; MAF 124/18; MAF 287/437.

[29] There is an interesting insight into how this could affect policy in an internal memo written by Mr Duke of MAFF after a meeting with Messrs Oake and Beattie of PIDA in 1961: 'PIDA at official level had been given something of a brush-off by Dr Edwards of the MMB when they asked to discuss the possibility of running pig AI as a commercial service along cattle AI . . . I expressed doubts as to whether it would be wise to the Ministry to intervene with the chairman of the MMB because it might put Dr Edwards's nose out of joint and he would be less co-operative then ever . . . we suggested, and Mr Oake agreed, that probably the best thing would be for him to arrange a luncheon or dinner party at which his Chairman and himself should entertain the Chairman of the MMB and Dr Edwards to discuss the problem with them. MAF 124/90 internal memo by C. H. A. Duke, 23 November 1961.

[30] MAF 189/869, ff. 23–24.

[31] Ibid.; MAF 124/90, f. 104A.

[32] According to Polge (2005), 'Hugh Reed collaborated quite a lot with workers in Holland because that was a country where pig AI was eventually used most extensively'.

[33] MAF 124/112.

[34] Robertson (1969), p. 29, noted that 'More recently, we have seen in this country [the UK] how the entry of poultry breeding firms into pig breeding has awakened the traditional pig breeders'. In the long run it was the specialist pig firms, such as Cotswold and PIC, rather than the poultry breeders, that came to dominate pig breeding.

> It was John Webb, when he joined Cotswolds from ABRO, who was the first to introduce AI into their breeding programme. He saw this as an ideal way of moving genetic resources between their nucleus herds without danger of moving animals and possibly disease. Later PIC also adopted some AI in their own breeding programme. (Ibid.)

By the 1990s the breeding companies were having the principal impact on the way that AI was perceived, provided and sold. They had taken over as the leading authority from the MLC and the PIDA, who had in turn superseded the scientists who initially developed the technique. Initially, as we have seen, the initiation of the technique came about as the result of pure science, but the scientist involved was part of a group that had close personal contacts with a wide range of national bodies, each of which, in various ways, had interests in promoting administering, controlling, providing, and, eventually, selling AI. From the 1950s to the 1990s, in short, different people and organisations had authority in the development of AI. But this does not explain how this authority was exercised, and to do this we must examine the activities of the authorities.

3.3. Activities and discourses

Scientists engage in science and use a scientific discourse in which knowledge is established through experimental methods and transmitted in technical language through scientific journals and conferences, and that is how pig AI was first introduced into the UK.[35] Thereafter the discourses of the principal authorities became more of a mixture, of the scientific, technical, legal, administrative, educational (that is, training and extension), and commercial. Almost from the beginning a conflict emerged within the activities of MAFF. When the Agricultural Improvement Council (AIC) met on 19 January 1955 to discuss the question of whether or not the Ministry should take powers to control pig AI, it gave its opinion that pig AI 'could have a relatively limited application although its importance would increase as progeny testing schemes began to bring to light boars of outstanding genetic quality'.[36] AI, in other words, was identified as a matter of livestock improvement. However, when the Central Advisory Committee on AI met in June 1955, Professor Hammond, from Cambridge, was more worried about disease risks.[37] The rest of the Committee did not share his anxiety, and in fact the Ministry's chief veterinary officer had already suggested that there was little to worry about as long as pigs in AI stations were not fed on

[35] In the context of science and scientists, discourse means the use of specific technical language in professionalized media such as scientific journals and conferences. Civil servants and farmers are likely to use different discourses.

[36] MAF 124/90, f. 28A, notes of the AIC meeting of 19 January 1955. The use of the term 'progeny testing' in the notes of the AIC meeting is interesting. Progeny testing is needed when the characteristic under test is not expressed by the animal under test. Thus a bull's ability to pass on high milk yields can only be assessed by testing the performance of his daughters—that is, his progeny. Progeny testing was originally known as 'contemporary comparison' and was introduced by the MMB, and associated with AI and milk (yield) recording. When the test characteristic is expressed by the animal under test it can be measured on the animal itself. Thus boars can be tested for growth rate and backfat thickness. This is known as 'performance testing', and was used by the MLC from the 1970s onwards. (I am grateful to Professor Peter Brooks for elucidating the difference.) The speakers at the AIC meeting were probably referring to performance testing, but since cattle AI was much more common than pig AI in 1955 they would be more familiar with the idea of progeny testing and so use that term.

[37] MAF 124/90, f. 40, minutes of the CACAI, 20 June 1955.

swill (which was perceived to be a possible source of Foot and Mouth Disease). Nevertheless, such was the concern in the Ministry about the possible impact of livestock disease that there was often an internal conflict between the veterinary and technical branches over whose expertise was the more relevant.[38] This conflict between disease control and livestock improvement was to rumble on within the Ministry for years. In 1966, for example, in an internal memo, a civil servant wrote

> How far is our AI control operated for animal health reasons and how far as a means of livestock improvement ... is it for us or PIDA (to be succeeded by the [Meat and Livestock] Commission) to look after the livestock improvement aspects of AI?[39]

In some ways, Hammond seems to have had the best of the argument. In 1958 draft regulations on pig AI were prepared for introduction 'when the need arose'. They simply stipulated that a licence would be required to distribute boar semen, the collection and storage of which should be supervised by a MAFF-approved vet. Much of the rest of the regulation concerned what should happen in the event of an outbreak of Foot and Mouth Disease. It was not until 1961 that Mr G. R. Oake of PIDA wrote Mr C. H. A. Duke of MAFF saying that the Authority would now like the regulation implemented because they were hearing of proposals to establish new AI centres. This began a process of consultation, and it was not until 2 November 1964 that Statutory Instrument No. 1172 came into operation as the Artificial Insemination of Pigs (England and Wales) Regulation 1964.[40]

The 1964 regulation thus introduced a legal licensing and control discourse into pig AI. Unfortunately, it soon came into conflict with the emerging technology. The regulation had been based on the cattle AI regulations, which naturally assumed that insemination would be carried out by visiting inseminators, who would be licensed by the Ministry. If individual farmers wished to use DIY AI they therefore needed a supplementary licence, the terms of which were extremely restrictive. The licence issued to Mr and Mrs Lockhart of Grange farm, Covington, in Huntingdonshire on 3 December 1964, for example, was

> for the purpose of the insemination of sows in their ownership or possession belonging to the Covington herd of pedigree large White pigs, such insemination to be carried out either by Mr R. D. Lockhart or Mrs U. Lockhart personally or by any veterinary surgeon[41]

and licences of this type had to be issued to anybody who wished to carry out DIY AI. It meant that the AI centres had to send long lists of their customers to MAFF, and in March 1966 Mr Horne of MAFF proposed a simplification of the system. This drew a sharp note from Mr H. T. Reade of the Ministry's legal branch: 'We had endless trouble agreeing these regulations, and within two years we are trying to ''get round'' them'. Horne responded: the regulations were based on cattle AI regulations,

[38] MAF 124/90, f. 19, 19 January 1955. For the ongoing problems caused by Foot and Mouth Disease in this period, see Woods (2004).
[39] MAF 124/112, internal memo from A. B. Bartlett, 24 August 1966.
[40] MAF 124/90, ff. 105A, 106, 105D; MAF 287/146, f. 53.
[41] MAF 124/113, f. 25, licence no. 4/4/Supplementary, 3 December 1964.

> but in practice the pig AI is developing on different lines for a variety of reasons . . . [because of disease risks] many breeders restrict entry to their herds to the minimum, a view upheld by our own veterinary service.

The arguments smouldered for nearly another two years without much happening, and then in December 1967 a meeting of PIDA staff, representatives from the Reading, Dartington and Norfolk AI centres, and Mrs Tait and Miss Marston from MAFF returned to the increasing popularity of DIY AI. In January 1968 Mrs Tait wrote to Mr Reade: whereas in 1966 the Ministry's vets had clung to the need for individual licences, 'they are now prepared for us to authorise centres in general terms (subject to suitable conditions) to send semen to any breeder or farmer'.[42] The result was that by April 1968 AI centres were simply asking recipients to sign an undertaking not to resell semen or to use it to inseminate pigs belonging to anybody else.[43]

What might seem like a minor bureaucratic spat has been discussed here in some detail because it illustrates the importance of authority in the emergence of a product. It was not simply a matter of the scientists at Cambridge developing pig AI, making it available to the AI centres, and waiting for the pig industry to take it or leave it. MAFF became involved at an early stage, and almost immediately became involved in an internal conflict over whether its role was encouragement or control (or both). The various branches of MAFF each had their different responsibilities, and while the livestock branch might be concerned with improving genetic quality, the vets were concerned with disease control, both national and international, and perhaps also with the role of their profession—why else make the provision about a vet in the supplementary licences? The construction of the product, in other words, became not only a technical matter involving a scientific and technical discourse, but also a legal and bureaucratic matter with a corresponding legal and regulatory discourse. These internal arguments within MAFF have interesting implications as far as the study of innovation is concerned. They produce copious historical records, assiduously preserved in national archives, and so provide evidence of the Ministry's interest and involvement in the process of innovation. To those working outside the Ministry at the time, however, the internal conflicts produced a different impression. Professor Polge recalling the beginning of pig AI, felt that

> the Ministry of Agriculture certainly had nothing to do with it . . . I don't know if the Ministry of Agriculture were particularly enthusiastic about pig AI and certainly they never provided me with any funding . . . The one Ministry person who was enthusiastic was Dick Melrose

who at the time was working at the Ministry's Reading AI Centre, and was thus not so closely involved in the arguments within MAFF headquarters (Polge, 2005).

There were also arguments between the Milk Marketing Board (MMB) and PIDA about who should run the pig AI stations. PIDA's initial view was that the MMB had an existing AI framework and it would be much easier and cheaper if pig AI were simply attached to it.[44] The MMB disagreed, and although semen continued to be available from Dartington and the Ministry's own AI centre at Reading, in 1964 PIDA felt the need to set

[42] MAF 287/146, and various internal memos at the front of file MAF124/113.
[43] MAF 124/113, f. 72/72A.
[44] MAF 124/90, internal memo at the front of file from C. H. A. Duke, 23 November 1961.

up its own AI centre at Thorpe Willoughby near Selby in Yorkshire, and by 1967 was looking to establish another one in the South West of England (which eventually became West Buckland).[45] Dartington ceased to offer a pig AI service in September 1968 (Stewart, 2004, pp. 85–87). In Professor Polge's view

> the grafting of pig AI on to Cattle Breeding Centres was a bit of a disaster as very poor pregnancy results were generally achieved. I think this was because the technique in pigs was quite different from that in cattle and the Inseminators were not able to adapt, particularly in making sure that the pigs they were inseminating were at the appropriate stage of oestrus. (Polge, 2005)

By 1969 it was clear that PIDA were taking over as the leading authority on pig AI. Not only were they running their own AI centre and co-ordinating the relationships between the other centres and MAFF, but their specialist pig officers were also running large demonstrations and smaller training events to popularise DIY AI.[46] This might be seen as a sort of generic advertising. Farmers were being encouraged to buy into the technique, rather than any one organisation's provision of the technique. The technical discourse, as it were, was reclaiming the central role from the legal discourse. This continued to be the case when MLC took over PIDA's work, and probably remained so until later in the 1980s. At some point, however, as the breeding companies increased in importance, it is possible to see a new commercial discourse emerging. Boars at AI are advertised as brands. Thus PIC, under the banner 'Britain's best boars come by post', advertises its Gene Transfer improvement (GTi) sirelines, 'delivered promptly from one of our four regional centres'.[47]

3.4. Media

These changing discourses were transmitted through changing media. Initially, it was a scientific discourse in the scientific literature, and then it spread to agricultural textbooks. The 1953 edition of *The agricultural notebook* carried an article on AI by Sir John Hammond, although he did not mention pig AI (Moore, 1953, pp. 62–66). Geoffrey Johnson's *Profitable pig farming*, published in 1959, asserted that 'It is a perfectly simple and practicable thing for a pig farmer to set up and operate artificial insemination arrangements on his own farm' (Johnson, 1959, p. 155), but Price's 1962 textbook was more circumspect, emphasising the problems and suggesting that 'it may be some years before we have an adequate cheap service' (Price, 1962, p. 98). But it was the farming press that probably had the greater impact. As we have already seen, Dr Polge wrote an article about AI in *Pig Farming* in 1954: 'The editor of *Pig Farming* used to visit the lab to see if we had any new advances that would be of interest to the farming community. I also used to do some broadcasts on the radio and TV' (Polge, 2005).[48] Subsequently the MAFF monthly journal *Agriculture* carried several articles. As a producer, Geoff Hearnden identified the press as one of his main sources of information:

> I don't remember it being an issue at college but I think it probably would have been in the farming press. I think the farming press has always been useful in spreading

[45] Anon. (1964, 1967).
[46] MAF 287/146, letter from Melrose (PIDA) to Brown (MAFF) 27 March 1969.
[47] PIC (2000).
[48] Polge (2005), and see n. 4 above.

> techniques right from the early days. The *Farmers Weekly* was always picking up innovation because it was always news. The *Farmer and Stockbreeder* and all those things always had innovatory stuff because that's what made the news.[49]

He also emphasised the importance of MLC's extension activities, which took the form not only of published output but also of numerous meeting and training events:

> the real push came from MLC, and when they sold out their AI interests it came from the breeding companies, who ran the AI services, and still do, and there's a commercial imperative then to sell the stuff.[50]

It is this commercial imperative that is now translated into the advertisements mentioned above, and the numerous breeding company websites that fulfil the same function.[51]

4. Theories, explanations, and conclusions

What is intended to emerge from this paper is a picture of a multi-dimensional process by which a new technique is constructed and used. Pig AI constitutes an interesting case study because it took some time to develop, unlike AI in cattle, which was widely adopted very quickly after 1945. In consequence, therefore, there were arguments and frustrations over long periods of time, which led to evidence remaining in the archives. More widely, it seems likely that similar dimensions could be examined in the construction of other agricultural innovations, from embryo transplants to genetically modified crops, and beyond agriculture in the construction of new technology more generally.[52] There are numerous theoretical approaches to the analysis of such technical changes, each of which could be applied to the developments discussed in this study: diffusionism, user co-construction, actor network theory, social worlds theory, conventions theory, all have some explanatory power on one or more of the dimensions of change discussed above, without quite explaining why they all occurred or how they relate to each other.[53]

It is also important to recognize that the multi-dimensional process is not sequential but contemporaneous. In other words, the various changes within the various dimensions can, and in all probability will, happen at the same time. What does *not* happen is that a technique is perfected, then handed over to the authorities, who change the way it is perceived and then use the media to tell potential users about it. Instead, all these processes go on, at differing rates of change, at the same time, often within a changing socio-economic context. Technical change might be much neater and more intelligible if it were otherwise, but it is not. But somehow the historian of technical change has to make sense of the whole complex multi-dimensional process. Therefore the purpose of Table 4 is to summarise the

[49] Interview with G. Hearnden, p. 6.
[50] Ibid., p. 9.
[51] I am grateful to Rob Wills of British Livestock Genetics for this information; www.britishlivestockgenetics.com provides links to breeding company websites.
[52] See, for example, Palladino (2002); Kloppenburg (1988).
[53] The classic work on diffusionism is Rogers (1995), the first edition of which was published in 1962. For a recent example of diffusionist work see Goldman & Eliason (2003). User co-construction is covered in Oudshoorn & Pinch (2003), actor network theory in Callon, Law, & Rip (1986), social worlds theory in Clarke (1998), and conventions theory in Murdoch, Marsden, & Banks (2000).

Table 4
The development of pig AI. For explanations of acronyms see text

1. Dates and development stages	2. Technique perceived by users	3. Authorities	4. Discourse	5. Media
1940s pre-pig AI	Natural service + travelling boars	Traditional breeders and breed societies	Natural and traditional	Herdbooks and shows
early 1950s scientific investigations	Natural service + AI by inseminators, low conception rates, untested boars	University scientists MAFF AIC CACAI	Scientific	Scientific literature
later 1950s commercial product available		CBCs MMB Vets Breed societies	Technical + Legal—approval, licensing and control	Agricultural textbooks Farming Press
1960s AI adopted by a few		PIDA MLC	Technical	
1970s DIY AI increasing *1980s* AI widely adopted	Natural service + DIY AI with effective equipment, high conception rates, proven boars			Extension activities—generic demonstration
1990		Breeding companies	Commercial branding	Adverts and websites

process and to show how the various changes in each dimension were linked across time. The discussion in the foregoing pages has treated each dimension in turn—techniques, then authorities, then discourses, then media—but Table 4 emphasises their contemporaneity. Thus in the 1940s, before AI techniques had been applied to pigs, their reproduction required natural service, usually but not exclusively by a boar kept on the farm. Insofar as this was controlled by anybody it was under the authority of traditional breeders and breed societies, and it was their standards of what constituted a good pig as opposed to a bad one that informed the Ministry's boar licensing inspectors. This authority was legitimised by the discourse of traditional breeders that was expressed in terms of natural mating between males and females of known parentage, with the results being tested by visual inspection by judges appointed by the breed societies. The medium through which this inspection took place was the agricultural show and the entry of the pedigrees of the animals in a herd book. Clearly not every pig, or even every boar, in the country was tested in this way, but those that were not were implicitly judged against those that were. By the 1990s, as the bottom of Table 4 shows, all these dimensions had changed. Reproduction was achieved by a mixture of natural service and AI, breeding companies used population genetics theory and performance testing to differentiate between boars of higher or lower quality, and they constituted the authority for recognizing this quality.[54] The discourse

[54] See Robertson (1969), pp. 31–32, for an explanation of the way in which performance testing was carried out in the late 1960s.

used to legitimise the decisions of the companies was one of commercial branding. In other words, the potential semen buyer had expectations of the quality of the semen simply by virtue of the brand attached to it, without needing to see the performance testing results, although various media, such as advertisements in trade journals and internet websites would be used to substantiate the quality of a brand. The 1940s and earlier, and the 1990s and later, might thus be seen as periods of stability as far as insemination is concerned; in between these two periods of stability there were in contrast dynamic periods in which some or all of the dimensions—techniques, authorities, discourse, media—were undergoing change.

Clearly most of this paper is concerned with what happened in the dynamic periods. As the summary in Table 4 shows, the early 1950s were a period when pig AI was a matter for scientific discourse in the scientific literature, and it was scientists and their concerns that determined what would be discussed. By the later 1950s, however, when their efforts had produced the initial, albeit imperfect, possibilities of AI, numerous other authorities were drawn in, and the discourse changed from the purely scientific to the technical, concerned with improving the details and consequently the effectiveness of the technique. At the same time, as a result of other concerns of the authorities, there was also a legal discourse, and both of these discourses were transmitted through the farming press. As far as the analysis of the authorities is concerned, this is one of the most interesting periods, mostly because of the number of authorities involved. MAFF's policy of agricultural expansion in the 1940–1980 period was not just left to setting high prices and allowing market signals to do the rest. Through formal bodies such as the Agricultural Improvement Council and the Central Advisory Council on AI, and through informal contacts between civil servants, scientists, workers at AI centres and so on, they formed a network of expertise and information. This is perhaps an aspect of the agricultural corporatism (i.e. the integration of government and industry) of the period that could be further investigated (see also Cox, Lowe, & Winter, 1986).

By the 1970s it was clear that the Meat and Livestock Commission (MLC) had become the dominant authority. Its employees, led by Drs Melrose and Reed, were perfecting the techniques and using a variety of extension activities to demonstrate them to potential and actual users, and approval, licensing and control were no longer seen as legal issues. These activities continued through the 1980s, by the end of which knowledge and acceptance of the technique was widespread through the pig industry. Obviously (and as Table 3 shows) there remain some pig farmers that do not use AI at all, and few commercial herds use AI exclusively, but the technique is now established as one of the reliable methods of impregnating sows, whereas before 1954 natural service was the only method available, and before the 1970s it was the only widespread and reliable method.

Few pig farms used AI in the late 1960s/early 1970s whereas many of them used it ten years later. At some point or short period of time between 1975 and 1985 all the necessary components of the system came together: the right diluents for the semen and an effective catheter to deliver it; training for farmers and their staff in the techniques, especially those of oestrus detection; provision of that training by PIDA and MLC; ever-tighter specifications by pigmeat processors providing an increasing financial incentive to use better genetic material from boars standing in AI stations to improve the carcase quality of fat pigs; and an environment favourable to technical change and output increase produced by a long run of government policies. When these were all available the use of AI

expanded rapidly.[55] As with many innovations, what initially appeared to be a fairly straightforward application of a scientific discovery turned out to be the development of a complex multi-dimensional system with economic, political, and social, as well as technical, components. This is why an examination of the scientific and technical changes by themselves is insufficient to explain when and why changes occurred. This is not a new conclusion; most of the economic and social theories of technical change are based on the same idea. But, ironically, these theories themselves then frequently privilege a single category of variables, whether micro or macro-economic, actors and networks, social worlds, or conventions. What might be claimed as novel in the present paper is the analysis of the authorities, discourses and media involved in the process and of their cross-dimensional temporal links. It is these that enable the critical components of the system to be identified. This is not to claim that the analysis presented here is complete. It does not, for example, examine the same processes in other countries, or probe in detail the differences between users and non-users of AI. It would also be interesting to apply the same approach to a different technical change. But it does seem possible at this point to claim that a multi-dimensional approach such as the one used here produces a more robust explanation of technical change than one that relies upon a single category of variables. The difficulty is then to maintain control of the resulting range of variables, but categorizing them as in Table 4 appears to be a useful approach worth further investigation and application to other technical changes.

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[55] For a similar explanation of delays in the adoption of nitrogenous fertilizers, high-yielding rice varieties, and silage, see Brassley (1996).

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